Q'@gile
Quantum Agile Manufacture of Internal Combustion Engines

by

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A Doctoral Thesis
Submitted in partial fulfilment of the
Requirements for the award of

Doctor of Philosophy

Loughborough University

Loughborough, 2005

To my son,

José

AKNOWLEDGEMENTS

I would like to express my gratitude to the following people and institutions:

My parents, José and Luísa for the gift of life and their love;

Professor Richard Weston, the supervisor of the authors' research studies; Mrs. Margaret Carden; Dr. Robert Harrison; Dr. Andrew West and all my contemporary colleagues at the MSI Research Institute, Loughborough University;

Charles Blossom from the Aeronautical and Automotive Engineering Department; Steve Newman, Shahin Rahimifard and Colin Garner from the Wolfson School of Mechanical and Manufacturing Engineering; Ian Campbell from the Department of Design and Technology;

Alison Cox from the Dagenham engine plant and John Ladbrook from the Dunton Engineering Centre, Ford Motor Co. UK;

The University of Minho, for the teaching leave that allowed me to conduct research at Loughborough University; Dr. Pedro Oliveira, Dr. Madalena Araújo and Dr. Lopes Nunes from the University of Minho;

Cristina and all the seven couples and their lovely children which are the base of my beloved family;

Joana Vasconcelos; Daniel; Radhmer; Immanuel and Vinitha, Xiong Ji; Giorgos; Richard and Anna; Suresh; Arvind and Grand Parents; Kavitha; Rui Sousa; Francesca; Veronica; Jing Jing and Fr. Philip, for their friendship, support or simply their earthly existence.

This research was supported by *Fundação para a Ciência e a Tecnologia* and *Fundo Social Europeu – III Quadro Comunitário de Apoio.*

ABSTRACT

Current trends in the automotive industry towards fuel efficient and low emission vehicles, are dictated by more environmental friendly customers, more strict environmental legislation, rising fuel costs and intensive competition. These factors are pressuring vehicle manufacturers to speed up R&D and improve the efficiency and flexibility of their manufacturing operations so that improved products can be introduced over shortened timeframes. Recent advances have been focused on improving the design of internal combustion engines, coupled with research into alternative fuels and related new forms of vehicle propulsion. Natural impacts of these advances have been shorter engine lifetimes, increased pace of engine innovations, and significant changes in propulsion type share: in Europe the diesel engine share is increasing relative to that of petrol engines while in the US and Japan hybrids are becoming popular. In the long term Fuel Cell and Hydrogen fuelled vehicles may largely make internal combustion engines obsolete.

Internal combustion engine manufacture has traditionally been realised via a Mass Production paradigm, capable of the inflexible realisation of single model engines in large volumes (fixed production capacity) at low cost. This paradigm and the supporting production systems naturally constrain the ability to economically produce several engine models during the lifetime of production systems. A further related outcome is that if required volumes of a particular engine type vary significantly then excess production capacity will be common and unit engine production costs will rise.

Vehicle manufacturers are addressing this problem by: a) establishing strategic alliances with respect to engine R&D and engine manufacture, in order to reduce the time to market and to minimise risks associated with high levels of investment in engine manufacturing facilities. Such an alliance can enable increased volumes of engines to be shared by several multiple vehicle manufacturers; b) rationalising the design of engine families to enable the production of several engines models using the same machining facilities; and c) deploying more flexible manufacturing technology and an agile manufacturing paradigm.

This thesis proposes and researches a novel Q'@gile manufacturing approach. Q'@gile was conceived to address problems of excess manufacturing capacity and the current lack of engine manufacturing agility. Q'@gile systems comprise a variable number of cells. Each cell is implemented via high speed CNC machining centres and represents a quantum of production capacity. It follows that engine plant capacity built from Q'@gile cells can be engineered and changed in quantum steps via systemic processes of cell instalment, dismantlement or reallocation.

To provide a capability to quantitatively assess the performance of Q'@gile systems relative to conventional engine manufacturing technology and associated paradigms, this research study has specified, developed and used a number of related models. One such model is a simulation model which has been used to contrast and compare the performance of Q'@gile engine production lines relative to that of Dedicated Transfer Line (DTL) technology. DTLs were chosen as a benchmark as they are currently the dominant technology used by the industry to produce car engines. The simulation model so created enables comparison to be drawn between conventional and proposed Q'@gile approaches when production lines are subjected to different patterns of major and minor change. Another thread of modelling has concerned that of predicting the nature of engine demand patterns over the next fifteen years. Here publications and proprietary data about alternative fuels, and their likely availability and cost, and about emerging engine propulsion technologies, and their predicted market penetration, were used to analyse possible future extremes of engine type and configuration share. This analysis identified 36 possible future scenarios and for each case quantifies likely impacts on engine demand. A third thread of modelling concerns investment analysis. Here an investment model was developed and used to predict relative economic performance of Q'@gile and DTL engine production lines, with respect to the 36 possible futures that the automotive industry might face.

Results of simulation and investment modelling work reported in the thesis have identified future conditions under which old and new technologies can be expected to out-perform each other.

Keywords: Internal Combustion Engine, Engine Parts Machining, Excess Capacity, Agile Manufacturing, System Flexibility, Q'@gile Manufacturing System

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LIST OF ABBREVIATIONS

ACEA	European Automobile Manufacturers Association
ASF	Audi Space Frame
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CBA	Component-Based Approach
cd	Aerodynamics drag coefficient
CGI	Compacted Graphite Iron
CIM	Computer-Integrated Manufacturing
CNC	Computer Numerical Control
DNC	Direct Numerical Control
DTL	Dedicated Transfer Line
EU	European Union
FCV	Fuel Cell Vehicle
FMS	Flexible Manufacturing System
G Language	Graphical programming language used in LabVIEW
H2-FCV	Fuel Cell Vehicle running on Hydrogen
H2-ICE	Internal Combustion Engine running on Hydrogen
HMI	Human-Machine Interface
ICE	Internal Combustion Engine
JAMA	Japan Automobile Manufacturers Association
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LED	Light Emitting Diode
mpg	Miles per Gallon
MSI	Manufacturing Systems Integration Research Institute
NC	Numerical Control
OPEC	Organization of the Petroleum Exporting Countries
PEMFC	Proton Exchange Membrane Fuel Cell
Q'@gile system	Quantum Agile Manufacturing System
R&D	Research and Development
SMMT	Society of Motor Manufacturers and Traders
UNFCCC	United Nations Framework Convention on Climate Change
VDA	*Verband der Automobilindustrie* (German Automotive Association)
VI	Virtual Instrument
WBCSD	World Business Council for Sustainable Development

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

The Automotive Industry constitutes one of the most dynamic and advanced sectors of global manufacturing activity. The European automotive industry accounts for about 3% of EU(15) GDP and produces about 17 Million new vehicles per year, which is about 34% of the worldwide production (ACEA 2004). The automotive manufacturing sector in Europe employs about 2 Million direct jobs (7% of the total manufacturing employment in the EU) and supports another 10 Million indirect jobs (Ibid). According to the ACEA[1] the European automotive industry is investing heavily by spending about 19 billion Euros yearly in Research and Development activities in order to gain competitive edge.

Among all transportation means the automotive industry is largely responsible for the levels of personal mobility we enjoy nowadays and for the transport of goods in all regions of the world. The transportation sector is also considered responsible for a considerable share of pollutant emissions which are co-related with the phenomenon of the global warming of the planet. The sector is also responsible for the demand of the greatest proportion of crude oil, accounting in 2001 for 47% of the total final oil consumption (OPEC 2004). Efforts have been made to lower the vehicle fuel consumption rates and

[1] ACEA, European Automobile Manufacturers Association

reduce their relative pollutant emissions rate. This has resulted in net reductions of the emissions per vehicle for light-duty vehicles. The overall outcome however has been a net increase in the global emissions of pollutants and a global increase in fuel consumption by the transportation sector (EC 2003) due essentially to: a) higher rates of vehicle ownerships; and b) growth in transport activity and average distance travelled (WBCSD 2004). Since (1) only about 12% of the global population own a vehicle nowadays; (2) the world population is growing; and (3) transportation needs are still increasing, it is expected that a net decrease of emissions from this sector could be achieved at short term by technological improvements to the internal combustion engine (ICE)[2] aiming at better fuel efficiency rates (ACEA 2004).

The emissions problem is of prominent importance given that the Kyoto protocol has been ratified and entered into force on the 16th of February 2005, after the parties responsible for at least 55% of the emissions accepted the protocol. As of the 12th of June 2005, 151 states and regional economic integration organizations have already signed the agreement (UNFCCC 2005). The Kyoto protocol is an agreement to reduce the emissions of greenhouse gases, such as Carbon Dioxide (CO_2). The CO_2 is one of the by products of the combustion of oil based fuels inside the ICE. North America, EU and Japan are introducing progressive stricter vehicle emissions legislation which is intended to bring cleaner vehicles to market. The Euro 4, the European Union vehicle emissions standard, entered into force this year and restricts further the vehicle emissions allowed until now by Euro 3. Furthermore it is already in the agenda to restrict further these standards by 2008 with the advent of the Euro 5. The automakers agree with the principles behind these measures, but this requires large research efforts and considerable investments to be made to design and produce vehicles which comply with such requirements.

Another big issue which impacts heavily in the automotive industry is the increasing cost of crude oil phenomenon. This phenomenon has been observed thorough 2004 and maintained its ascending course in the first semester of 2005. The higher the oil-based fuel costs the more the focus on alternative fuels and fuel-efficient vehicles. Global oil demand is still growing, due essentially to a flourishing economy in South East Asia (China and India). From the oil production side, the production capacity and refining capacity has not grown according to the demand. The eventual advent of the oil production peak (point

[2] The term ICE or simply 'engine' will be used throughout this thesis denoting automotive internal

where demand outstrips production) would trigger significant increase in fuel prices. Some scientists forecast this event to happen in the present decade. Alternative powertrains (e.g. hybrid vehicles) and a mix of alternative fuels, such as the biofuels, BTL[3], CNG[4], LPG[5], and synthetic fuels can reduce the crude oil dependency and the CO_2 emissions. However, in the long term hydrogen is regarded as the most promising universal energy carrier since: a) it can be made from a diversity of energy sources, such as from renewable energies; b) emissions from Fuel Cell vehicles running on hydrogen produces zero emissions; c) hydrogen fuels can be produced around the globe, therefore it is a secure energy supply; d) electricity (a universal form of energy) can be used to make hydrogen and *vice-versa.*

At the present time the automotive industry is subject to enormous pressure from governments, organisations and consumers in several dimensions: a) strong competition among manufacturers; b) shorter design-to-product cycles; c) more complex products which incorporate advanced pieces of technology d) stricter vehicle emission legislation; e) steady increase in the cost of oil based fuels. When combined, these factors clearly demand the introduction of better automotive products in shorter time frames, i.e. more cost effective vehicles with improved design, lower fuel consumption rates, lower pollutant emissions, improved reliability, quality, driving safety and comfort and other aggregated features which makes travelling a pleasant activity.

These pressures make current auto businesses complex and challenging. However in meeting general requirements, companies have new opportunities to evolve and become stronger. In such a climate of change, companies able to devise business strategies and develop technologies which fit present business requirements and evolve accordingly can flourish relative to their competitors.

From the engine manufacturing point of view, requirements for lower fuel consumption rates, lower emissions vehicles and shorter engine model lifecycle is usually synonymous of a higher rate of change in the engine models and production volumes. This is turn requires higher levels of manufacturing flexibility at the most basic operations, such as in the machining operations of the prime engine parts at the shop floor. A requirement to stay competitive in this business is that the manufacturing approach embeds a level of agility

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combustion engine.
[3] BTL – Biomass-to-liquid
[4] CNG - Compressed Natural Gas
[5] LPG – Liquid Petroleum Gas

which enables it to react faster to global market changes in economic ways. On the other hand, to remain competitive the engine manufacturer has not only to be able to switch production to different engine models in economic ways, but also to reduce waste arising in their multiple forms from manufacturing systems. Hence there is a need to seek to optimise the operation of automotive production systems. Excess production capacity, reported for many years on the Automotive Industry (PWC 2005), is one such form of waste that places significant constraints on profitability because this industry is required to invest heavily in production systems. The excess capacity problem is derived from current industry practice of installing production capacity based on expected sale forecasts which may not become reality (Shimokawa 1999; Landmann 2001). As discussed later in this thesis, the problem of excess capacity is directly related to problems of lack of manufacturing flexibility.

The Manufacturing Systems Integration Research Institute (MSI/RI) from Loughborough University has been involved in research programs in the last years in the search for technologies and manufacturing approaches which would advance the build, testing and commissioning of engine machining systems, so that engineering activities were accomplished in shorter time frames while economic issues remain stable or improved. Several companies have been involved in these projects which directly relate to the production of machinery to machine prime engine parts and the subsequent production of the engine parts. MSI looked into the Component Based Approach (CBA) which was intended to design and implement prime engine parts production machinery, more specifically to advance the technology of dedicated transfer lines which use fixed machines.

Bearing in mind the context outlined in the present section, the study reported on this thesis has researched a number of questions which will be addressed throughout the thesis.

1.2 PRIMARY RESEARCH QUESTIONS

1. What is the nature of the manufacturing approaches currently used during the machining of prime parts of ICEs ? What are the main characteristics and limitations of these approaches from productivity and flexibility viewpoints ?

2. What is the rationale behind the use of present approaches used to machine engine parts ? Will they remain a feasible option with respect to emerging requirements for propulsion systems ?

3. What alternative propulsion technologies or alternative fuels under current development worldwide will have a significant impact on the ICE manufacturing Business ? Can statistical evidence be gathered and deployed to quantify key aspects of those likely impacts ?

4. Is it possible to improve the overall performance of (individual and collective) engine manufacturing businesses, so that ICE manufacturers remain competitive as future alternative propulsion systems come on stream ?

1.3 THESIS STRUCTURE

A general review of relevant literature is presented in Chapter 2. This includes a short historical review of primary technological developments. The emergent trend towards increased automotive product variety is also subject to analysis. General production approaches are reviewed as are current industrial practices within engine manufacturing businesses. Literature concerned with the global availability of energy (to propel vehicles) is reviewed which considers current and future predictions about new fuels, fuel prices, available vehicle propulsion, fuel efficient vehicles and vehicle emissions.

Chapter 3 provides a brief review of general research methodologies and describes the choice of methods adopted during the research study. Chapter 3 also describes the aims, objectives and expected outcomes of the study.

Chapter 4 analyses current and new future industrial practices when producing prime parts of ICEs with a view to identifying their characteristic limitations. Chapter 4 also introduces the Q'@gile concept developed by the author with a view to overcoming those limitations. Antecipated business improvements and likely future benefits are also considered in Chapter 4.

Chapter 5 presents a simulation model which contrasts and compares current ICE production practice with new practices based upon use of the proposed Q'@gile concept.

Also presented is model validation data and simulation results.

Chapter 6 presents a case study which for a chosen company enables predictions to be made about 36 future alternative scenarios for powertrain types share. Following which, Chapter 7 introduces an investment model which compares predicted investments needed for Q'@gile production systems with corresponding investments needed in dedicated transfer lines.

In Chapter 8 the research results are analysed. In Chapter 9 reflections are made about the validity of the research, the contributions to knowledge made and outstanding weakness of thesis arguments and evidence.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Motor vehicles currently guarantee high rates of personal mobility in industrialized and developing regions of the world. The automotive industry is a prime facilitator of a highly dynamic worldwide economy which enables access to goods from most parts of our world at affordable prices. The automotive industry has developed greatly subsequent to three major events: (1) industrialisation of the extraction of crude oil, in the 1850s in Pennsylvania-U.S.A., and the subsequent availability of an abundant and affordable fuel; (2) the invention of the four-stroke ICE in 1867 by Nikolaus Otto; and (3) the production of the first petrol fuelled vehicles by Carl Benz, Gottlieb Daimler and Wilhelm Maybach in 1886. The oil industry grew slowly in the second half of the 19th century until the introduction of the ICE and the mass production of vehicles, initiated in the beginning of the 20th century. Since then the demand for oil has grown steadily. When considered at a global level, the automotive industry has also been successful, sustained largely by the availability of a cheap fuel. Today the automotive industry constitutes the largest manufacturing activity worldwide, producing nearly 60 million new vehicles each year. Crude oil based fuels account for more than 95% of the energy used for transportation.

A literature survey has been conducted in several fields which relate directly to the automotive engine manufacturing industry. The fields of study cover key aspects of:

present and future world mobility; contemporary trends for product customisation and manufacturing agility; relative share of engine types (i.e. petrol, diesel and hybrid engines); availability of affordable fuels; and emergent technologies to propel vehicles. The literature study led the author to consider further the development of fuel-efficient vehicles, improved vehicle emissions, global energy demand, oil resources, and other factors that impact on sustainable mobility. With these understandings in mind, the current practice of prime engine parts manufacturing is reviewed in chapter 4, as are manufacturing constraints that impact on the utilisation rate, efficiency and agility of engine manufacturing facilities worldwide.

2.2 MOBILITY

A recent study was carried out by the World Business Council for Sustainable Development (WBCSD) as part of the so called *Sustainable Mobility Project.* The study gained consensus views from key firms operating in the transport sector, which considered mobility to be an essential human need which directly influences the quality of life of individuals and their societal interaction (WBCSD 2001). The project observed that:

> *"Mobility is almost universally acknowledged to be one of the most important prerequisites to achieve improved standards of living. Enhanced personal mobility increases access to essential services as well as to services that serve to make life more enjoyable."... "Enhanced goods mobility provide consumers with a greatly widened range of products and services at more affordable prices."*
>
> (WBCSD 2004)

Mobility has evolved greatly in the history of mankind, from a pace a person could walk, the speed a horse could gallop, an ox could draw a cart or a ship with sails could move through the water (WBCSD 2001). Most of the planet was discovered by using such transport means. Mobility has thereafter evolved greatly enabling human access to goods and exchange of knowledge in the most remote and previously inaccessible locations of the globe. By the early nineteenth century humans devised a way to use steam energy to transport goods and people at a faster pace and in a more convenient way by developing the steam train and the railways. By the end of the same century petroleum-fuelled motor vehicles had been invented (petroleum had already been discovered, drilled and pumped from the ground) giving rise to the most extraordinary expansion of mankind's mobility. Along with the invention of the airplane (invented in the beginning of the twentieth century) the automobile and the availability of an affordable oil based fuel led to greater speed of travel and travel flexibility. Due to these events and discoveries the last century was a golden age for mobility (WBCSD 2004).

Motor transport is nowadays the backbone of the passenger transport system. Cars are the preferred means of transport offering a set of advantages, namely (VDA 2003):

- flexibility;
- availability at all times;
- capacity to transport people directly from door to door;
- suitability for virtually every type of journey.

At present, in Germany, 97% of all journeys are made by road (not including walking and cycling), which represents 133 million journeys a day, with the average journey being 10 kms (VDA 2003). Car journeys account for 83% of all passenger travel, in terms of the number of passenger kilometres travelled. If the public road transport is also included, then together they represent 92% of all passenger transport. These facts, which are considered to be representative of much of the industrialised world, and to a lesser extent of developing countries, imply that road transport vehicles are prime guarantors of mobility in present day societies. Europeans travel an average of 35 kilometres per day. In 2000, nearly 80% (3,789 billions of passenger kilometres) of all passenger travel was made by car. This number has steadily increased in the last decades and is projected to follow the same pattern in the current decade, namely the pattern depicted in Figure 2.1. Although with lower, and in some years even negative, rates of growth of vehicle sales (e.g. -3% and -1% growth rates in Western Europe[6] in 2002 and 2003, respectively) the average distance travelled per person still grew. This phenomenon has been observed in most of industrialized regions of the world.

[6] Western Europe: European Union (15) countries: Austria, Belgium, Denmark, Finland, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom ; plus: Iceland, Norway and Switzerland.

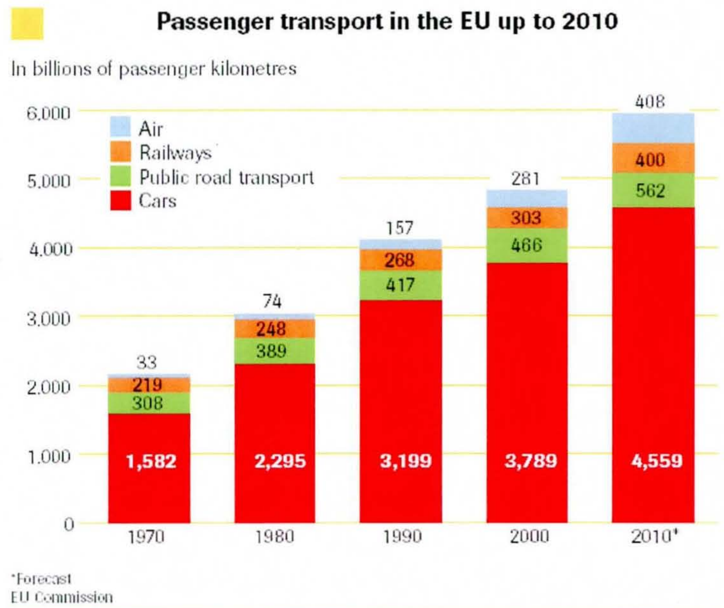


Figure 2.1 Passenger transport in EU up to 2010. Source: European Commission, in VDA auto annual report 2003 (VDA 2004), pp. 96.

Apparently three major automotive markets, i.e. Western Europe, North America and Japan, have reached near stagnation in sales growth (EC 2003). This is considered to be due to already high levels of vehicle ownership. But the Asian market grew by 11% in 2003. Much of this growth has been attributed to China which had a market growth of 35% (4.4 million vehicles registered in 2003, following a 37% growth in 2002). In India there was a 23% growth in 2003 (where 1.1 million vehicles were registered in 2003). Figure 2.2 clearly elucidates that at present in the EU, North America and Japan/Pacific[7] regions, vehicle ownership has almost reached one vehicle for each couple of people. In comparison Africa and Asia regions have very low ownership rates. In Latin American countries, in the Community of Independent Countries (CIS)[8] and in Countries of Eastern and Central Europe (CEEC)[9] vehicle ownership rates are also growning.

[7] Pacific countries as define in EC (2003). World energy, technology and climate policy outlook 2030. European Comission (EC), European Union. [available online]: http://europa.eu.int/comm/research/energy/pdf/weto_final_report.pdf., pp. 111: Australia, New Zealand, Papua New Guinea, Fiji, Kiribati, Samoa (Western), Solomon Islands, Tonga, Vanuatu.

[8] CIS countries as define in Ibid., pp. 111: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyz Rep., Moldova, Russia, Tajkistan,Turkmenistan, Ukraine, Uzbekistan.

[9] CEEC countries as define in Ibid., pp. 111: Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Macedonia, Poland, Romania, Serbia&Montenegro, Slovak Republic, Slovenia.

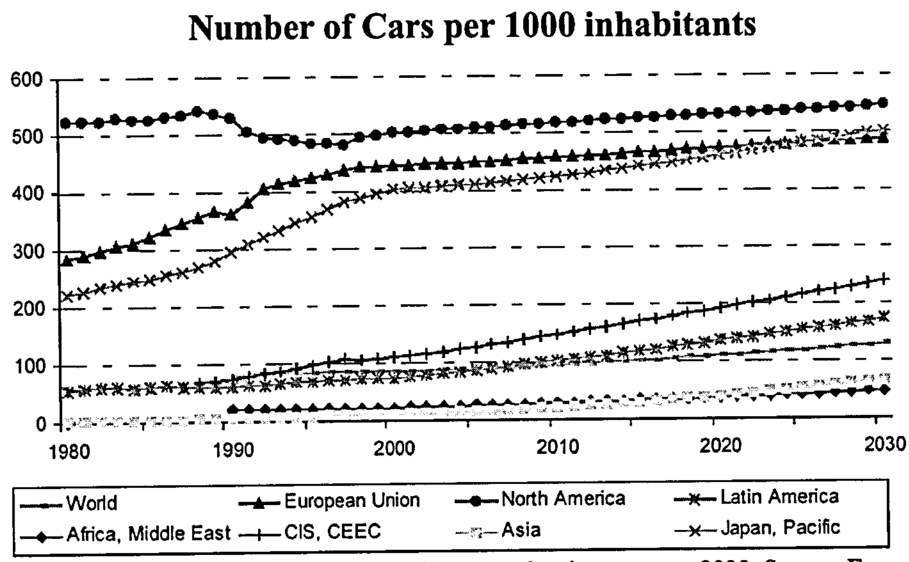


Figure 2.2 Number of cars per 1000 inhabitants and estimates up to 2030. Source: European Commission WETO Report 2003 (EC 2003) pp. 52.

The densely populated region of South-East Asia has been a prime area of growth for the global automotive industry in both 2002 and 2003. This region is also projected to be key for the next few years. This is thought to be a consequence of a booming regional economy and a poor vehicle ownership rate at these regions. The global sales of automobiles has reached 56.3 million units (+2% over 2002 levels) and the respective global production achieved a record level of 59.2 million units (+2% over 2002 levels) in 2003 (VDA 2004). Figure 2.3 shows the regional figures and the world total production of automobiles from 1987 to 2003.

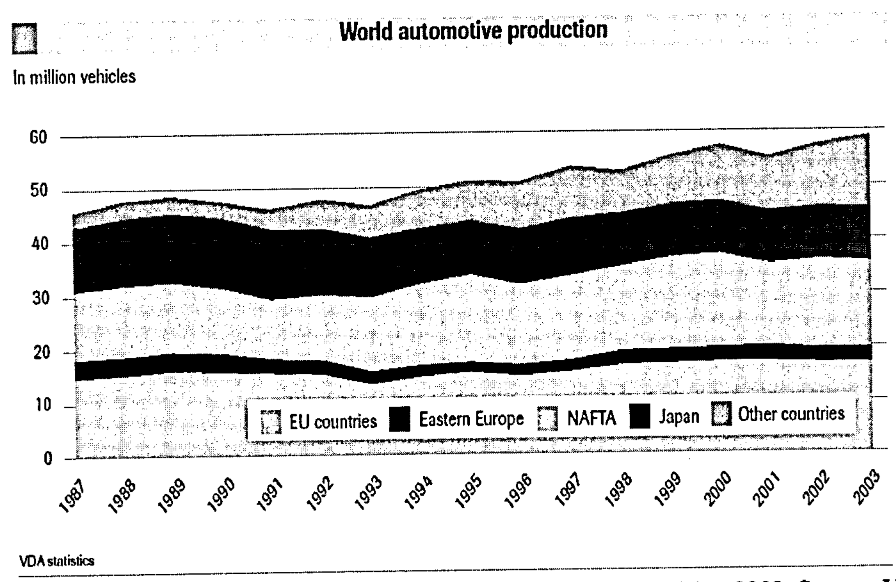


Figure 2.3 World automotive production by world region from 1987 to 2003. Source: VDA auto annual report 2004 (VDA 2004), pp. 29.

There is clearly a desire on a global scale for enhanced mobility to improve the quality of life and productivity of people. The use of personal transport systems, mainly cars, continues to grow. This is particularly so in economically strong areas of the world that presently have relatively low levels of vehicle ownership.

2.3 PRODUCT VARIETY TREND

A literature survey focused on emerging trends in product variety has also been conducted. Significant evidence was observed for a general trend towards increased product variety and mass customisation of products (Cox and Alm 1998; Huang and Nof 1999; Vernadat 1999; Harrison et al. 2001; Gunasekaran and Yusuf 2002). In the automotive industry the trend towards higher rates of product variety has also been observed. A growing number of vehicle segments and new vehicle models are introduced in the market place at shorter timeframes (Reithofer/BMW 2002; DaimlerChrysler 2003; VDA 2003). In such segments and models distinctive and innovative features of engine systems have been observed.

Manufacturing Industry in general has been subject to an evolutionary process since the industrial revolution (circa 1770) when hand production (artisans) moved to mechanisation and the use of simple production machines. Mass Production, based on the use of fixed automatic mechanisms and transfer lines, was first deployed at the turn of the 20th century. These mechanisms and lines utilised machine tools (with simple automatic controls). In the early 1950s machine tool technology advanced significantly with the introduction of Numerical Controls (NC). Then as computer technology became readily available and affordable Direct Numerical Control (DNC), Computer Numerical Control (CNC) and Adaptive Control (AC) technologies were adopted industrially. By the early 1960s first generation commercial robots were deployed but it took more than a decade for robot technology to play a major role in manufacturing plants. The industrial adoption of computer controlled machinery, was complemented by other computer based developments, such as Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) and this led onto development of Flexible Manufacturing Systems (FMS).

Technology adoption by the automotive industry has mirrored (and often led) general manufacturing industry trends. Vehicles, such as the 1911 Springfield, were custom-made

(made to order) and were exorbitantly priced. Henry Ford sacrificed individualism for much increased productivity. This enabled cars to be sold at an affordable price to a much wider market. Figure 2.4 depicts Henry Ford along with the first automotive assembly lines in the early 20th century.

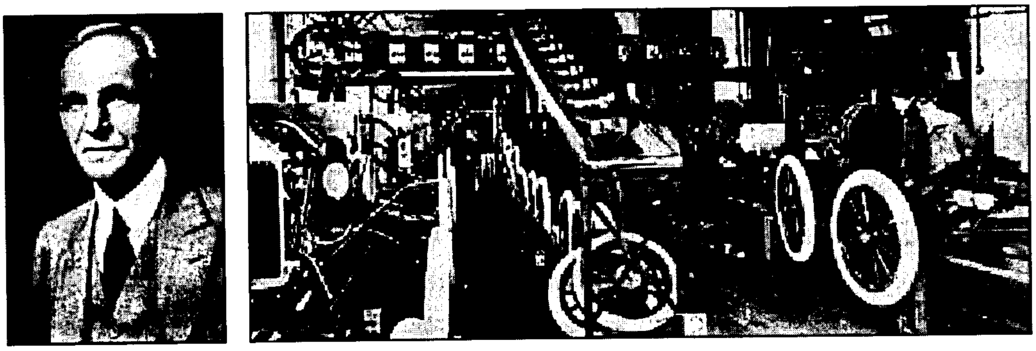


Figure 2.4 Left: Henry Ford; born 30th July 1863, built his first car in 1896, 10 years after the auto was invented. Right: Assembly line. Source: Federal Reserve Bank of Dallas 1998 Annual Report. (Cox and Alm 1998), pp. 18.

"The consumer can have any colour he wants so long as it's black."...

"I will build a motorcar for a great multitude.... It will be so low in price that no man... will be unable to own one."

Henry Ford, cited in (Cox and Alm 1998)

Nowadays, a customer willing to buy a car has an option to choose a vehicle which conforms to their needs; choosing from numerous options (possibly depicted by a manufacturer's web site) and, surprisingly, not having to pay an exorbitant price for the degree of customisation made available.

Twenty years ago Yoram Koren (Koren 1983) observed that the "*the age of mass production is gone and the era of flexible production is being started*" and characterized the concept of the "*factory of the future*", in response to change in consumer preferences in modern society characterized by shorter product life cycles. Those characteristics included:

- Rapid introduction of new products;
- Quick modifications to products with similar function;
- Manufacturing of small quantities at competitive production costs;
- Consistent quality control;
- Ability to produce a variety of products;
- Ability to produce a basic product with customer-requested special modification.

He also identified key concepts and technologies that would help meet these requirements: Computer-Integrated Manufacturing (CIM) system; integrated Computer-Aided Design and Manufacturing (CAD/CAM) and associated processes that shorten the time between concept and manufacturing of a new product; Flexible Manufacturing Systems (FMS) to enable the production of a new product by downloading a new program into its supervisory computer; Automatic Inspection to maintain high quality of products. Mikell Groover (Groover 1987) confirmed Koren forecasts: "*shorter product life cycle*", "*increased emphasis on quality and reliability*", "*more customised products*" and "*greater use of Computer Integrated Manufacturing*".

A report dated 1998 stated that historical data, on buying patterns in USA from the early 70s to late 90s, showed a growth in product variety in several industries (Cox and Alm 1998). That growth is shown in Table 2.1. Markets have now satisfied many customer's individual taste, this also confirming Koren's foresight.

Table 2.1 Product variety in the USA. Source: Federal Reserve Bank of Dallas 1998 Annual Report (Cox and Alm 1998), pp. 4.

Item	Early 70s	Late 90s
Vehicle models	140	260
Personal Computer models	0	400
Web Sites	0	4,757,394
Amusement parks	362	1,174
TV screen sizes	5	15
Breakfast cereals	160	340
Bottled water brands	16	50
Milk types	4	19
Running shoe styles	5	285
Bicycle types	8	31
...		

The customisation phenomenon is however relatively recent, having been fuelled by advances in technology and human knowledge. Those advances enable the management of complexity that arises consequent on a need to design, build and manage manufacturing systems that can deliver the flexibility and production rates needed, at acceptable cost and quality. Modern technologies are shifting the relative competitiveness of different business paradigms from producer-centred productivity to consumer-centred customisation. Figure 2.5 illustrates an example from the shoe industry. Footmaxx uses computer technology to scan individual's unique gait and foot and then to build and manufacture custom orthotics (Cox and Alm 1998). Many other examples can be found in computer, automotive, furniture and clothing industries.

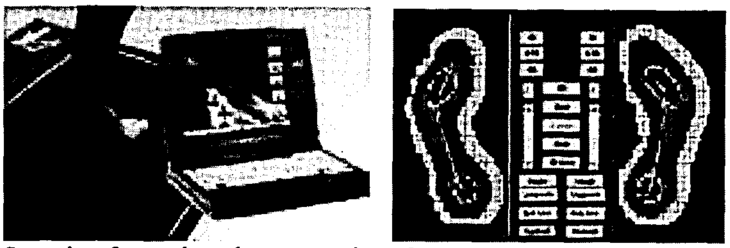


Figure 2.5 Scanning feet gait and pressure data. Source: Federal Reserve Bank of Dallas 1998 Annual Report (Cox and Alm 1998), pp. 17.

Customisation delivers well fitted products to customer's individual taste and particular market specifics; particular product utilisation patterns; or simply better match to personal budget constraints. Customisation however normally requires higher levels of knowledge relating to specific markets (including studies of groups of individuals with similar taste or utilisation patterns), along with manufacturing systems with higher levels of complexity and versatility. Thus enabling the economic production of a multitude of products over shorter production lifespan.

In the automotive industry there has been a clear move to increased variety in vehicle models on offer. Companies are compelled to react to competitor initiatives that introduce 'better' new and renewed vehicle models. This has resulted not only in an increased number of new models on the market, but also a decrease in the total production volume per each model, as illustrated by Figure 2.6. A study from Salomon Smith Barney (1999) with forecasts to 2001 indicates an increased demand for niche models, which urges vehicle manufacturers to react promptly following the successful introduction of new niche products by competitors.

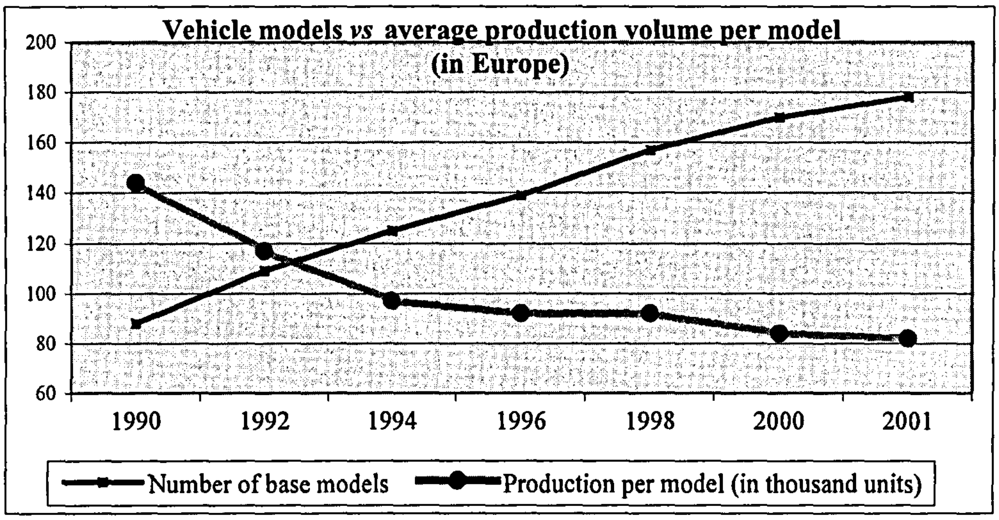


Figure 2.6 Proliferation of vehicle models in Europe. Source: Adapted from Salomon Smith Barney in (Sako and Warburton 1999), pp. 20

2.4 MANUFACTURING APPROACHES

A manufacturing approach is key to the business since it encodes the strengths and emphasis of an organisation. However if the chosen approach does not fit the nature of the business in which the organization operates (such as in a market where products have a short lifespan) it can lead to great losses (since for example it might deploy specific technologies and specific production strategies). Manufacturing approaches generally relevant to the production sector are reviewed in following sections.

2.4.1 Mass Production

Early assembly lines[10] were simple in concept. Relatively complex tasks were decomposed into simple elemental tasks and activities with similar processing times, enabling high production rates whilst bringing order and simplifying production planning and control activities (Haslehurst 1981). Several stations, grouped together in a flow line layout, carried their specialized machining operation on the work part. Work parts were automatically shifted from station to station by transport automation. The cycle time 't' was calculated by adding the time of the "slowest" of the stations to the transport time, i.e. the time the transport system took to deliver the work part from one station to the following one. Therefore each unit of the final product arrives at the end of the assembly line within 't' units of time. Such an assembly line can be represented as shown in Figure 2.7.

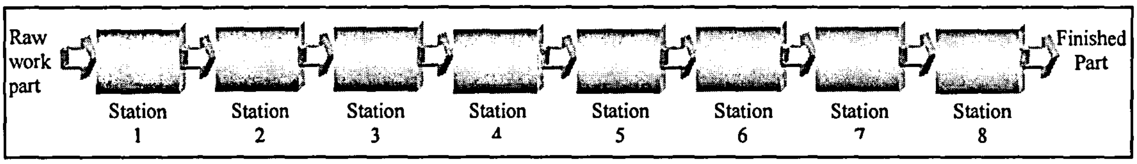


Figure 2.7 Simple Assembly Line for Mass Production. Adapted from (Groover 1987) pp. 84.

With increasing demand for product variety several assembly rearrangements would be introduced to improve the flexibility of the assembly lines, namely the introduction of alternative work part pathways. What was initially simple and efficient became

[10] - also known as flow lines or transfer lines.

increasingly complex and typically productivity would fall due to unbalanced production lines, as represented in Figure 2.8. In some cases a small but critical number of stations were replaced by CNC machines thereby increasing the machining flexibility of the assembly line.

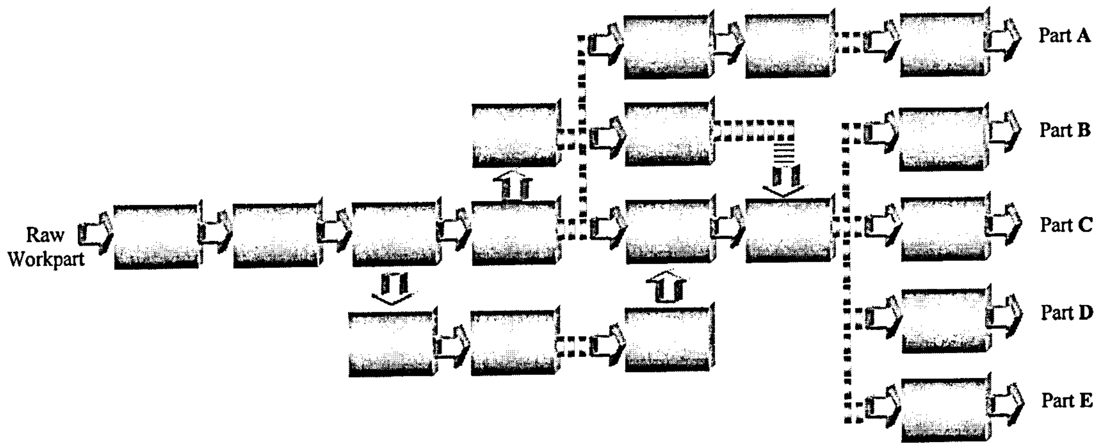


Figure 2.8 Assembly Line with several branches.

2.4.2 Flexible Manufacturing Systems

Flexible Manufacturing Systems (FMS) commonly include (Groover 1987): numerically controlled machines with automatic download of NC programs and automated exchange of tools; automated devices for materials handling and transportation; and other specialist automation devices (such as Robots and Automated Storage and Retrieval System (AS/RS)). Key to the FMS concept was an attempt to reduce the time spent on non-processing activities and thereby compete with the higher production rates achievable with mass production techniques.

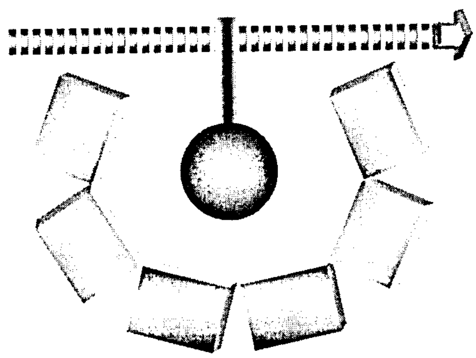


Figure 2.9 Flexible Manufacturing Cell.

Typically, if the demand for a particular product is stable over time, the best technology to adopt is likely to be assembly lines: as it provides an efficient and cost effective automation solution in the long term. Such a solution is likely to be attractive because it results in low cost production processes, although it is based on the use of relatively inflexible equipment. The confidence that minor equipment changes can cater for a limited number of predictable product changes has led enterprises to adopt this type of technology on a widespread basis.

When selecting a suitable technology for a particular manufacturing system, it is important to have enough knowledge and predictive capacity to best fit technology to a likely product market evolution, enabling a characterisation and quantification of essential system properties to be determined. If a particular system requires high production volume at low unit cost then likely the best option is mass production technology (e.g. synchronous transfer lines). If the main requirement is diversity of production, even if the penalty is increased unit production costs, then the best option likely to be some form of flexible technology (such as FMS technology). There have been some technological developments that seek to bring benefits of both worlds: by increasing the productivity of FMS (compromising system variety to some extent, possibly due to client demand for lower price products); and the reverse way round, by increasing the flexibility of transfer lines (compromising system productivity to some extent, possibly due to customer demand for product variety).

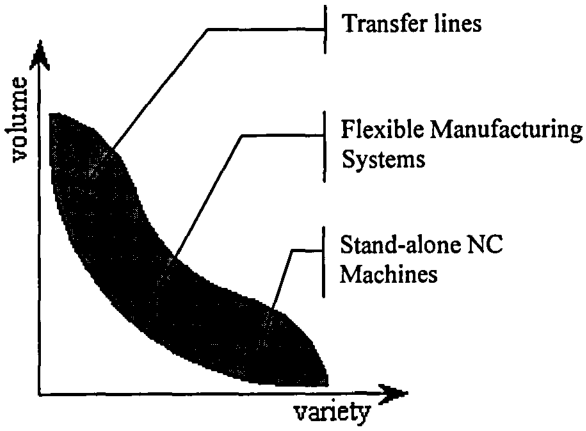


Figure 2.10 Production volume versus product variety. Source: Adapted from (Groover 1987) pp. 465

Present manufacturing industry trends already require customised products at mass production costs as discussed in section 2.3. The same requirement will be of significant importance in the future (Gunasekaran and Yusuf 2002). This necessitates use of a different manufacturing paradigm. Of course this requirement may not apply to all product types or industries. There will remain some craft industries that offer the best solution to their particular business. The same applies with some mass production industries. But in general terms, it is widely accepted by the research community that there is an increasing product customisation requirement which requires change at strategic, tactical and operational levels of businesses (Goldman et al. 1995; Brown 2000). The "*the consumer can have any colour he wants so long as it's black.*" will not work well nowadays, in a 'mutating' and 'colourfully painted' world.

The main characteristics of different manufacturing paradigms were synthesised by Brown (Brown 2000) in Figure 2.11:

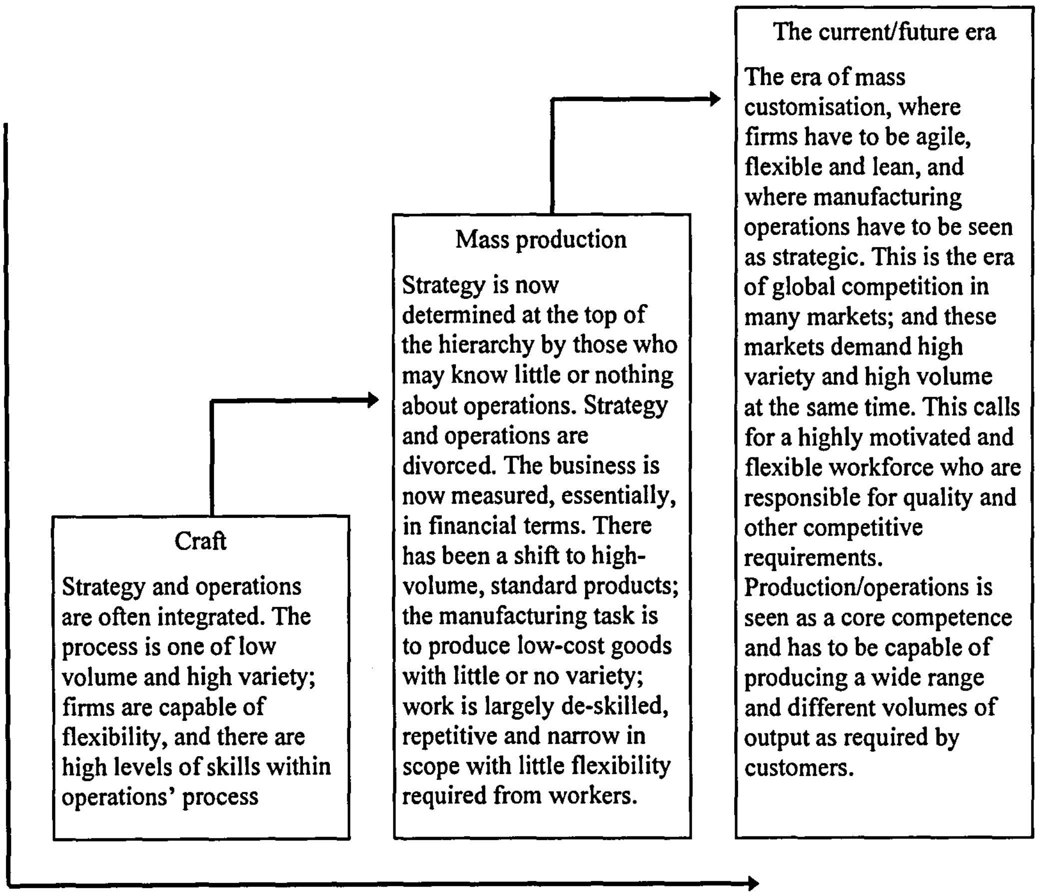


Figure 2.11 The changing role of strategy in different Manufacturing eras. Source: Manufacturing the Future, Steve Brown, (Brown 2000) pp. 18.

At the present time, there is a general recognition, that manufacturing industry is under major pressures due to global competition and a different attitude amongst customers, who demand high quality customised products at low-cost. This recognition has been observed in (Goldman et al. 1995); (Harrison et al. 2001); (Vernadat 1999); (Huang and Nof 1999); (Gunasekaran and Yusuf 2002).

2.4.3 Agile Manufacturing

According to Kidd (1994) and Vernadat (1999) the concept of Agile Manufacturing was developed in 1991 and is still an emerging concept in industry. The concept ***Agility*** is defined by François Vernadat (Vernadat 1999) as: "*the ability to closely align enterprise systems to changing business needs in order to achieve competitive advantage*". Gunasekaran and Yusuf (Gunasekaran and Yusuf 2002) state that: "*It demands a manufacturing system that is able to produce effectively a large variety of products and to be reconfigurable to accommodate changes in product mix and product design.*". Which is a confirmation of Amir Hormozi believes back in 1994 (Hormozi 1994): "*Agile Manufacturing implies mass customisation instead of mass production. It means producing highly customised products, where and when the customer wants.*"

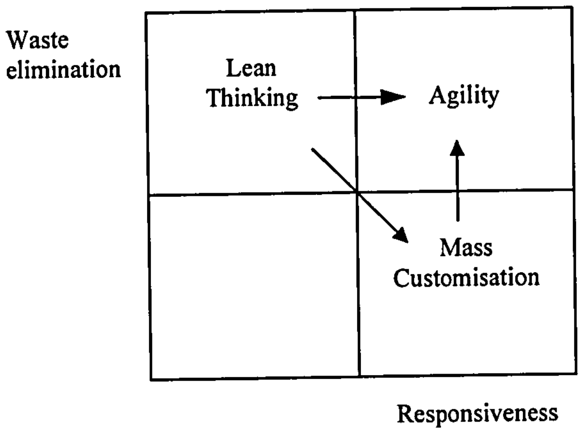


Figure 2.12 Leagility concept. Source: (Hoek 2000) pp. 200.

Agile systems combine efficient and responsive operations (Hoek 2000), enabling high quality products to be manufactured in an efficient way, thus enabling competitive prices and being responsive to customers (Goldman et al. 1995). Figure 2.12 shows two dimensions of Agility: efficiency (achieved through waste elimination) and responsiveness. A way to achieve Lean responsiveness is by adding postponement at the operational level. Postponement is centred around delaying manufacturing activities, that conform the product to particular client specifications, until customer orders release, rather than manufacturing based on sales forecasts. The manufacturing activities are performed with a focus on efficiency and customisation.

Huang and Nof (Huang and Nof 1999) state that enterprise agility must be accomplished through agility in business, organizational, operational and logistic systems, and that without information technology, enterprise agility at all the enterprise levels would be impossible. Paul Kidd (Kidd 1994) reinforces the requirement for a methodology that integrates three fundamental elements needed to sustain Agile Manufacturing: *Organization* (innovative management structures and organizations), *People* (Skill base knowledgeable and empowered people) and *Technology* (Flexible and intelligent technologies). The same three aspects were also found in Vernadat (1999). Agile manufacturing is a broad approach that involves taking a balanced consideration of all necessary fundamental elements in an integrative way.

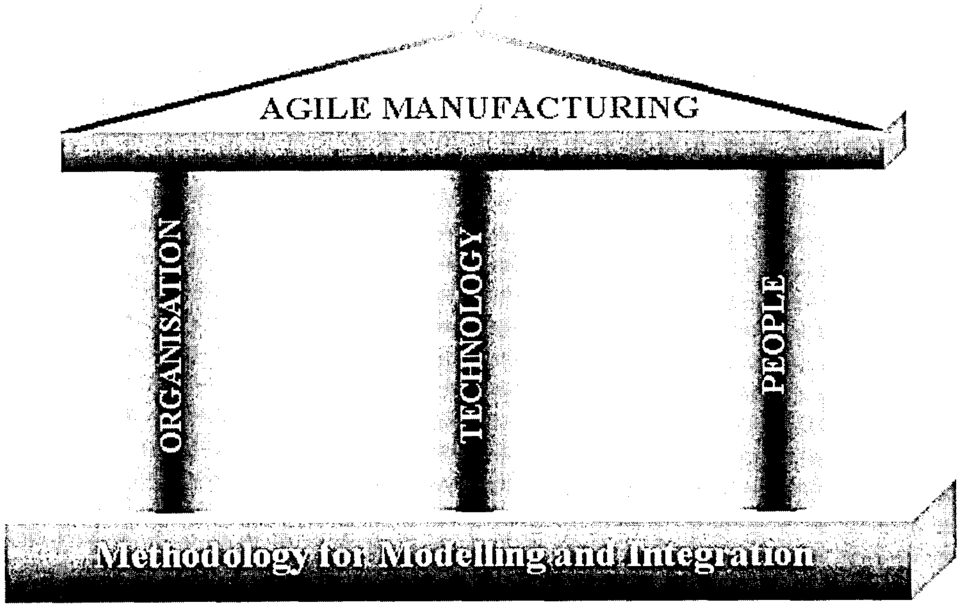


Figure 2.13 Agile manufacturing conceptual representation. Source: adapted from (Kidd 1994) pp.11,62.

However, as found in (Kidd 1994), and represented in Figure 2.13, a balanced manufacturing response is required, not an exclusively technological one. Kidd summarises that the aims should be on creating an environment to support human skills exercise, use of creativity and knowledge, making full use of modern computer based technologies. These two goals would be main requirements that shape the development of successful manufacturing systems in the future.

2.4.4 Lean Manufacturing

It can be argued that Agile Manufacturing is a natural development of Lean Manufacturing which is itself a characterisation of the Toyota Production System, developed and perfected by Taiichi Ohno after the Second World War. Lean Manufacturing was applied with great success especially in the automotive industry in Japan. In 1950 Eiji Toyoda made a visit to Ford's rouge plant in Detroit. The Toyota Motor Company faced tremendous problems at that time and production was insignificant at a world level. After returning to Japan Eiji Toyoda and Taiichi Ohno concluded that the mass production paradigm (which was in use in Detroit at that time) could never work in Japan (Womack et al. 1990) because: a) the domestic market was tiny and demanded a wide variety of vehicles; b) after the war the Japanese economy was in a downturn, therefore not ready for massive investments in the latest western production technology; c) the western world had many highly competitive vehicle producers anxious to establish operations in Japan and ready to defend their established markets against Japanese exports. Therefore, Eiji Toyoda and Taiichi Ohno decided to embrace a different approach. This focused on a strong commitment with the employees, a lean supply chain, the Just-in-Time production philosophy (i.e. items in the required quantities at the required time, without accumulation), a readily and permanent elimination of waste, i.e. the removal of all non-value-added activities and overproduction, quality assurance (namely by asking 'why' questions, such as why a fault has occurred in the first place, tracing the problem to its origins right from the first instant the fault was detected and assuring a permanent solution for it), continuous improvement and a closer relationship with the customer, including a strong market research (Shingo 1989; Womack et al. 1990).

According to Womack et al. (1990) in 1990 the Japanese automotive companies were making around 125,000 copies per year of their car models and renewing the models each 4-year period, on average. The western mass producers were making around 200,000 per year on average, and keeping the same models in production for around 10 years. This equates to a half million production figure per model for the Japanese companies (125,000 x 4 = 500,000) when compared to a 2 million figure for the western companies, i.e. the Japanese were producing one quarter of the typical western production volumes per model. The economies of scale that apparently should have resulted from the higher western production volumes have not resulted in terms of competitive edge in the long term. Toyota mastered the flexibility to produce several vehicle models in the same plant, while for long time GM and Ford had goals to produce a single model in each plant. Toyota, and the Japanese companies in general, achieved a higher total product portfolio, while maintaining higher productivity and quality standards. This approach seems to have met the changing pattern of consumer demand for less standard cars and more customised products, leading to the proliferation of new vehicle segments and new models. Partially this explains the incontestable success of Toyota and of the Lean Manufacturing concept.

2.4.5 Multi-Component Flexible Manpower Lines

Recently there were other alternative proposals to manufacturing systems (which lack universal acceptance), so as to deal with changes in volume and variety of parts, such as the one proposed by England et al. (2002) Multi-Component Flexible Manpower Lines (MCFML). MCFML proposes the use of flexible transfer lines through the use of modern machine tool technology and human operators to provide flexibility through part handling, part transportation and decision-making (England et al. 2002). This proposal however, when applied to the engine machining sector seems to be inadequate. In fact prime engine parts, high quality machining standards and part weight considerations are leading the industry to follow exactly the opposite direction, i.e. the adoption of higher levels of automation rates, lowering the content of human based tasks. In the engine assembly sector, in opposition to the machining sector, lower automation rates have been introduced recently, favouring the use of human skills to resource engine assembly tasks (Cox 2003; Reakes 2003). Both Ford Dagenham and BMW Hams Hall engine plants follow this trend. Increasing automation content in engine prime parts machining is envisaged for the near future, as opposed to increasing human based tasks in engine assembly.

2.4.6 Automotive sector industrial practice

Vehicle manufacturers are addressing the flexibility issue at the operations level by adopting new organisational and technological solutions (Womack et al. 1990). These solutions seek efficient processes whilst enabling multiple vehicle models to be produced simultaneously and faster introduction of new models.

However, it remains the case that at the strategic level, engine manufacture is still highly based in economies of scale, which have been achieved by installing high volume-low variability production systems. To achieve mass production, highly automated Dedicated Transfer Lines (DTL) have been installed to machine main engine components. DTLs are technological solutions which require intensive capital expenditure. Their economic justification relies on a steady demand of undifferentiated products over a considerable period of time. This enables an attractive unit production cost since the initial investment is dissolved over a high production volume. As demand for engine improvement continues, engine lifetimes reduce and changes in engine volumes become more frequent, DTL pose serious technological limitations. Under such circumstances, another major problem occurs, the existence of excess capacity. Indeed excess capacity is a recurring problem in the automotive industry. Excess capacity ultimately occurs because of lack of manufacturing flexibility and agility. The BMW's Hams Hall engine plant provides a good example of the excess capacity problem. Opened in February 2001 with an installed capacity of 440,000 engines per year, the plant has been running since that time at under 35% capacity utilisation and only by 2008 is forecasted to reach full capacity. Despite this situation BMW is buying diesel engines from Toyota in order to meet engine requirements of the Mini brand. A more detailed and profound presentation and analysis of engine manufacturing approaches is presented in Chapter 4.

2.5 World Energy Demand *vs.* Fuel Prices

2.5.1 World energy demand

A scenario for future world energy system is described in a recent publication by the European Commission (2003). This scenario is based on assumptions that there will be a continuation of on-going trends and structural changes in technological progress, world population growth and oil and gas resources. The scenario predicts that the world energy consumption will rise 70%, by increasing at a rate of about 1.8% a year between 2000 and 2030. This predicted growth is linked to predictions of economic and population growth of 3.1% and 1% a year on average, respectively (EC 2003). Figure 2.14 illustrates an increase in worldwide energy consumption, which has occurred in the last two decades and is projected three decades into the future.

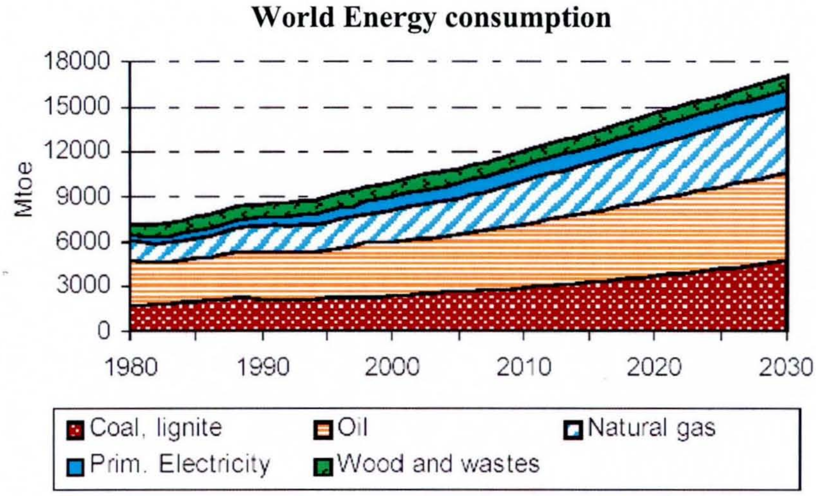


Figure 2.14 World energy consumption. Source: World energy, technology and climate policy outlook 2030 (EC 2003) pp. 24.

The rise of world energy consumption is underpinned by a substantial increase in oil, natural gas and coal production. When combined, these fossil fuels represented 81% of the total energy sources used in the year 2000. Fossil fuels dependency is projected to rise to 88% by the year 2030 (EC 2003). In the year 2000 oil represented the largest share of energy sources with a 34% share. Oil is projected to remain the primary source of energy in the next decades. Oil reserves are expected to decline over the period 2000-2030 by 22%. The decline is set to begin at the middle of the present decade. As a consequence, the world reserves-to-production ratio is likely to decrease from 40 years to 18 years by 2030 (EC 2003), as shown in Figure 2.15. These projected changes are set to increase the price of fuels from the end of the current decade onwards.

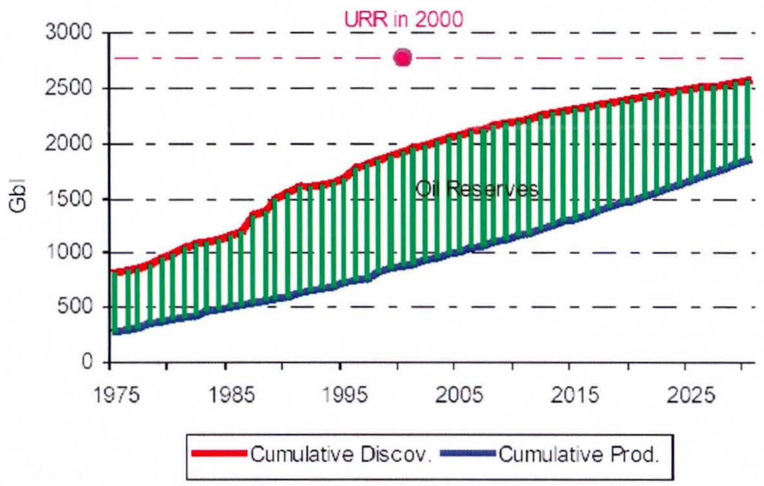


Figure 2.15 World conventional oil resources. Source: World energy, technology and climate policy outlook 2030, (EC 2003), pp. 40.

The world oil reserves are mainly located within OPEC[11] countries. This organization has been deeply involved in devising strategies and means to stabilise oil prices in the international markets so that unnecessary fluctuations are kept at a minimum level. In the course of the year 2004 the oil price in the international markets had reached historical highs, even after successive OPEC decisions to increase production. The phenomenon is justified by a set of factors affecting this sector, namely: (1) unexpected and extraordinary high in world oil demand; (2) production difficulties at specific locations (including high instability and successive attacks on oil fields in Iraq, strikes in Nigeria and Venezuela, economic problems in the Yukos oil company (a major oil producer in Russia), typhoons affecting the US Golf coast region disrupting oil production); and (3) oil market speculation. The actual volatility in oil crude prices is also linked with market concerns with present low margins in OPEC spare production capacity. Only OPEC has sufficient reserves to meet growing oil demand.

> *"...while demand has been growing at an annual rate of 1.5% over the last 5 years, production capacity has grown at only 0.2%. The result has been a gradual erosion of the global spare capacity cushion, which has now shrunk to the point where, although there is no shortage of oil, markets are nevertheless nervous about potential supply disruptions and have driven prices relentlessly upwards."*
>
> In OPEC Bulletin, September 2004 (OPEC 2004), pp 3.

The estimated OPEC spare production capacity in September 2004 was 1.0 to 1.5 million b/day (EIA 2004; OPEC 2004). It has been forecasted that the world oil supply will have an increasing reliance on OPEC countries in the near future. This dependency is projected to reach 60% of all oil supply by 2030 (WBCSD 2004). At the present time OPEC countries supply 40% of the total.

[11] OPEC countries: Iran, Iraq, Kuwait, Saudi Arabia, Venezuela, Qatar, Indonesia, Libya, United Arab Emirates, Algeria and Nigeria.

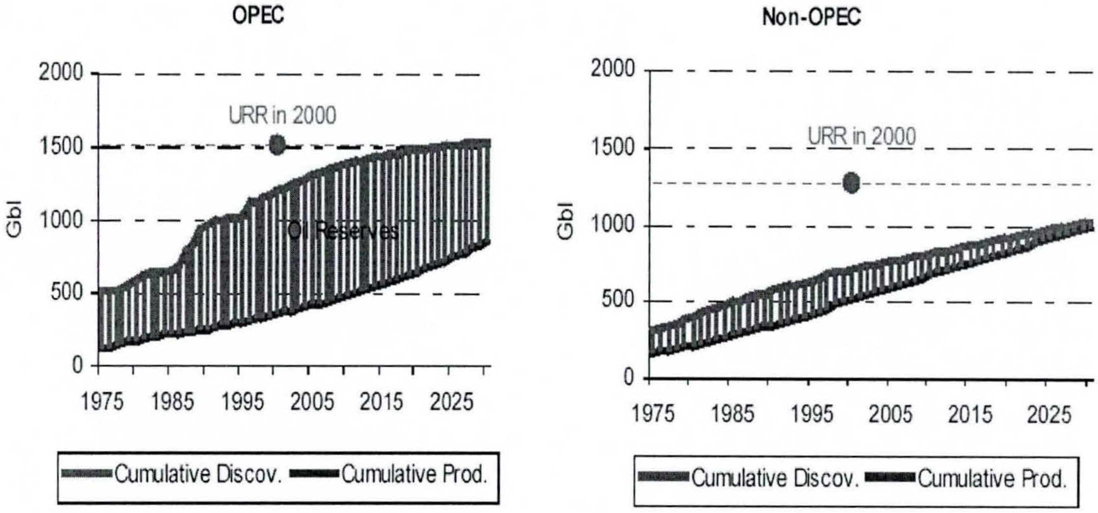


Figure 2.16 OPEC and non-OPEC conventional oil resources. Source: World energy, technology and climate policy outlook 2030, (EC 2003), pp. 41.

Oil demand has been growing at a fast pace, especially in some developing countries such as in China and India. At present, crude oil is the primary feedstock for transport fuels, accounting for more than 90% of all fuels transport energy (Aleklett and Campbell 2003; SMMT 2004; WBCSD 2004).

Progressive increase in fuel costs and more environmentally conscientious customers, demand more fuel efficient and low emission vehicles. This trend is set to continue and, as fuel prices escalate (especially in Europe), fuel economic vehicles, efficient propulsion systems and alternative fuels will become increasingly attractive.

2.5.2 Hubbert peak

In 1956 Hubbert predicted that the oil production in the U.S. would peak in the 1970s. This accurate prediction was confirmed in 1971 (Bentley 2002). Since then oil production in the U.S. has been decreasing, leading to a progressive dependency on external oil to face the growing internal demand. At present U.S. imports 60% of its oil, which represents 28% of the world's production (Campbell and Sivertsson 2003). North Sea total oil production peaked in 2000 at 6.4 million barrels per day (UK production peaked in 1999 with 2.9 M b/d; Norway in 2001 with 3.4 M b/d, Denmark and others in 2003 with 0,47 M b/d) (Skrebowski 2003). The "Hubbert Peak" Theory, attributed to the geophysicist Hubbert, also known as Peak Oil, predicts that oil production follows a pattern: (1) a steady increase of production; (2) a plateau; (3) a slow decline after the "peak"; and (4) a steep decline of production. The peak oil concept is widely accepted but there is wide disagreement on the date of the eventual world peak with estimates between 2004 and 2015 (Bentley 2002; Campbell and Sivertsson 2003; SMMT 2004). Recent studies predict that the world peak in oil production will be in 2008 (Campbell 2004). Figure 2.17 shows the past oil and gas production and projected future production decay after reaching "Peak Oil". Cavallo (2004) refutes this prediction and states that this event will be delayed until: "sometime after 2010 for non-OPEC producers, and sometime after 2020 for the world as a whole"(Cavallo 2004).

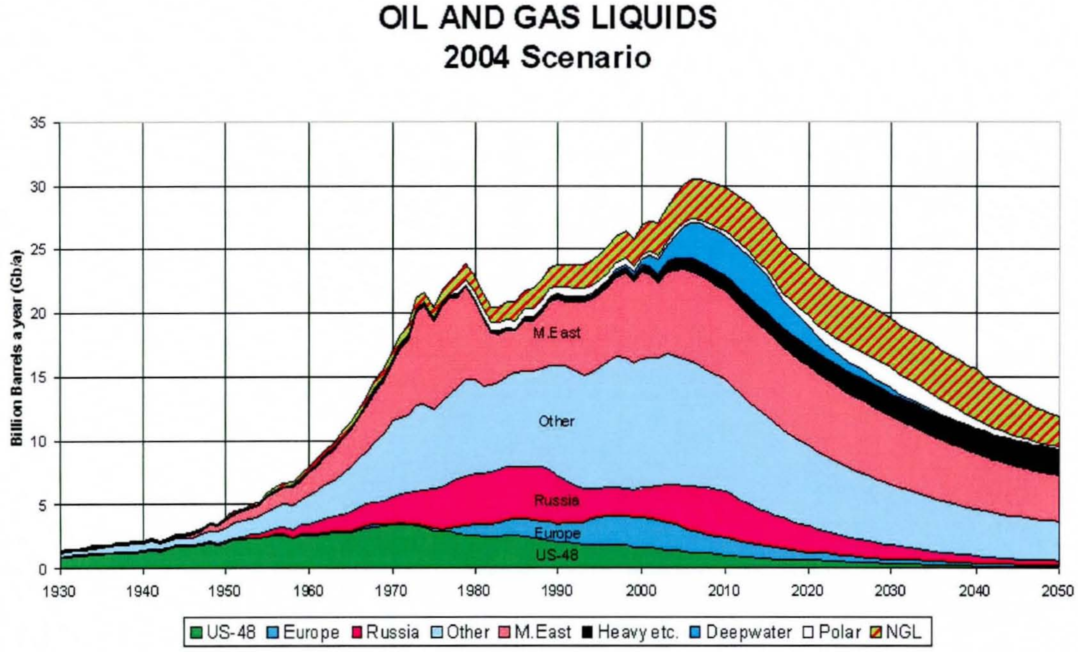


Figure 2.17 Oil and Gas production 2004 based scenario. Source: Uppsala Hydrocarbon Depletion Study Group (Campbell 2004).

Aleklett and Campbell (2003) have warned that the present reported reserves (especially those held by Russia and OPEC) lack scientific evidence, and that there might be a deficit of 30% in Russia and in OPEC countries. This is because these sources declared a 50% increase in their oil reserves overnight, some of these countries even suggesting greater than a doubling of their reserves; although apparently nothing special changed in their oil fields. Kuwait declared 90.0 billion barrels (Bb) in 1985 (against 63.9 Bb declared in 1984). In 1988 Venezuela reported it had 56.3 Bb (against 25.0 Bb in 1987). This led the remaining OPEC countries to report huge increases in their oil reserves to protect their production quotas, which were linked to their projected reserves. Aleklett and Campbell

(2003) also state that the reserves reported by OPEC have remained unchanged for many years despite increased production. Therefore the reported reserves may be highly spurious (Aleklett and Campbell 2003). These authors consider that the widely used Reserves to Production ratio measure, which divides the declared reserves by the annual production gives unsatisfactory and unreliable information.

Thus the public data on oil reserves is weak. Oil and gas resources are however finite, consequently oil exploitation will inevitably lead to depletion, and the higher the production rates realized the shorter will be the lifespan. Another historical fact is that oil discoveries peaked in the 1960s and have been in decline thereafter (Campbell and Sivertsson 2003; Zittel and Schindler 2003). The timing of the Peak Oil is however a big issue (relative to the depletion one), since after that time production will start to decline and demand will outstrip supply. Increasingly the remaining oil will become more inefficient to extract. Thereafter the remaining fossil fuels will have to be used in a highly rationalized way and new alternative energy sources found or the existing alternative energy sources will need to achieve new exploitation levels.

Population growth and economic prosperity affect the global oil demand. A shortage in oil supply, or highly priced crude oil, may also lead to cycles of economic recession: "... the world has entered a vicious circle whereby any improvement in the economy would lead to increased oil demand that would again soon hit the falling capacity limit causing higher prices that would in-turn re-impose recession."(Aleklett and Campbell 2003). In 2004, world consumption of crude oil was targeted to surpass 82 million barrels per day, i.e. around 30 billion barrels in the full year. This seems to put consumption equal to production leaving no surplus capacity. However this situation has not been officially confirmed. At the present time there is an unknown limit on the increase of oil production capacity and there is no confirmed estimate of additional global investments being made in oil production, transportation and refining facilities. The OPEC official price range for crude oil for 2004 was set at $22 to $28 per barrel. Surprisingly, by the year end the price of crude oil jumped to over $50 per barrel. In late 2004 the crude oil price was therefore twice the average value of the official range.

The widespread availability of a cheap fossil fuel has been key to population explosion and present lifestyles. The Oil Peak may impact drastically on modern societies and their high dependency on fossil fuels.

2.6 FUEL EFFICIENCY

Automobiles are developed to satisfy customers requirements for affordable and a convenient means of transport. According to the Japanese Automobile Manufacturers Association (JAMA): "...low fuel consumption, is a critically important issue for the automotive industry. There is now a particularly pressing need for even greater fuel economy in order to decrease CO_2 emissions so as to prevent further global warming." (JAMA 2004).

Aware of customer requirements for fuel efficient vehicles and low emission vehicles, along with stricter vehicle emissions legislation, manufacturers strategically decided to advance propulsion technology by intensifying R&D programs and by establishing power train alliances. Diesel engines in particular, have been an object of great interest in Europe, while more recently in the U.S. and Japan interest in hybrid-electric engines has surged. Further there has been worldwide research activity aimed at developing vehicles powered by fuel cell technology in order to advance them to competitive performance and cost levels as the ICE. Some of the reported engine improvements include lower fuel consumption, lower emissions, better performance and lighter engines. However, improving vehicle propulsion technology constitutes only one of a number of possible ways of realizing more fuel efficient vehicles. Other approaches include: replacing petrol engines with diesel engine equivalents (or with hybrid-electric engines); reducing the overall vehicle weight; improving the vehicle aerodynamics; improving the transmission efficiency; reducing the vehicle rolling resistance; and downsizing engines. Of course benefits can be gained by combining the use of a number of these approaches.

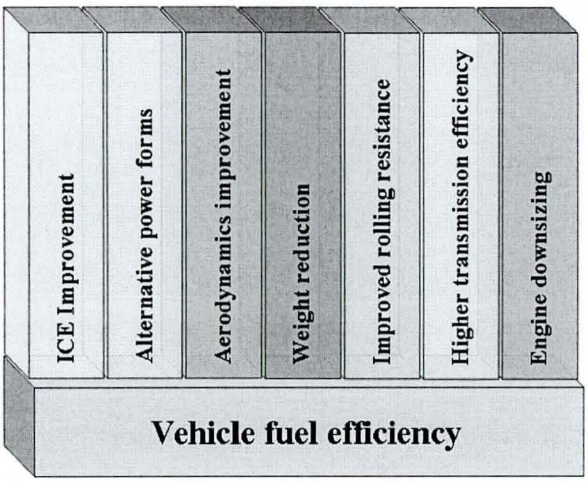


Figure 2.18 Alternative ways of increasing the fuel efficiency of vehicles.

2.6.1 Improving the internal combustion engine

Manufacturers are adopting different strategies to increase vehicle efficiencies, but it appears that nearly all of them have sought to improve the conventional ICE. Such developments are linked to the essence of the automotive industry which has made improvements of this type since its inception at the end of the 19th century. It is well known that the petrol and diesel ICEs have poor efficiencies relative to other forms of actuator. The automotive industry widely accepts that there are still significant opportunities for engine efficiency improvements. During the past decade there has been global research activity aimed at realising engine improvement, involving both automotive industry and research institutes. Modern petrol engines have efficiencies of around 16% (Toyota 2004). Modern diesel engines have efficiencies around 22%. Electric hybrid engines, as well as diesel engines are more fuel efficient than equivalent petrol engines. Therefore one obvious way of improving vehicle fuel efficiency is to increase the use of diesel engines or electric-hybrid engines, as substitutes for petrol engines. The Toyota Prius electric-hybrid petrol vehicle is claimed to have an efficiency of about 37% (Toyota 2004). Figure 2.19 shows the overall efficiency of a petrol powered vehicle.

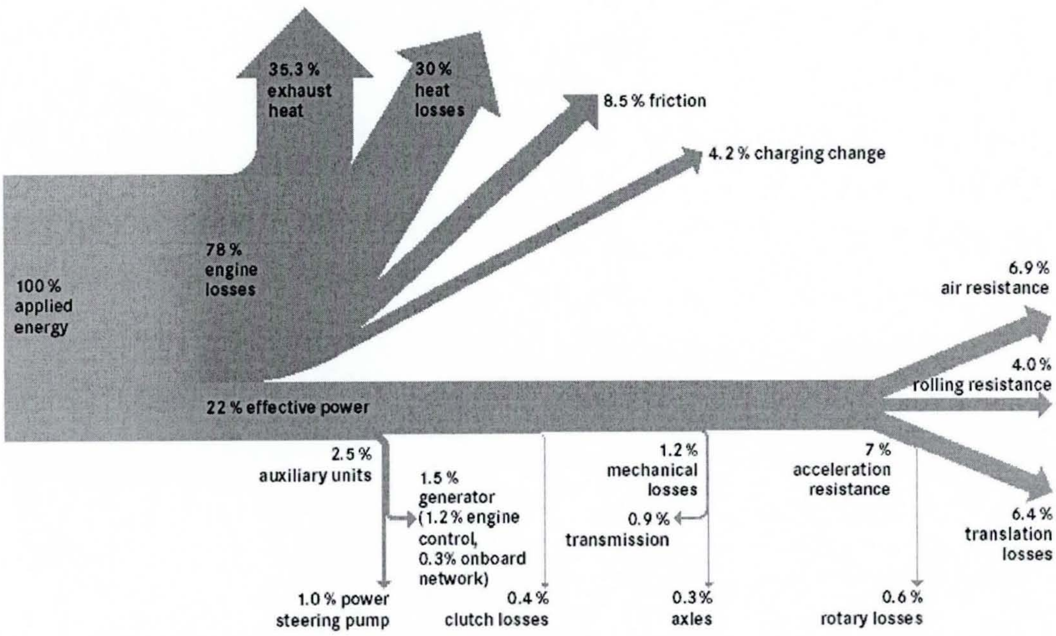


Figure 2.19 Efficiency of the internal combustion engine. Source: DaimlerChrysler Hightech Report, Research and Technology issue 1/2002, Optimized drive trains, (DaimlerChrysler 2002) pp. 62-63.

Technological advances made to ICEs have resulted in net savings in vehicle fuel consumption. Engine efficiency gains were used primarily to increase the vehicles' acceleration and power, with marginal gains realised in fuel consumption rate despite increases in vehicle weight (Sperling et al. 2004). As illustrated by Figure 2.20 and Figure 2.21 there has been an average increase in the engine power (linked to an increase in average engine size) within new car models sold in Western Europe between 1990 and 2003.

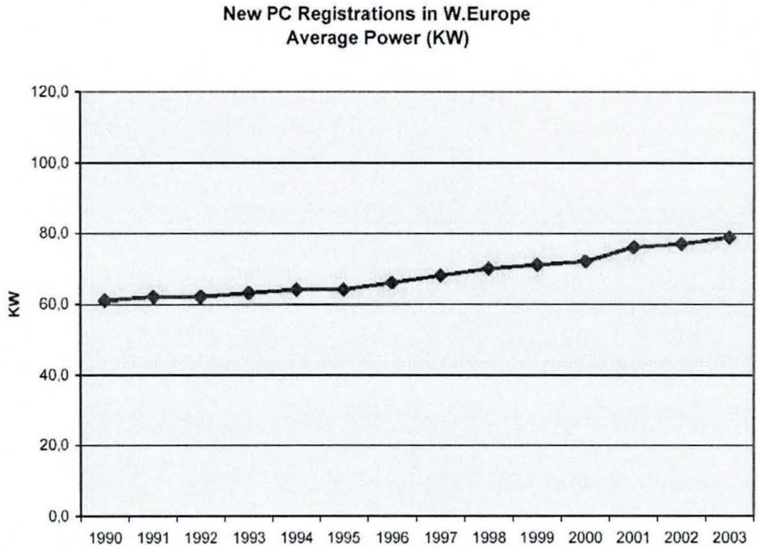


Figure 2.20 Average power of new personal vehicle registrations in Western Europe. Source: Association of the European Automobile Manufacturers (ACEA 2004).

From 1990 to 2003 the average power of personal vehicles in Western Europe has increased from 61KW to 79KW (ACEA 2004). Engine size grew during the same period from 1,591 cm^3 to 1,743 cm^3 (ACEA 2004).

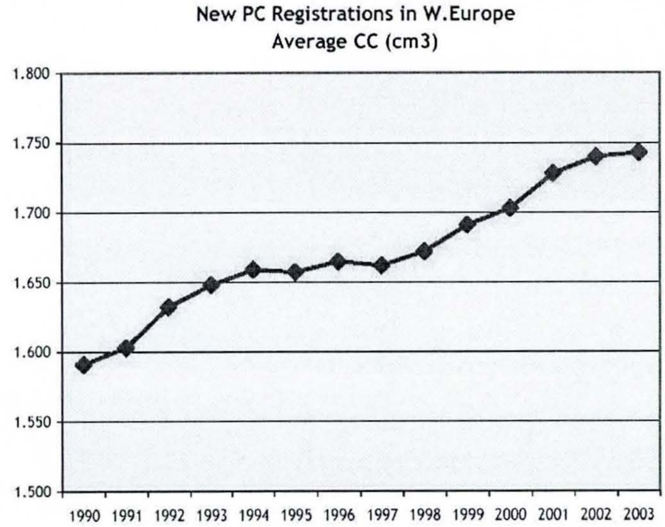


Figure 2.21 Average engine volume of new personal vehicle registrations in Western Europe. Source: ACEA (ACEA 2004).

This increase in engine size and power has been counterbalanced however by technological advances in the engines. Therefore a net positive fuel economy has been achieved. Figure 2.22 shows the combined increase in engine capacity, vehicle mass and power, and a corresponding reduction in CO_2 emissions in vehicles produced in the EU.

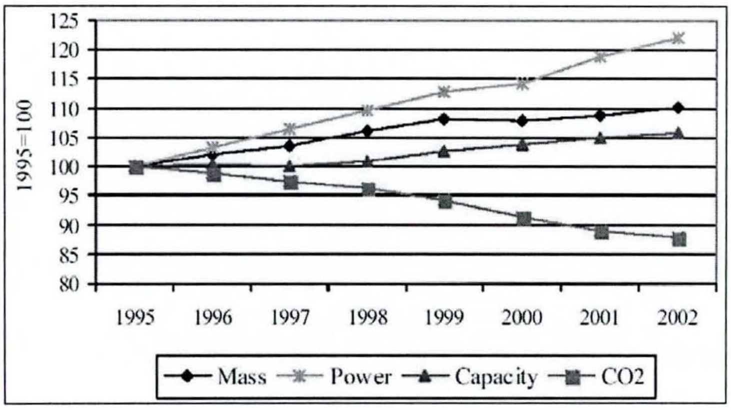


Figure 2.22 Average vehicle mass, engine power, engine capacity and CO2 vehicle emissions in ACEA members. Source: ACEA (ACEA 2003), pp. 6

From 1990 to 2002 there was a 20% reduction in fuel consumption of vehicles made in Germany (VDA 2003). Figure 2.23 depicts the positive evolution of fuel economy in German vehicles. This reduction is attributed to advances in engine efficiency and to an increase in share of new vehicles propelled by diesel engines. Diesel vehicles have lower fuel consumption rates, thereby an increase in its share will naturally lead to a decrease in average fuel consumption rate.

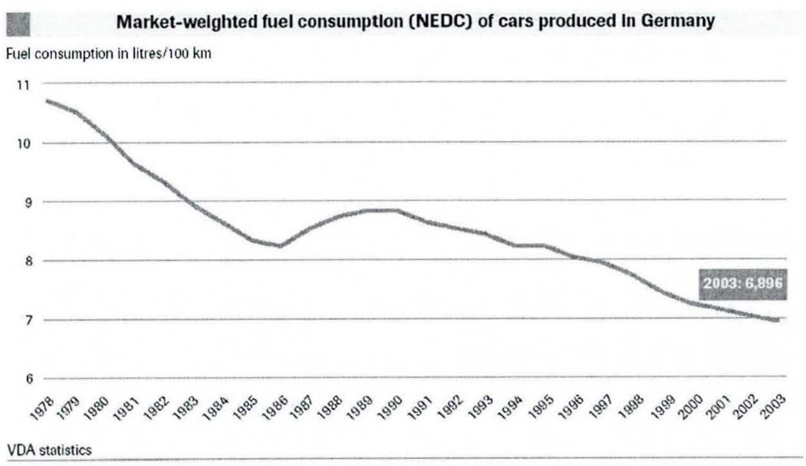


Figure 2.23 Average fuel consumption of cars produced in Germany 1978-2003. Source: German Association of the Automotive Industry (VDA 2004), pp.119.

2.6.2 Reducing vehicle weight

A progressive increase in vehicle weight, resulting essentially from improved performance, increased comfort, safety and assisted driving devices has limited fuel consumption gains. These gains derive from improved engine efficiency resulting from technological advance in the propulsion system. The widespread use of these devices, such as ABS[12], airbags, power assisted steering, air conditioning, etc., has constrained further the evolution of favourable fuel economy gains. Figure 2.24 presents developments made, from 1990 to 2001, by adopting such devices. As mentioned previously, gains in fuel consumption have been achieved despite the fact that bigger and more powerful engines have been fitted into the cars. Vehicle weight is estimated to have increased by 10% between 1995 and 2002 (ACEA 2003).

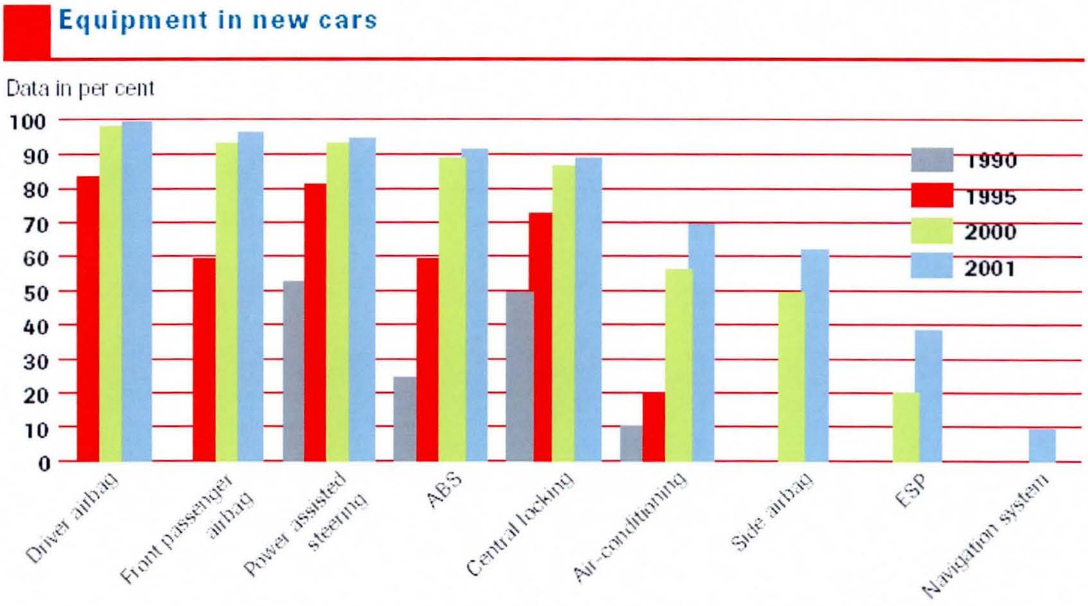


Figure 2.24 Wide spread use of several automotive devices from 1990 to 2001 in Germany. Source: VDA Auto annual report 2002,(VDA 2002), pp. 185.

Never the less, since the engine itself is one of the heaviest components of a vehicle, most manufacturers have made a shift from cast iron blocks and cylinder heads to aluminium alloys (Nieuwenhuis and Wells 1997). The Ford-PSA engine partnership has recently started to produce a 2.7 Litre V6 diesel engine, at Dagenham engine plant, with a block made of CGI (Compacted Graphite Iron (CGI) is a high strength material). This engine is made with thinner walls, but has reinforced durability, thereby reducing the engine weight.

[12] ABS: Anti-lock Braking System.

Weight reduction has been described as being one of the greatest challenges facing the automotive industry (Knell 2001). Vehicle weight reduction programs have been undertaken by many manufacturers in order to reduce the overall fuel consumption of the vehicle. It is reported that for each 100 kg reduction in vehicle weight there is a net saving of about 0.3 to 0.6 L per 100 kms (EAA 2003). Important weight savings can be made to the vehicle chassis, body, engine, transmission, suspension, and other vehicle parts by using lighter materials, such as: aluminium; plastics; magnesium or metal-matrix composites. The use of thinner high-strength steels and related design improvements to various parts may also reduce vehicle weight. Also important is that primary weight reduction programs can lead to secondary reductions such as downsizing the engine and introducing lighter transmission and lighter suspension systems while maintaining equivalent performance and security to that of similar but heavier cars. Unfortunately lighter materials are also more expensive and require different manufacturing technologies and processes. In 1994 the approximate cost of: (A) steel was $0.75/Kg; (B) aluminium was $3/Kg; (C) structural carbon fibre was $18 to $22/Kg (Moore and Lovins 1995).

Some companies, such as Audi AG have pioneered the introduction of the aluminium body with the Audi Space Frame (ASF) to some mass produced models, such as with the Audi A8 and Audi A2 models. This has been justified mainly by weight considerations, which enable significative fuel savings. Aluminium has good stifness characteristics and a high energy absortion potential which enables the construction of vehicles with equivalent safety levels. Recent world-class top successful crash tests of Audi A8 and very low fuel consumption rates of only 3 liters per 100 kms for the Audi A2 1.2 TDI diesel vehicle, seem to confirm Audi's vision. Audi A2 1.2 TDI (855 kg) along with VW Lupo 3L (830kg) diesel vehicles are the most fuel efficient mass produced vehicles in the world; including the mass produced electric-hybrid vehicles of Toyota and Honda.

Steel has a volumetric density of 7.85 g/cm^3 which makes it 3 times heavier than Aluminium, which has a density of 2.7 g/cm^3. In some automotive parts it is possible to replace a steel element by one made of aluminium of the same thickness. Where this can be achieved a weight reduction factor of 3 to 1 can be realised, i.e. around 67% weight reduction. For the majority of parts however, it is necessary to increase the thickness by a ratio of 1.5, e.g. a 0.8mm thick steel element may be replaced by a 1.2mm thick element made of aluminium, this equating to a weight improvement of 50% (EAA 2003).

Aluminium might also help to improve vehicle safety, since aluminium has good rigidity and excellent capacity to absorb kinetic energy. Automotive aluminium recycling is economically viable and has become a successful business in many regions of the globe at present times. The aluminium recycling rate from automobiles is at present around 95%. Production from aluminium recycling represents up to 95% of energy savings when compared to primary metal production.

Magnesium is a premium material in the automotive industry, it is lighter than Aluminium, with a density of only 1.738 g/cm^3; i.e. Aluminium is 1.5 times heavier than Magnesium. Magnesium is very expensive which limits its use to prime applications, such as Formula 1 car parts where costs are not the prime issue. Never the less some volume manufacturers have introduced magnesium in prime model parts in the past and the future use of this material in automotive applications seems bright.

The use of stiff plastics in cars has also increased lately but their widespread use is constrained by environmental legislation, such as the European end-of-life vehicle directive, which is progressively introducing higher rates of end-of-life vehicle re-use and recycling. Developments in this field are likely to produce low cost high stiffness and less environmental disruptive products thereby allowing the substitution of several parts of the vehicle, such as body panels and transmission parts (SMMT 2004). Madza has announced recently its intention to begin the substitution of steel body panels with stiff plastics in the Mazda6 vehicle model.

The percentage of light materials in vehicles has increased progressively. Light materials however are not used in a systemic and generalized way so as to improve the vehicle fuel consumption. This is mainly due to an unavoidable increase in vehicle material costs along with a required change in manufacturing processes. Generally the use of light materials has counterbalanced the introduction of an increasing number of devices in the vehicles which necessarily have added weight. Only a small number of manufacturers have been introducing light materials in their car range in a strategic manner, so as to substantially decrease the weight of the vehicle, and thereby enable the use of smaller engines; which in turn enables fuel consumption economies and pollutant emission reduction.

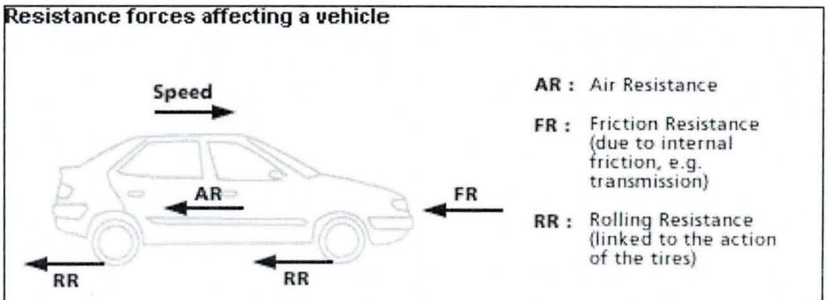
2.6.3 Improving vehicle aerodynamics

A significant part of the useful energy used to propel a vehicle is to overcome the resistance of the air. In rough terms the resistance depends on the size of the frontal area, the shape of the vehicle and the vehicle speed, among others. The aerodynamic drag coefficient (cd) measures the efficiency with which a vehicle overcomes that resistance. The lower the drag coefficient the better, i.e. the lower the effect of air resistance on the movement of the vehicle. A typical drag coefficient for a 5-passenger car is 0.35 (i.e. somewhere between 0.25 and 0.45). There have been commercial vehicles with excellent aerodynamics, such as the Opel Calibra which exhibited a drag coefficient of only 0.26. The more recent Audi A2 has a very low drag coefficient of 0.25. Several sources state that it is not possible to keep improving vehicle aerodynamics because of limits arising from the average human size and their need for comfortable positions during transportation. Increasingly hard to achieve and relatively marginal gains in vehicle aerodynamics are expected in the future. However lowering the drag coefficient during the vehicle design stage introduces only a small marginal cost per vehicle but can lead to significant fuel consumption economies during the life span of the vehicle.

2.6.4 Reducing the vehicle rolling resistance

Fuel consumption improvements can also be realised by reducing the resistance between the contact zone of tires and the road. Improvements can take the form of new tread patterns, tire materials, tire structures and the automatic monitoring of optimum tire pressures (lower tire pressure increases the rolling resistance). These improvements can lead to an improved fuel economy without hampering vehicle handling, brake performance and tire durability. In 1992 Michelin launched the first generation of "green" tires. Michelin announced that the green" tires offered a 4% reduction in fuel consumption. Since 1992 Michelin has sold around 500 million "green" tires. With the XSE tires, Michelin claims to have reduced rolling resistance by about 17% compared to previous best original equipment tires specified for production vehicles. Goodyear demonstrated their Momentum Radial very low resistance tires for Chrysler and Aero Radials for GM. Rolling resistance is the product of vehicle mass and the coefficient of tire rolling resistance, with the addition of small parasitic losses from wheel bearings and brake drag (Moore and Lovins 1995). Michelin XSE has a rolling resistance coefficient of 0.008 and

Aero Radials tires from Goodyear a resistance coefficient of 0.0048. The power needed to overcome rolling resistance rises linearly with vehicle speed (Moore and Lovins 1995). Figure 2.25 illustrates the resistance forces affecting a vehicle: at a speed of 100 km/h the rolling resistance force equates to 20% of the total.



At a constant speed of 100 km/h, the relative influence of these forces is:

CAR:	TRUCK :
65% AR	50% AR
15% FR	10% FR
20% RR	40% RR

Figure 2.25 Diagram of the resistance forces affecting a vehicle. Source: Michelin (Michelin 2003)

2.6.5 Engine downsizing

Engine downsizing corresponds to reducing the engine in either displacement (volume), power or both. Examples of engine downsizing include the replacement of a V6 engine by an I4, or a 2.0 L I4 by a 1.8 L I4. Engine downsizing may be required or freely chosen in order to:

1) provide an adequate propulsion system for a vehicle subjected to a weight improvement program;

2) maintain equivalent vehicle performance as a result of improved power-to-engine-size ratio due to engine technological advances;

3) fit a turbo charger, which allows a reduction in the engine displacement;

4) decrease the engine size after it has been acknowledged that the engine was oversized for customer requirements or should those requirements change;

5) take economic advantage of specific markets with tax systems that favours

smaller engines and engine downsizing does not affect consumer awareness of vehicle performance.

In general, engine downsizing in all the above cases, results in lower rates of fuel consumption. Present generation vehicles have reached exacerbated driving performances which are not at all compatible with driving safety and driving speed limit legislation across most countries in Europe. A significant percentage of vehicles achieve top speeds well beyond the highest speed limits of the European highways. Countryside driving and City driving require much lower driving speeds. At the same time only a fraction of the European daily journeys are done on highways. Therefore in general over-rated cars are used through most of their useful life-time and this equates to a well below ideal driving regime. In turn this results in a wasteful use of fuel. Engine downsizing could be one key answer to this problem, but it would require a significant customer requirements shift from rating driving performance above fuel economy. Substantial increase in transport fuel prices projected for the next decades may bring a deeper awareness of this situation. This may lead to more rational decisions that link choice of vehicle characteristics more overtly to personal driving patterns.

2.6.6 Synthesis

Different combined strategies can be developed to decrease the overall fuel consumption of vehicles, namely some combination of the following: (1) improvement in ICE efficiency; (2) use of more efficient diesel or hybrid engines; (3) use of lighter materials to decrease vehicle weight; (4) aerodynamic improvements at design stage; (5) use of lower rolling resistant drag tires; and (6) engine downsizing. Some manufacturers have already begun to take such an holistic approach and are beginning to mass produce vehicles that unquestionably are a step ahead of competitors in terms of fuel consumption rates.

Most of the strategies available to reduce vehicle fuel consumption result in cost penalties or restrict the degrees of freedom available during vehicle design. All major vehicle manufacturers are active in programs aimed at reducing fuel consumption, namely in programs seeking ICE improvements, because the market is clearly demanding more fuel-efficient vehicles. Fuel cell driven engines and hydrogen-fuelled engines, apparently the most promising alternative power forms, are a subject of further analysis in section 2.9.

2.7 VEHICLE EMISSIONS

By 2005 the **Euro 4**, the European Union vehicle emissions standard, will come into action. This will restrict to roughly half those vehicle emissions allowed by **Euro 3** (a standard that has been in use in Europe since the year 2000). In 2008 the **Euro 5** will replace and restrict further Euro 4 emission levels. Figure 2.26 shows directive progressive reductions in vehicle emissions of Carbon Monoxide (CO), Hydro Carbons (HC), Nitrogen Oxides (NOx) and Particulate Matter (PM).

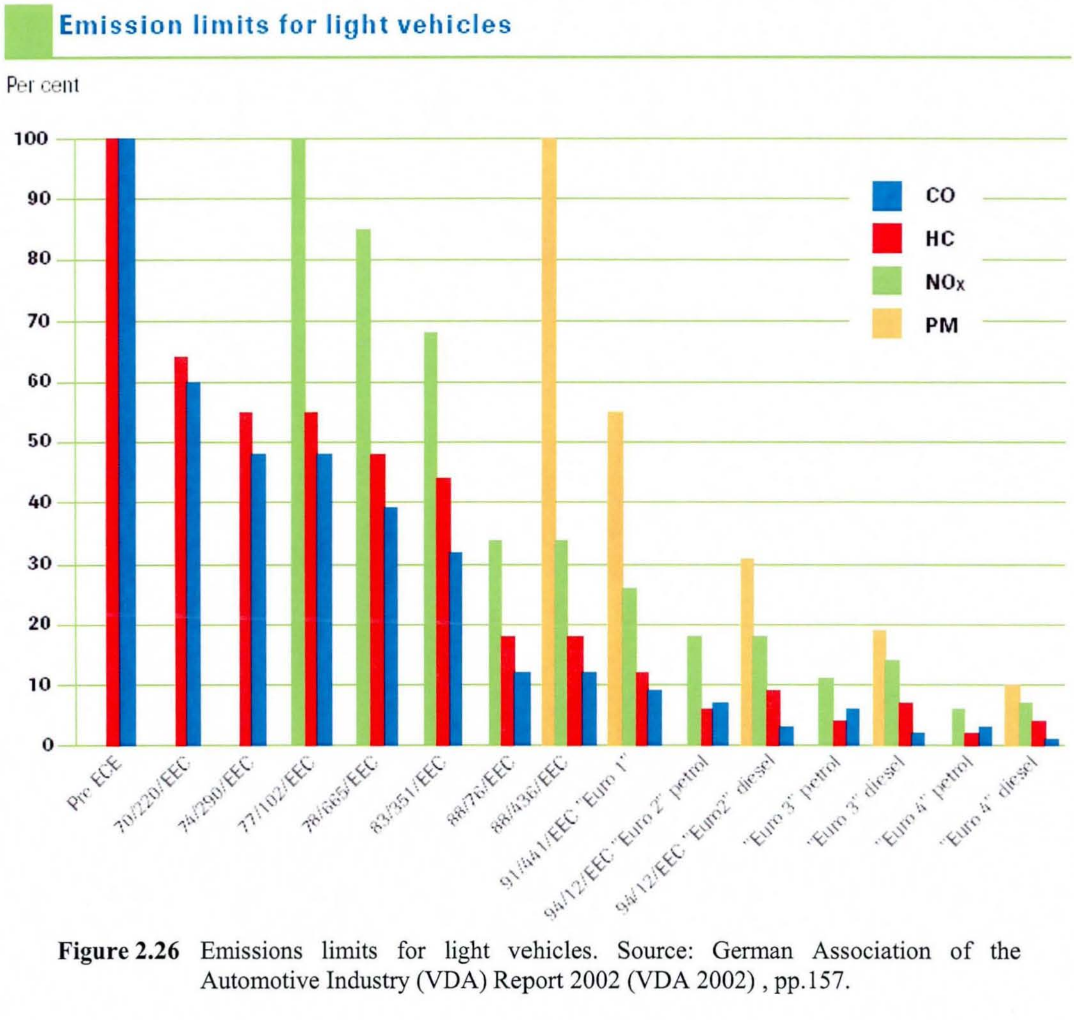


Figure 2.26 Emissions limits for light vehicles. Source: German Association of the Automotive Industry (VDA) Report 2002 (VDA 2002) , pp.157.

In 1998 the European Automobile Manufacturers Association (ACEA) made a voluntary commitment to reduce "the new car fleet" average CO_2 emissions to 140g/km by 2008 (ACEA 2002). In 2001, over 2.8 million ACEA cars were sold with CO_2 levels of 140g/km (or inferior), which represents an increase of almost 40% with respect to the year 2000. These vehicles already comply with the agreed target that ACEA set to the year 2008. ACEA is planning to make a further commitment by constraining even further the CO_2 vehicle emissions to 120g per km by 2012. Figure 2.27 show a progressive increase in the share of EU made vehicles emitting less than 140g of CO_2 per km.

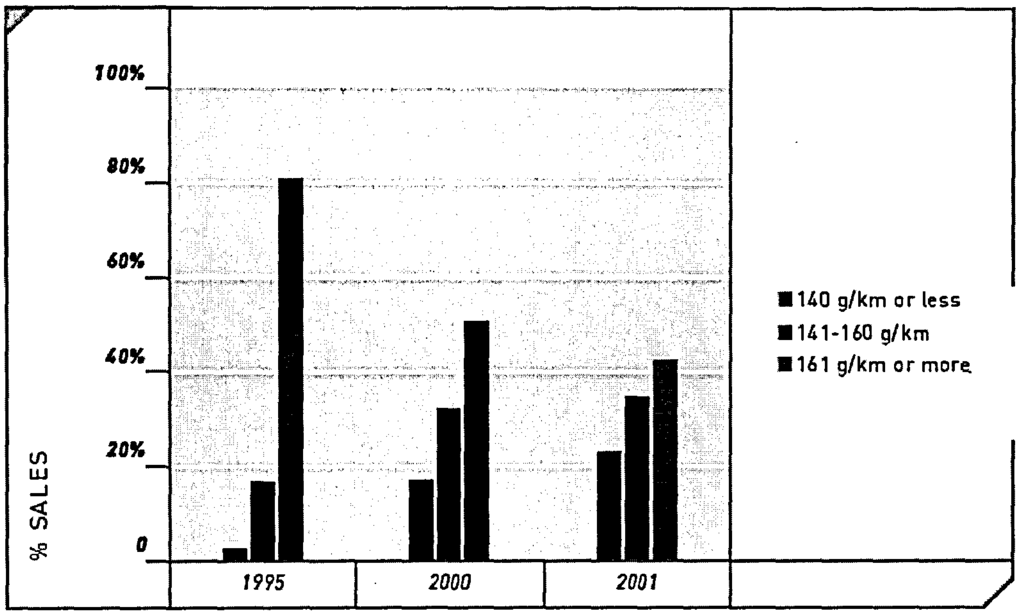


Figure 2.27 ACEA's Sales by CO2 Categories. Source: ACEA's CO2 Commitment, European Automobile Manufacturers Association (ACEA 2002) pp. 9.

The quest for lower emission vehicles has been essentially linked with lower vehicle fuel consumption, i.e. reductions in the emissions of vehicle pollutants can be achieved by reducing vehicle fuel consumption levels. This is particularly true for CO_2 emissions. In addition however, diesel engines naturally emit less CO_2 than equivalent petrol engines, which means that the widespread adoption of diesel engines could further decrease the overall emission of CO_2. However, diesel engines naturally emit much higher levels of Particulate Matter (PM). The emission of PM is essentially insignificant in petrol engines. To substantially decrease emissions of PM some vehicle manufacturers are installing Diesel Particulate Filters (DPF) in their upper segment models. Others manufacturers have recently announced their intention to expand the use of DPFs to all of their diesel fleet.

Following widespread introduction of lead-free fuels, the EU is progressively seeking to decrease the sulphur content of fuels. This was reduced to 350ppm in 2000 and will be lowered to 50ppm by 2005. Meanwhile the European Commission has adopted a proposal to introduce sulphur-free diesel throughout the EU by 2011 (DTF 2001).

The U.S. emissions standard and the EU emissions standards are not directly comparable since they are based on different test cycles. Never the less, some basic comparations can be drawn. For instance, relating to diesel vehicles, the US emission standard is more stringent with regard to Nox and PM emissions, while the EU emissions standard is more stringent about CO and has made a substantial commitment to reducing CO_2 emissions. In 2001 the average vehicle emission in Europe was 167g of CO_2/km (ACEA 2003), whilst in the U.S. it was 333g of CO_2/US mile (i.e. 207g of CO_2/km) (DTF 2001). The JAMA[13] and KAMA[14] are also committed to equivalent ACEA's CO_2 reduction targets.

Progressively stricter vehicle emission legislation is a mandatory fact of life in all major regions of the world, including EU, USA and Japan. The long term vision is clearly to have much "cleaner vehicles" than those used presently.

2.8 PETROL/DIESEL/HYBRIDS MARKET SHARE

A literature survey was carried out on the share of Diesel/Petrol/Hybrid cars (ACEA 2004) (JDPA-LMC 2003; VDA 2003; Winter and Kelly 2003). This shows that in Europe, the customer desire for fuel efficiency is manifest in a steady increase in demand for diesel vehicles. Diesel fuel contains around 11% more energy than petrol fuel (DTF 2001). Diesel engines also operate at higher compression ratios giving a substantial fuel economy advantage when compared to petrol engines. Diesel vehicles provide 20% to 50% greater overall fuel efficiency over equivalent petrol-powered vehicles (DTF 2001; Sperling et al. 2004). In 2003 the average cost of diesel fuel in the European Union (EU15) countries amounted to 0.8 Euro per litre, against the petrol average of 1.0 Euro per litre, i.e. a 20% lower cost.When combined, higher energy content, greater engine efficiency and lower fuel cost, diesel vehicles give an overall fuel related cost reduction of 36% to 52% over

[13] JAMA : Japan Automobile Manufacturers Association.
[14] KAMA: Korean Automobile Manufacturers Association

similar petrol vehicles, on average in the EU countries. This substantial reduction in fuel expenditure explains why Europeans are willing to pay a premium price for a diesel car. Figure 2.28 depicts the share of diesel cars in new personal car registrations in Western Europe, from 1990 to 2002.

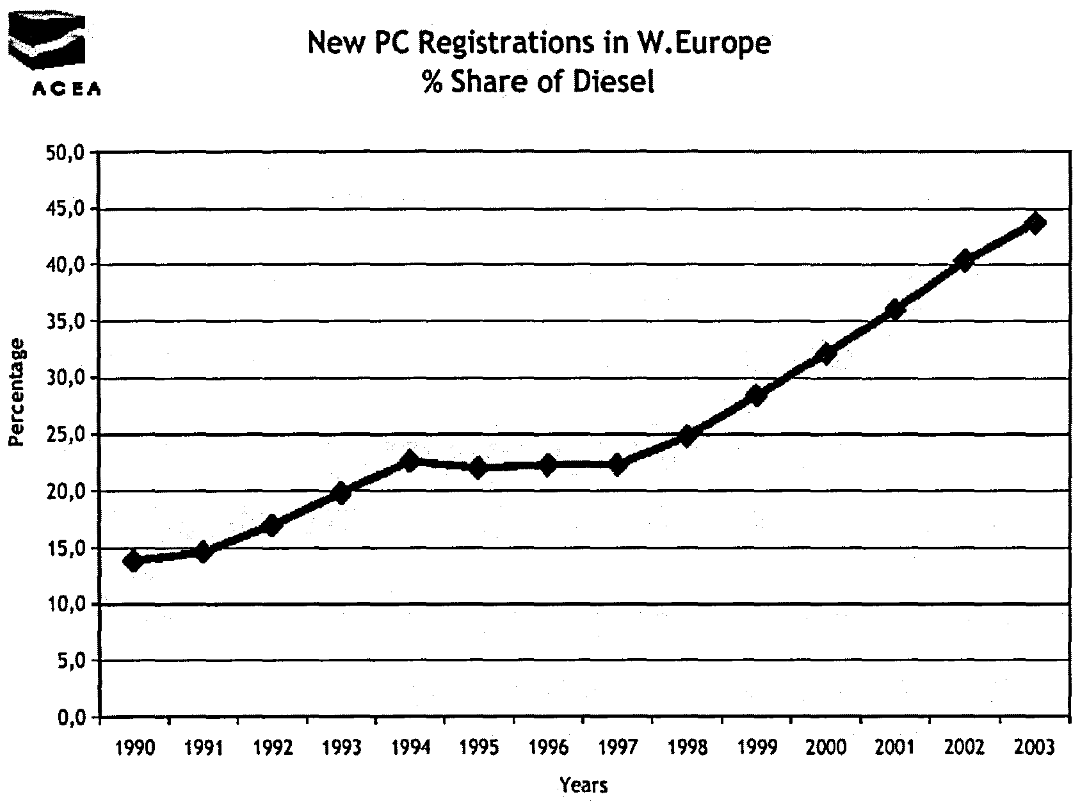


Figure 2.28 Diesel share of new Passenger Cars in Western Europe. Source: European Automobile Manufacturers Association (ACEA 2004).

Diesel demand in Western Europe has grown to around 44% in 2003 (+6% over 2002 levels) whereas a decade before its market share was less than half that value. Petrol based vehicle share has changed (fallen) in inverse proportion to diesel share. In 2003, registrations of new petrol cars in western Europe was 7% down.

The pace of growth in diesel share has been common to almost all Western European countries and is forecasted to surpass the share of petrol powered vehicles by the end of 2005. In 2002 the diesel share in wider western European automotive markets grew as follows: France 7.0%, Spain 4.8%, Italy 7.7%, Germany 3.4% and UK 5.5% (VDA 2003). Austria is a paradigmatic example of this trend with a diesel share of 71.5% in 2003 that is still growing. Figure 2.29 depicts 2003 diesel shares in Western European countries.

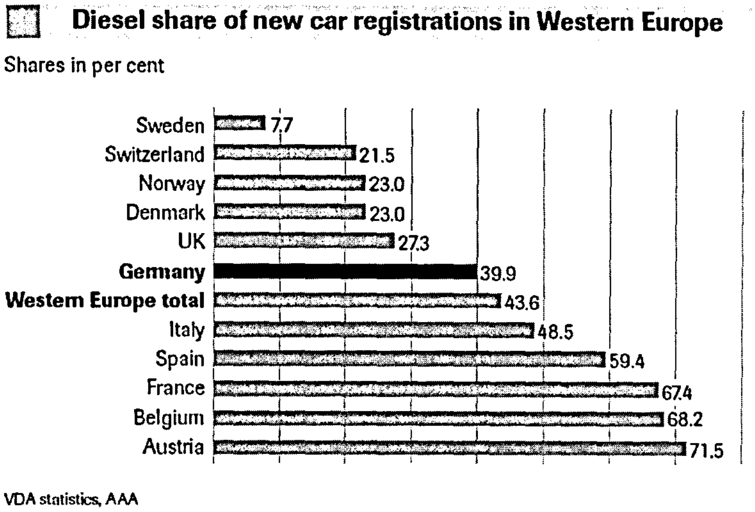


Figure 2.29 Diesel share of new vehicle registrations in Western Europe in 2003. Source: German Association of the Automotive Industry (VDA) Report 2004 (VDA 2004), pp.40.

On the other hand in the US the share of diesel vehicles is relatively negligible (see Figure 2.30). This is assumed to be the case because of the very bad image that diesel vehicles have among US consumers. For many years US consumers regarded them as being "noisy, dirty and smelly" vehicles. Also in the US cheap petrol fuel has remained available. Thereby fuel expenditure has not been a major concern for American consumers.

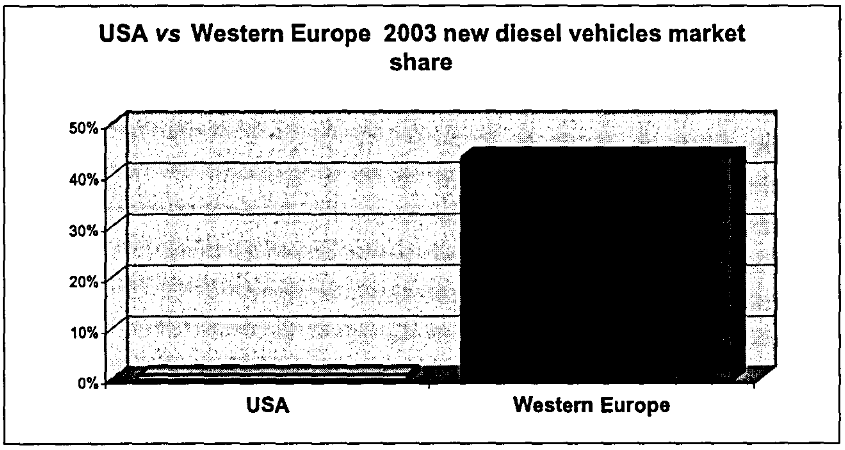


Figure 2.30 Year 2003 comparison of the US and Western Europe diesel market share. Source: based on data from the US Diesel Technology Forum (DTF 2001) and from the German Association of the Automotive Industry (VDA 2004).

Hybrid-Electric Vehicles

Electric hybrid vehicles combine the use of an ICE with an electric motor. The main purpose of a hybrid vehicle is to use the high-speed power provided by the ICE with the clean efficiency of an electric motor. Hybrid vehicles are more efficient than equivalent ICE based vehicles, therefore subjected to lower fuel consumption rates and lower pollutant emissions. Hybrid vehicles use regenerative braking to generate electrical power which is stored in a battery. The energy is afterwards used by the electrical engine to power the vehicle at low-speed (the ICE is least efficient precisely in this driving regime) or to assist the main engine with additional power during acceleration or hill climbing. The main engine can therefore be downsized. Hybrid vehicles have automatic shutdown and automatic restart of the main engine. When the vehicle comes to a stop the engine is shutdown. When accelerating again the electrical engine will be in charge of propelling the vehicle until the driving conditions require additional power firing up an automatic restart of the main engine. This optimised operation of the propulsion system prevents waste of energy when idling. For a typical hybrid vehicle, Figure 2.31 depicts several stages of the driving cycle.

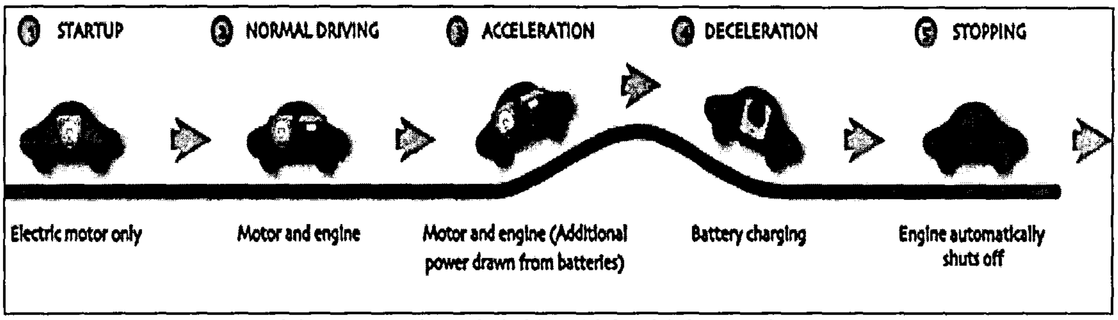
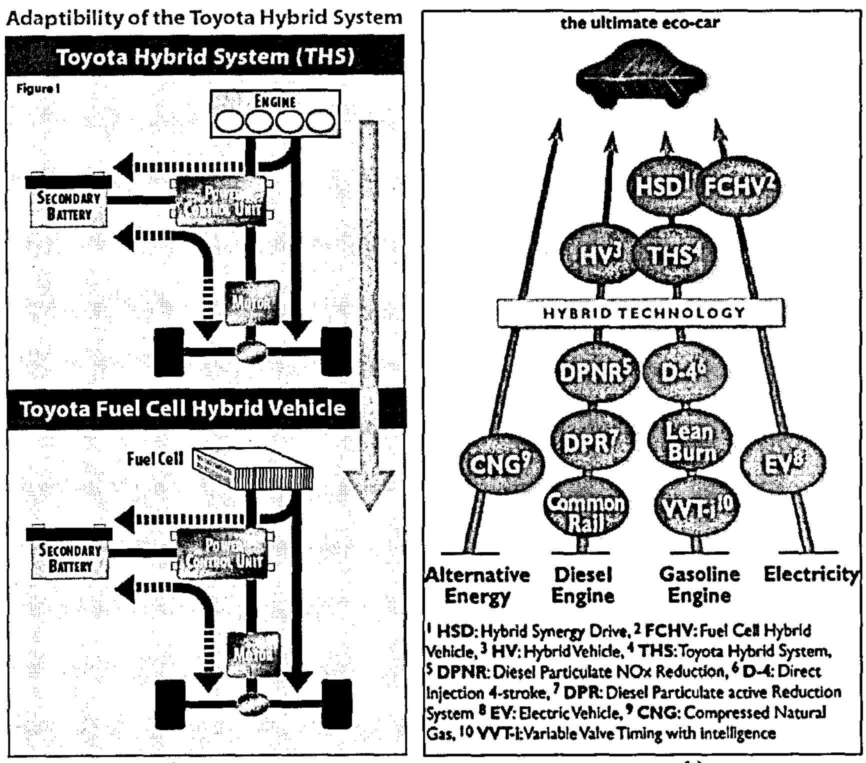


Figure 2.31 Propulsion stages in a hybrid vehicle driving cycle. Source: Toyota Motor co.(Toyota 2004)

In December 1997 Toyota launched in Japan the first mass produced gasoline-electric hybrid vehicle, namely the Prius. The model was released on sale in the U.S., Europe and other regions in 2000. Honda also launched mass produced hybrid powered vehicles in the market, such as the Honda Civic Hybrid and the Honda Insight. Generally hybrid powered vehicles have been well accepted because they enable a better fuel consumption economy. But, because fuel cost is not a major concern in North America their commercial success has so far been limited. Currently there are four hybrid models available in the US market: the Ford Escape Hybrid, Honda Insight, Honda Civic Hybrid and Toyota Prius. These models are ranked as the most fuel-efficient vehicles in their respective segment and are among the cleanest running vehicles available in the US (US_DOE/US_EPA 2003). There was a growing demand in the US market during 2004, which is forecasted to reach 45,000 Prius units in 2005 (25,000 units being sold in 2003), Toyota is planning to expand its

Prius production for the North American market to 100,000 vehicles by the end of 2005. Toyota also predicts a total world market of 180,000 units in 2005, rising from 120,000 units in 2004 (Toyota 2004).

Toyota is committed to the production and development of electric-hybrid vehicles for the foreseeable future. This is one of their prime responses to consumers concerns about fuel consumption and vehicle emissions. However in the longer term, this technology is regarded as being an intermediate step to fuel cell powered vehicles (FCV). Figure 2.32 a) contrasts the Toyota Hybrid System and the Toyota Fuel Cell Hybrid Vehicle. It is worth noting similarities between the two systems. Figure 2.32 b) shows Toyota's vision of future propulsion technologies, ultimately leading to advanced hybrid powered and fuel cell powered vehicles. At present the Toyota Hybrid System propels the Prius model using a petrol ICE. The ICE could however be replaced by a Fuel Cell since the propulsion system was designed in a modular way to comply with future propulsion requirements.



a) b)

Figure 2.32 a) Toyota's modular approach to electric-hybrid powered vehicles and fuel cell hybrid powered vehicles. Source: Toyota Motor co. (Toyota 2004). b) Toyota vision on vehicle propulsion technology (Toyota 2004).

At present the new version of the Toyota Prius, considered the most advanced hybrid vehicle in the market, is said to have an overall efficiency of 32%, which is more than double that of a petrol-ICE, which is around 14% efficient. Table 2.2 presents a comparison of efficiency rates achieved by Toyota car models equipped with ICE, Hybrid Electric-ICE and Fuel Cells. The Toyota Prius hybrid vehicle has a fuel consumption rate of 52 US mpg (4.5 L per 100 kms) in city driving conditions and 45 US mpg (5.2 L per 100 kms) in highway conditions (OTT 2004). The Prius model has an excellent coefficient drag (cd), i.e. 0.29 (typically cd = 0.355 for a 5-passenger car). It comes with a 1.5-litre, 4-cylinder petrol engine with cast-aluminium head and block. The full weight of the Prius is 2765 lb (1254 Kg). Prius meets the SULEV[15] emissions standard.

Table 2.2 Petrol vs. Hybrid vs. Fuel Cell vehicles well-to-wheel overall efficiency. Source: Toyota Motor co. (Toyota 2004).

	Well-to-Tank[1] (fuel production efficiency) (%)	Tank-to-Wheel[2] (vehicle efficiency) (%)	Overall efficiency (Well-to-Tank x Tank-to-Wheel) (%)
Recent Gasoline Car	88	16	14
Previous Prius	88	32	28
New Prius		37	32
Toyota FCHV[3]	58	50	29
FCHV Target[3]	70	60	42

1. Source: Toyota study, Japanese energy conditions 2. Source: Toyota In-house testing, Japanese 10/15 mode 3. Hydrogen from CNG

The Honda Insight hybrid is a 2-seat vehicle with a fuel consumption rate of 61 US mpg (3.9 L per 100 kms) in city conditions and 68 US mpg (3.5 L per 100 kms) on the highway (OTT 2004). The Honda Insight has an excellent coefficient drag, being of 0.25. Insight's body is 40% lighter than an equivalent car body, major body panels are made of aluminium alloy panels and the remaining body components are made of plastic. The engine is a lightweight 1.0-litre, 3-cylinder petrol engine made of aluminium. The full weight of this car is 1856 lb (842 Kg). The Insight meets the ULEV[16] (with manual transmission) and the SULEV (with CVT automatic transmission) emission standards. The Honda Civic hybrid has a fuel consumption rate of 48 US mpg (4.9 L per 100 kms) in city

[15] SULEV: Super Ultra Low Emissons Vehicle standards (Califórnia, USA).

conditions and 47 US mpg (5.0 L per 100 kms) on the highway (OTT 2004). The engine is a lightweight 1.3-litres, 4-cylinder petrol engine made of aluminum. The full weight of this car is 2732 lb (1239 Kg). The Civic Hybrid also meets the SULEV emission standard.

Ford launched the Escape hybrid SUV last year in the North American market, followed by the Honda Accord Hybrid model (a high volume model) and the Lexus Rx 400h model. In 2005 Toyota launched the Highlander Hybrid. Several other new hybrid vehicles are planned to be introduced in the market in the next years, see Table 2.3. This is especially the case in North America where currently hybrid vehicles do not have major competition from diesel vehicles.

Table 2.3 New Hybrid vehicles in the US market. Sources:U.S. Department of Energy in (DOE 2004) based in J.D. Power-LMC; Energy & Environmental Analysis (EEA), Inc.

Manufacturer	Model	Type	Estimated Date Available
Model Year 2005			
Dodge	Ram Contractor Special	Fullsize Pickup	Fall 2004
Honda	Accord Hybrid	Midsize Car	Fall 2004
Lexus	RX 400h	Midsize SUV	Fall 2004
Toyota	Highlander	Midsize SUV	Spring 2005
Model Year 2006-2008			
Saturn	VUE	SUV	2006
Mercury	Mariner Hybrid	Midsize SUV	2006
Nissan	Altima Hybrid	Midsize Car	2006
Chevrolet	Malibu/Equinox	Midsize Car/ SUV	2007
Chevrolet	Tahoe (AHS II)	SUV	2007
GMC	Yukon Hybrid (AHS II)	SUV	2007
Ford	Futura	Midsize Car	2007
GMC	Sierra Hybrid (AHS II)	Fullsize Pickup	2008
Chevrolet	Silverado Hybrid (AHS II)	Fullsize Pickup	2008

The proliferation of new vehicle models heralds a projected growth for hybrid vehicles in the US market place. Currently though the actual numbers of hybrids in the US market is quite limited, probably because of the availability of cheap fuel in the U.S. (DTF 2001). However, recent US studies show growing concerns about the price instability of crude oil and about US dependency on external oil sources (DTF 2001; US_DOE 2003).

Thus far the success of hybrid vehicles in Europe has been quite modest. This is probably a result of the availability of many efficient diesel powered vehicles. Currently

[16] ULEV: Ultra Low Emissons Vehicle standards (Califórnia, USA).

diesel powered vehicles achieve better fuel consumption rates than current forms of petrol based hybrid. Until now European manufacturers have regarded hybrids as a poor option since they carry both an ICE and an electrical engine, thereby increasing the vehicle weight and vehicle cost. A future launch of diesel-hybrid vehicles in Europe could probably combine the best of diesels and hybrids, therefore improving further the fuel advantage of diesel vehicles and thereby gaining wide acceptance in European markets.

Changes in diesel/petrol/hybrid engine shares have an important bearing on the thread of thinking and research which underpins this Ph.D study. Using current automotive industry practices, normally requires the prime parts of different types of engine to be machined in different transfer lines. Since transfer lines have an essentially fixed (economic and maximum) production capacity, changes to engine part volumes invariably leads to wasted capacity and possibly uneconomic product manufacture (when required engine volumes decrease) while further investment will be required if engine demands exceed the maximum plant capacity). It also follows for instance that the production of hybrid vehicles (from Toyota and Honda) will require relative small numbers of specific engine model to be manufactured via suitable production plant and production methods, so as to satisfy both local area and global customer needs. Therefore it is questionable whether conventional transfer line production systems would provide a satisfactory and competitive solution to a hybrid vehicle demand which is difficult to predict.

2.9 FUEL CELLS AND HYDROGEN FUEL

The fuel cell concept was conceived in 1839 by the British physicist Sir William Robert Grove. Grove discovered that hydrogen and oxygen can be combined to produce water and electricity by using a device known as fuel cell (Dunn 2002). In 1874, in his book *Mysterious Island,* Jules Verne prophetically described a world that would be powered by water (H_2O). In the 1880's Fredrick Ostwald provided the theoretical foundations for fuel cells and made experimental tests to the fuel cell system parts developed by Grove. In the late 1950's Francis Bakon's research team at Cambridge developed a more advanced fuel cell which would be used some years later in U.S. space programs. In 1968 NASA used alkaline fuel cells for the Apollo space missions. These fuel cells had electrical efficiencies of up to 70% and the waste product – hot pure water, was used for drinking and cooking (Harper and Foat 2003). Up to the end of the 1980's fuel cell development work was essentially carried out by universities, government and independent laboratories, and a small number of companies. From the 1990's onwards there has been an increasing interest and an explosion of activities related to fuel cells. A large number of companies became involved with the automotive industry. Presently there are many fuel cell field installations, especially stationary fuel cells for energy back up and energy generation. A number of companies, located essentially in Canada, USA, Germany and Japan, are already commercialising fully developed FC systems. In the transport sector, there have been fuel cell vehicles (FCV) on the road since the end of 2002 on an experimental basis.

2.9.1 Fuel Cells

Fuel cells are electrochemical energy converters that produce electrical power from hydrogen. Apart from hydrogen, fuel cells also require oxygen from the air, and as by-products they generate water and heat. This is essentially the reverse of the well known process of electrolysis of water. Figure 2.33 shows a diagram of the structure of a single fuel cell and illustrates the principle of operation. The basics of a Proton Exchange Membrane fuel cell (PEMFC) is (USFCC 2003):

1. The Hydrogen fuel flows into one electrode (anode);
2. The electrode coated with a catalyst strips the hydrogen into electrons and protons;
3. The movement of the electrons generates electricity;
4. The protons pass through the proton exchange membrane to the other electrode (cathode);
5. The oxygen flows into the other electrode (cathode), where it combines with the hydrogen to produce water vapour.

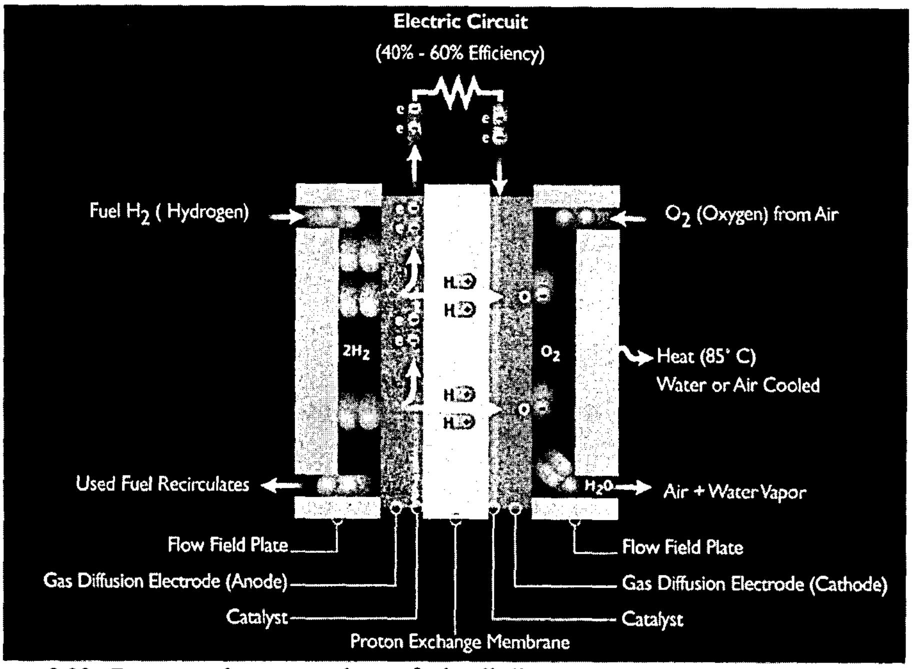


Figure 2.33 Proton exchange membrane fuel cell diagram. Source: Ballard Power Systems, in Fuel Cell Power for mobility, US Fuel Cell Council (USFCC 2003) pp. 3

As presented in the foregoing discussion, fuel cells were developed well before the ICE was invented. The high cost of developing fuel cells was prohibitive for the majority of applications, including the transport sector. In recent decades however a several fold increase in power density and efficiency, along with significant reductions in fuel cell production costs and developments in hydrogen storage devices has resulted in enthusiastic interest within the automotive industry, governments and energy related industries.

> *"Only few megatrends exist that are of special importance to the future of the automotive industry. Sustainable mobility is one of them, and fuel cells are a key technology for it"*
>
> Prof. Klaus-Dieter Voheringer[17] *in* (USFCC 2003).

The automotive industry regards fuel cells and hydrogen fuel as the ultimate vehicle propulsion technology and energy source, since they represent a step forward in efficiency and low emission vehicles. At the present time there is also a general acceptance that fuel cells represent the only realistic future alternative to a dependency on fossil fuels. Hydrogen fuel and fuel cell technology are not yet price competitive, both with respect to the fossil fuel prices and the cost of the ICE. Current fuel cells convert fuel into traction

[17] President of the shareholder committee of XCELLSIS and president of research and technology of DaimlerChrysler.

three to four times more efficiently than a conventional ICE. The efficiency of producing hydrogen fuel is however much lower than extracting and refining fossil fuels. FCs have also few moving parts to wear out, make almost no noise, and emit pure water only, if hydrogen is used as feedstock.

Table 2.4 Advantages and disadvantages of Fuel Cells. Source: Adapted from (Government_of_Canada 2003), pp. 9.

Fuel Cells Advantages	Fuel Cells Disadvantages
• High efficiency • Zero or low emissions, depending on the fuel used • Modular design, allowing flexibility in size and manufacturing efficiency • Low noise • Few moving parts (potentially low maintenance and long operating life) • Increased efficiency when combined with heating and power purposes	• Loss of efficiency with time • High investment costs • Unknown lifetime • Low availability • Few technology providers • Absence of fuel infrastructure for most applications

Enormous potential advances in engine technology and expected technological breakthroughs have highly motivated a growing number of companies. Many have invested and developed the technology so that in the not too distant future the world may move from being a carbon based oil economy to a carbon free, hydrogen economy. When using hydrogen from renewable energy sources the pollutant emissions from fuel cells are nearly zero.

Types of Fuel cells

There are five main types of Fuel Cell categorised by the electrolyte they employ (Government_of_Canada 2003; Harper and Foat 2003):

- The **Polymer Electrolyte Membrane Fuel Cell (PEMFC)**, also known as the Proton Exchange Membrane fuel cell, is fuelled by pure hydrogen and is regarded as the most promising of the fuel cells for the automotive sector. All major automotive companies have Fuel Cell Vehicle (FCV) development programmes based on PEMFC. This type of FC can also be used in stationary applications.

- **Alkaline fuel cell** (AFC) is fuelled by pure hydrogen and has a lower power density, i.e. ten times lower than PEMFCs, but a good efficiency rate. AFCs are expensive and used mainly in prime applications, such as in space programs.

- The **Phosphoric Acid fuel cell** (PAFC) can be fuelled by hydrogen and natural gas. It is being developed for medium to large-scale stationary power systems. PAFC are the most commercially advanced technology with over 200 units operating globally. This type of fuel cell is unfit for automotive applications due to high operating temperatures and high start-up time.

- The **Solid Oxide fuel cell** (SOFC) can be fuelled by hydrogen, petrol, natural gas and other fuels. SOFCs use a solid ceramic electrolyte – usually solid zirconium oxide stabilised with ytrria. These cells are being developed for use in automotive applications such as to power vehicle auxiliary electrical units.

- The **Molten Carbon fuel cell** (MCFC) can be fuelled by hydrogen, natural gas, petroleum, propane, landfill gas, diesel, coal methane and other fuels. MCFCs are being developed for large-scale industrial stationary applications.

Some companies are also developing the **Direct Methanol fuel cell** (DMFC). This type of fuel cell is fuelled by methanol and does not need an external reformer since the methanol is converted into hydrogen and carbon dioxide at the anode. DMFC is being developed for the automotive industry, portable electronics and other applications. Two factors are restricting its wider use at present: DMFCs have a low efficiency and methanol is toxic. This has led some companies to develop a Direct Ethanol Fuel Cell (DEFC) instead.

Table 2.5 Main fuel cell types. Source: Adapted from (Government_of_Canada 2003), pp. 73-74; (Greaves et al. 2003), pp. 92-94; (Greaves et al. 2003) (Harper and Foat 2003) and California Hydrogen Business Council.

Fuel Cell type	Electrolyte	Operating temperature	Efficiency	Fuel
Proton exchange membrane	Solid perfluorosulphonic acid polymer	60-100 °C	40 – 45%	Hydrogen
Alkaline	Aqueous solution of potassium hydroxide soaked in a matrix	90-100 °C	60%	Hydrogen
Phosphoric acid	Liquid phosphoric acid soaked in a matrix	175-200 °C	40 – 45%	Hydrogen
Molten carbonate	Liquid solution of lithium, sodium or potassium carbonates, soaked in a matrix	600-1000 °C	50%	Hydro-carbon fuels
Solid oxide	Solid zirconium oxide with trace of ytrria	600-1000 °C	50 – 55%	Natural gas
Direct methanol	Solid polymer	50-100 °C	30 – 40%	Methanol

Companies and products

At present Canada seems to be a global leader in fuel cell technology with many companies at the forefront. In 2003, 17 Canadian companies were operating in the production or system integration of fuel cells, while many more companies were supplying these companies. Japan, Singapore, USA and some European countries, such as Germany, are also at the forefront of development of the technology. The target industries include stationary applications (such as distributed power generation in homes and plants), transportation (propulsion technology for vehicles and auxiliary power units) and portable electronics (such as mobile phones and laptops). Backup power and power for mobile phones and laptop applications already exist in the marketplace.

Leading companies operating at this area include: Ballard Power Systems Inc. (considered world leader in FC technology); Hydrogenics Corporation Inc.; Proton Energy Systems; Quantum Technologies Inc.; PEM Technologies; Aluminium-Power Inc; Fuel Cell Technologies Ltd.; Honda Motor Co.; Toyota Motor Co.; Nissan Motor Co.; Ford Motor Co.; General Motors Corporation.; DaimlerChrysler; Nuvera; GE Power Systems, UTC Fuel Cells; H Power, Proton Motor Fuel Cell GmbH, etc.

An update internet based list of fuel cell vehicles (FCV) can be found at (USFCC 2004). The end of 2004 FCV list, with the FC system providers, is presented in **Appendix A.**

Price of Fuel Cell systems

Fuel cells are very expensive at the present time, ranging from $2000 to $20000 per KW. This price is for a custom built model, not that for a mass produced fuel cell. The price target for fuel cell systems used for automotive applications is set at around $50 per KW (Greaves et al. 2003), in order to compete with the ICE. With the current state of fuel cell technology it is projected that a 50KW PEM transportation fuel cell, when produced in volumes of more than half million units per year, would cost around $300 per KW (Greaves et al. 2003). For stationary applications (such as gas turbines) the cost is likely to be lower, from $400 to $600 per KW. However fuel cells are still an emergent technology. Mass production of this technology along with major cost reduction improvements on several system components is key to its market acceptance. SOFCs are expected to be cost competitive at around $400 per KW. At present SOFCs cost around $4,500 per KW. Volume production may substantially reduce this value but other major technological advances are also needed before SOFCs become cost competitive.

A recent study from Japan targets the cost of an automotive PEMFC system at 5000 yen per KW (Kosugi et al. 2004), this corresponds to roughly US $40 per KW, which is equivalent to the present ICE cost. The performance target is set at around 70 to 90 KW for a normal scale passenger vehicle.

Intensive research on Fuel Cells (FC) and the deployment of hydrogen fuel has led to significant technological advance. Fuel cells and hydrogen fuel are expected to have an important impact on world economies in the near future, and are expected to switch the basis of the world economy from carbon to hydrogen. Ferdinand Panik, head of DaimlerChrysler fuel cell project, cited in (Green_Consumer_Guide_Editorial 2001) has predicted that around a quarter of all new cars in 2020 will use fuel cells.

> *"I believe fuel cell vehicles will finally end the 100-year reign of the internal combustion engine as the dominant source of power for personal transportation"*
>
> William Clay Ford Jr.[18]

Strategic Investment in Fuel Cells

The fuel cell industry has received billions of US dollars of strategic investment from the private sector. Also EU, Japanese and US governmental bodies have committed more than $5 billion to a number of three to five year programs to develop Fuel Cell systems and Hydrogen fuelling infrastructures (Government_of_Canada 2003). There has been unprecedented release of private and governmental fundings and this gives a clear message that this technology has become highly promising. Funding in the US has amounted to a total of $1.7 billion over a 5 year period (announced in January 2003) (Bush 2003). In October 2002, the European Commission announced that €2.12 billion would be invested over 2003-2006 in renewable energy development, mostly related to hydrogen and fuel cells (US_DOE 2003). In Japan the corresponding budget for the 2003 Japanese fiscal year was $280 million (US_DOE 2003). The Japanese Ministry of Economy, Trade and

Industry (METI) announced initial commercialisation targets of 50,000 FCV by 2010 and 5 million by 2020, (EC 2003); (Spencer and Barret 2003).

There are already a number of fuel cell vehicles on the road and fuel cell stationary applications in operation. All major automotive manufacturers are involved in programs aimed at developing Fuel Cell technology and introducing them to the market place. Toyota and Honda already have fuel cell vehicles[19] on the road in Japan and in the US. Both brands are expanding their experimental fleet of fuel cell vehicles. By the end of 2004 DaimlerChrysler plans to have 60 A-Class based Fuel Cell vehicles on the road. DaimlerChrysler already have a fleet of 30 Mercedes-Benz Citaro buses running in 10 major European cities (including London). Many other manufacturers have experimental vehicles running on hydrogen. These include Daihatsu, Daewoo, Fiat, Ford, GM, Hyundai, Mazda, Mitsubishi, Nissan, PSA, Renault, Suzuki and VW.

The global market for fuel cells and related products is projected to reach $46 billion by 2011, and has claimed potential to reach $2.6 trillion by 2021(Government_of_Canada 2003).

2.9.2 Hydrogen Fuel

Hydrogen is the most abundant and lightest element in the universe, representing 70% of the mass of the universe (Harper and Foat 2003). Hydrogen is 14 times lighter than air, it is colourless, odourless and non-toxic. Hydrogen does not naturally exist in its elemental form on Earth, i.e. it is always bound to other substances, such as in fossil fuels, in biomass and in water (H_2O). Therefore hydrogen has to be produced from these substances through three alternative processes, namely: (1) thermal; (2) electrolytic; and (3) photolytic. Figure 2.34 presents the alternative sources for hydrogen production along with the respective production alternatives. In the U.S., approximately 95% of hydrogen is currently produced via steam reforming[20]. This is the most efficient technology currently available (DOE 2002). Renewable and nuclear systems can produce hydrogen from water using electrolytic

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[18] Chairman, Ford Motor Company

[19] Toyota has the FCHV and Honda the FCX model.

[20] Steam reforming is a thermal process, typically carried out over a nickel-based catalyst, that involves reacting natural gas or other light hydrocarbons with steam.

or thermal processes, but these processes are not efficient nor cost effective when compared to the process of reforming fossil fuels.

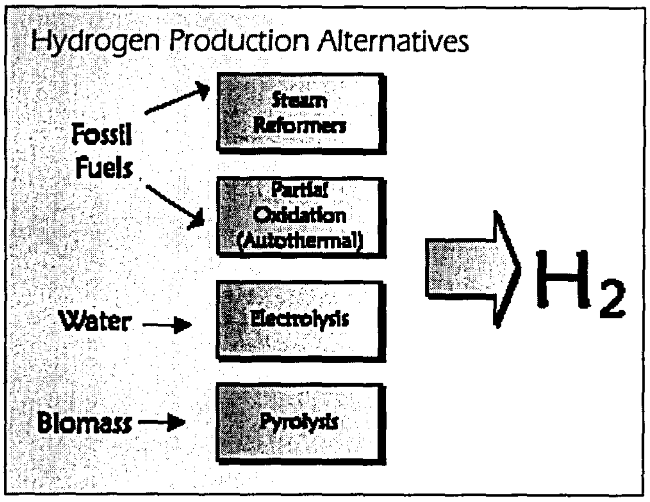


Figure 2.34 Hydrogen production alternatives. Source: United States Department of Energy (DOE 2002) pp. 4

The fuels historically used to power the world since the industrial revolution, have registered successive declines in carbon content: from coal, to oil to natural gas. Hydrogen seems to be the most promising successor, and is the ultimate fuel from the perspective of low carbon content, i.e. zero carbon. Hydrogen can be produced from a wide range of sources, however if fossil fuels such as oil and natural gas are used to obtain hydrogen the steam reforming or partial oxidation processes will inevitably produce undesirable substances, such as carbon dioxide. Current world production of hydrogen is around 50 million tonnes/year (Greaves et al. 2003).

The most promising sources of hydrogen, from an environmental and sustainability point of view, are the ones where the hydrogen is produced from renewable sources, such as from wind energy, solar energy, hydroelectric energy, geothermal energy, wave energy, etc., which allow CO_2-free energy conversion and do not deplete. The amount of energy needed to power all activities of mankind on the planet is an infinitely small part of the total amount of energy offered to earth everyday in a renewable form. For instance, the sun is a reliable and inexhaustible provider of energy: "In one hour the sun sends to earth around the same amount of energy as that used by the whole of mankind in a year"(BMW 2003).

In transport applications, hydrogen can be converted to energy via combustion inside a traditional engine or through electrochemical processes using fuel cells (BMW 2003):

1. Hydrogen can be combusted in a similar form as petrol, diesel or natural gas. The benefit of using hydrogen combustion over fossil fuel combustion is that it releases fewer emissions. There are no CO_2 emissions, and nitrogen oxide emissions are very low, the only major by-product is water. The BMW brand has had hydrogen internal combustion engine (H_2-ICE) powered vehicles since 1979. At present BMW offers the 745hL and 750hL models along with a MINI concept car that are powered via a H_2-ICE .

2. Fuel cells utilize the chemical energy of hydrogen to produce electricity and thermal energy. A fuel cell is a quiet and clean source of energy. Water is the only by-product it emits if it uses hydrogen directly. Since electrochemical reactions generate energy more efficiently than combustion, fuel cells can achieve higher efficiencies than H_2-ICE. Current fuel cell efficiencies are in the 40% to 50% range, with up to 80% efficiency reported when used in combined heat and power applications.

According to Bossel *et* al. (2003) using 2003 energy prices, hydrogen production by reforming natural gas (H_2=$5.60/GJ) was around two times more expensive than petrol cost ($3.00/GJ, before taxes), using the same energy content as a reference for both fuels; hydrogen production using coal (H_2=$10.30/GJ) was around 3.4 times more expensive than petrol production; and hydrogen production using electrolysis of water ($20.10/GJ) was around 7 times more expensive than petrol production (Bossel et al. 2003).

Particular regions of the planet, exhibiting strong availability of renewable energy sources are already making strategic movements towards a long term transition to Hydrogen power. Iceland has announced in 1999 its intention to become the first world's hydrogen society. Iceland intends to produce hydrogen from abundant supplies of geothermal and hydroelectric energy available in the country. Hawaii depends on oil for as much as 88% of its total energy demand. Hawaii intends to use their plentiful geothermal, solar and wind resources to split the water and produce hydrogen.

Fuel Cells *vs.* internal combustion engine business

In the automotive field, fuel cells essentially mean low emission (or emission free) quiet vehicles, running at a much higher efficiency than those propelled by the ICE. However, present cost disadvantages of fuel cell systems, when compared to equivalent ICE and hybrid engines, and cheaper petrol/diesel fuel, when compared to hydrogen fuel, mitigates against the mass production of hydrogen propelled vehicles.

In the future however, the impact of viable mass produced fuel cell vehicles could prove disastrous to the ICE business (including engine manufacturers and engine machining system builders). Fuel cells will be made by completely different manufacturing processes and using very different materials. This implies a total disruption in the production of vehicle propulsion technology. Moreover Fuel Cells have an intrinsically modular design, allowing flexibility in size (power) and manufacturing efficiencies to be gained. It is envisaged that fuel cells varying from 40KW (54hp) to 180KW (245hp) (a typical power range for most vehicle requirements), would easily be made at the same production plant and even on the same production line if required. This compares favourably with present engine plants, where 54-250hp engines are manufactured at several engine plants using multiple production lines, due to engine specifics and the limited flexibility of current machining systems (the 54-250hp power range encompasses a variety of engines such as: 3-cyl., 4-cyl., 5-cyl., 6-cyl. In-line and V6, all in either diesel or petrol engine forms).

This means that hypothetically, at some future point in time, when ICEs are still competing with fuel cells, ICEs will be under even greater pressure to be more efficient and less pollutant. This will require even faster ICE replacement by newer models. Under these conditions engine plant capacity utilisation can be expected to drop to unprecedentaly low levels unless new manufacturing paradigms are devised and adopted. This is likely to drive up the price of ICEs as plant investment cost will need to be recouped over fewer engine units. Further future ICE production volumes will probably vary substantially.

2.10 RELEVANCE OF THE FOREGOING DISCUSSION

2.10.1 Engine plant investment

A study conducted in 1995 by the International Motor Vehicle Program (IMVP-MIT) shows that new engine plants are significantly capital intensive assets, requiring on average $300 to $800 million capital investment in equipment and facilities. Such plants are essentially composed of a machining area and an assembly area. The machining area is the most capital intensive part, accounting for as much as 80% of the total capital investment and can represent 50 to 70% of the complete plant floor area (Whitney et al. 1997). BMW for instance has invested around £400 million in the Hams Hall engine plant, officially opened on the 8^{th} February 2001.

Traditional engine plants encompass one single engine model, such as a 4-cyl. petrol engine (which may include several engine volumes, e.g. 1.4L; 1.6L and 2.0L), or several engine models (such as 3-cyl. petrol and 4-cyl. petrol engines). In a single engine model plant the machining area is composed of distinct transfer lines, one for each prime part. Normally there are three transfer lines. On multiple engine model plants the engine machining area is typically divided into sections. Each section is dedicated to the production of a single engine model and encompasses three (or more) transfer lines for machining each prime engine part. BMW's Hams Hall engine plant produces a single engine model, the 4-cylinder valvetronic petrol engine (which is produced in 3 volume variants: 1.6L; 1.8L and 2.0L) and comprises three transfer lines for machining respectively the engine blocks, the cylinder heads and the crankshafts (Moreira 2003).

The United Kingdom has 13 automotive engine plants. Details to these plants are shown in **Appendix B** – entitled **"Guide to engine and transmission plants in Europe"**. The UK has a greater number of engine plants than Germany, even though German vehicle assembly plants produce approximately three times the number of vehicles produced in UK each year. These facts indicate the importance of this industry to the United Kingdom, and possibly, the need to find ways of creating more efficient and/or more flexible and agile plants.

2.10.2 Relevance to the study

The foregoing discussion has highlighted several automotive related issues which affect the widespread availability and sustainability of present means of personal mobility. This has shown the importance of personal mobility in the industrialized world and developing countries, as the main guarantor of higher levels of standard of living, personal fulfilment and economic development.

Several challenges are high on the agenda of global automotive companies, fuel suppliers and governments. These challenges must be undertaken to secure the availability of sufficient energy to satisfy an increasing power demand, to reduce greenhouse gas emissions and to optimise vehicle propulsion technologies so as to reduce fuel consumption and pollutant emissions. The Kyoto greenhouse gas emissions protocol has triggered a series of individual government measures to ensure needed reductions in such emissions in order to overcome the global warming phenomenon. These measures include new legislation, with progressively stricter vehicle emission constraints, that directly affect automotive companies.

The foregoing also reviewed contemporary problems faced by the engine manufacturing business, that are derived from a historical strategy of seeking economy of scales from volume production, with associated lack of flexibility. Engine manufacturers face strong challenges to remain competitive and make profits while trying to comply with an increasing demand for optimised engines that have a shorter engine production lifespan. It naturally follows that greater engine variety and lower production volumes will probably become the norm.

The study has also reviewed insights into likely futures of propulsion technologies, such as fuel cells and hydrogen fuel, which are projected to gain significant market share by 2010. If these predictions become reality, further uncertainty will impact on the ICE business, which will require that business to evolve new best practice product engineering and manufacture.

Summary of expected trends driving future automotive scenarios:

- Expected increase in fuel prices by the end of this decade;
- Progressively more strict legislation on vehicle emissions;
- Progressive gains in market share by diesel and hybrid-electric vehicles;
- Market introduction of fuel cell propelled vehicles by 2010;

- Improvements in the ICE and other vehicle characteristics so as to improve fuel consumption and emissions;

At present, engine manufacturing plants already face problems from lack of production flexibility which reduces their competitiveness edge or necessitates further high levels of (re-)investment in already obsolete machining technology. Current engine manufacturing systems are capital intensive assets that may not reach their planned economic lifespan. As argued in the foregoing, in the near future, engine plants will be under even greater pressure to introduce new engines into the market, with as little lead-time as possible. This will necessitate ways of realising lower economic production volumes. Therefore an underpinning assumption made by the author, which has promoted much of the research investigation reported in this thesis, is that new forms of engine machining system have to be devised in order to accommodate present and future requirements.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

The automotive industry is a highly mature industry which has been operating in a global arena for many decades. To maintain competitive advantage on a worldwide scale the companies operating in this area must consistently accomplish outstanding technological improvements, while improving and renewing their production systems and rationalising them globally. This is a continuous self improvement process. The companies that are able to realise improvements most successfully and more regularly will, in general, realise greatest commercial success, higher profitability, and ultimately a better position to self fund strategies that promise to grant them future competitive advantage.

Current trends observed in the automotive industry towards the development of fuel efficient and lower emission vehicles led to intensive research programs for optimization of the design of the ICE. As a result, a growing number of innovations are taking place, imposing frequent changes in engine types and models, therefore lowering the overall time frame over which engines stay in production. In turn, this has inevitably resulted in increased frequency of needed changes to engine machining facilities and, in some cases, the decommissioning and scrapping of whole machining facilities before they have reached their economic lifespan. It follows that changes occurring in the environment and market within which automotive companies work can cause them production losses and the need for additional, sometimes risky, financial investment. Car engine manufacturing plants were invariably designed for volume production, required very significant capital investment programmes and in general are inflexible. This is particularly true for engine machining facilities.

Current automotive trends have led automotive companies to make major strategic decisions in order to optimize the deployment of their engine production systems and to protect their current and future investments, namely:

(1) Strategic alliances have been formed with respect to engine R&D and engine manufacturing;

(2) Engine designs have been rationalised with the aim of enabling the production of several engines belonging to the same product family by using the same machining facilities;

(3) Ways of deploying more flexible machining facilities are being analysed and developed.

3.2 RESEARCH AIM AND SCOPE OF RESEARCH

The research aim of this study is to investigate possible improvements to the overall performance of engine manufacturing businesses by conceiving and testing (via simulation) strategies that rationalise the global production of engines and by deploying responsive production systems that better protect production systems investments over their lifespan.

The research focus will be on ICE prime parts manufacturing problems and the machining solutions proposed will be constrained such that state of the art and proven commercial machining technologies can be deployed.

Therefore this study will be mainly concerned with strategy (3), as presented above, with the intention of promoting higher levels of manufacturing agility within the automotive engine business. However discussion in Chapter 8 of this thesis will also consider dependencies with strategies (1) and (2).

3.3 RESEARCH OBJECTIVES AND EXPECTED OUTCOMES

The objectives of this research study are:

O_1 – Document understandings about factors that have dictated developments leading to main engine component machining approaches. Coupled to this will be an analysis of constraints arising from using contemporary engine manufacturing approaches and their apparent inability to satisfy present and emerging global requirements for engine volumes and variants.

O_2 - Provide insights into promising automotive propulsion technologies and new insights into their possible impacts on the ICE manufacturing business, that occur from changes in powertrain types shares, as new engine technologies come on stream.

O_3 – Conceive and develop concepts related to a new engine machining approach which addresses limitations of industrial practice (in terms of both engine volume fluctuations and diversity of engine variants), and has potential to overcome those limitations by satisfying both current and emerging business needs effectively and economically.

O_4 – Generate predictions about future powertrain type share scenarios and engine volume requirements, over timeframes normally associated with one lifespan engine machining facilities. Here it is envisaged that the scenarios will be used to contrast and compare current best practice performance with predicted performance of the new approach to prime engine parts machining. The scenarios are to be developed from a new analysis of historical data and by considering strategic goals set and published by automotive companies, automotive and energy related associations, and governmental authorities.

O_5 - Develop a simulation model which has analytic capabilities and user interface facilities that readily enable contrasts and comparisons to be drawn between traditional engine machining approaches and the proposed engine machining approach. Test and validate use of the elements of the simulation system and recommend possible needed enhancements.

O_6 - Use a cost engineering method to compare patterns of investment required by the manufacturing systems in order to produce the demands stipulated in each scenario using both the traditional and the new approach, and thereby to report the most economical one.

O_7 – Use the simulation model, demand scenarios and investment studies, to analyse likely benefits and limitations of the new engine machining concepts proposed by this research study. By such means to theoretically validate, or otherwise, a business case for the proposed change in machining technology.

It is envisaged that future industrial applications of the concepts and new engine machining approach proposed in this study will lead to beneficial outcomes in three main respects, namely by:

- Enabling phased investment in machining systems, by systematically enabling the installation of incremental capacity such that it can closely match changing production demands, and thereby reduce risks associated with major investments needed to create engine machining facilities.

- Reducing lead times and production time losses (when machining facilities reconfiguration or machining facilities substitution is required to cope with needed change in engine parts), thereby improving the overall responsiveness of automotive organisations.

- Decreasing the costs involved in reconfiguration or substitution of machining facilities, such as by decreasing the technicians working hours required, and by reducing the investment required for machine modules replacement, whole machines or even whole system replacement.

3.4 RESEARCH METHODOLOGY - THEORY

Saunders et al. (2003) argue that a research methodology provides a theory of how research should be undertaken, while research methods refer to tools and techniques used to obtain and analyse data. The main classifications of research given by these authors show their various perspectives, namely: nature of research, research approaches, research strategies and methods of data collection. A sub-set of these methodologies has been selected as being potentially suited to this study and its different objectives and stages.

3.4.1 Fundamental and applied research

On the nature of research (Saunders et al. 2003) two types have been considered to be at extremes of a continuum:

- **Basic, fundamental or pure research**
- **Applied research**

Fundamental research is undertaken purely to understand 'processes' and 'outcomes', it does not relate directly to the existence of practical applications. Expansion of knowledge is considered a major purpose, along with findings about universal principles that apply to processes and their relationship with outcomes. The findings are generally of significance and value to society in general.

Applied research addresses practical issues which are defined as important and of immediate relevance. The main purpose of applied research resides in its improving the understanding of particular business problems, with the new knowledge applied to a particular problem only. The findings focus on practical relevance and on solutions to problems.

Gibbons et al. (1994) confirm these differences between fundamental and applied research (referring to these as Mode 1 and Mode 2 research respectively) and differentiate between them further by referring to the transdisciplinary nature, and heterarchical and transient organisational form of Mode 2, in comparison to the disciplinary nature and common hierarchical organisational form of Mode 1. Gibbons et al. (1994) also point out that competition is at the forefront of knowledge production, but that the role it plays in knowledge generation is not widely understood, nor recognised that the nature of competition changes according to historical circumstances. "Today, competition is experienced as a force in a process of continuous change, a process in which knowledge is generated not only about the market it self, but also about the physical world and technologies which shape it. Later decisions and investments are constrained by prior ones, and to reverse them is either not possible or carries high economic and social costs." (Gibbons et al. 1994).

The author of the present study considers the research undertaken to be positioned more closely to applied research than fundamental research as its aims are closely linked to advancing best practice. Although the research topic was formulated in an academic setting and was independent of industrial sponsorship, it was constrained by the industrial context observed in respect to the automotive industry, so that study findings could be of relevance to that industry over the next decade and beyond.

3.4.2 Research approaches

When designing a research project two basic research approaches can be adopted as follows:

1. **Deductive approach**

   In broad terms in a deductive approach a theory and hypotheses are developed, and a research strategy is designed to test the hypotheses. According to Robson (1993) deductive research should progress sequentially through five stages (Robson 1993):

   1. deducing a hypothesis from the theory;
   2. expressing the hypothesis in operational terms (indicating exactly how the variables are to be measured), which propose a relationship between two (or more) specific variables;
   3. testing this operational hypothesis;
   4. examining the specific outcome of the test;
   5. if necessary, modifying the theory in the light of the findings.

   If the theory was reformulated, then it must be verified by returning to the first step and repeating the whole cycle.

2. **Inductive approach**

   Using an inductive approach one collects particular but reliable data, and develops a theory as a result of a process of data analysis (Lakatos and Marconi 1985;

Saunders et al. 2003). The process of data acquisition and analysis might take long periods of time and the ideas often emerge gradually throughout the process. The process normally leads to a rich picture which creates a better understanding of the nature of the problem. The results from the data analysing process trigger the discovery of relationships between variables or new variables, thus leading to the proposal of a new theory.

According to (Saunders et al. 2003) "...we have conveyed the impression that there are rigid divisions between the two approaches (deductive, inductive) to research. This would be misleading. Not only is it perfectly possible to combine the two approaches within the same piece of research, but in our experience it is often advantageous to do so".

In fact, during the present study both approaches were used at different stages of the study progression. In the first stages inductive research was used. A significant amount of time was used to gather information and develop a rich picture of understandings relating: engine manufacturing business; the main challenges that present automotive engine industry faces; the most promising propulsion technologies; and the relevant factors that most likely will impact on this industry at short, medium and long term. This has resulted in the proposed new approach to machining main ICE parts. The essence of the remaining stages of the research was a deductive approach. This second focus was needed to validate concepts associated with the model proposed.

3.4.3 Research strategies

A research strategy defines the general framework for the research work. It elucidates on the particular way and logic used for collecting and analysing empirical evidence (Yin 2003). Various research strategies reported in (Saunders et al. 2003) are considered in outline in the following paragraphs.

Experiment

Experiment is a classical form of research, traditionally attached to natural sciences, which enables a systematically test of hypotheses and theories. The control achieved over some variables is however not always representative of the real world. This fact may limit the extension of the results to real life problems. It involves typically the:

- definition of a theoretical hypothesis;
- selection of samples from known populations and allocation of samples to different experimental conditions;
- introduction of planned change on one or more of the variables, and measurement on a small number of the dependent variables;
- control of other variables.

Survey

Survey is a research strategy that involves a structured collection of data from a sizeable population. These data are standardized allowing an easy comparison. It normally uses questionnaires to gather data, but it can also use techniques such as structured observation and structured interviews.

Case Study

Robson (2002) defines case study as "a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence" (Robson 2002). The case study strategy is said to be of particular interest when gaining a rich understanding of the context of the research and processes being enacted (Morris and Wood 1991).

Grounded theory

Grounded theory is a research strategy which begins with data collection without a prior theoretical framework. The data is generated from a series of observations. A data analysis process follows leading to a theory formulation. Predictions are then generated and subsequently tested in further observations, which may confirm or refute the predictions. Grounded theory is often considered the best example of the inductive approach. However, some authors consider ground theory an inductive/deductive approach due to the continual use of data for theory formulation, support and refutation.

Ethnography

The ethnography strategy is rooted in the anthropology field and intends to describe and interpret the social world of the research participants. It is a strategy based upon inductive approach, which uses essentially the participant observation research method.

Action research

Action research is a research strategy which possesses an explicit focus on action, i.e. it is intended not only to promote an understanding and explain the organization phenomena but also to change them. The researcher is actively involved in the change process and in the application of the knowledge gained in further change processes.

Three strategies were deployed during the study. Grounded theory was used during most stages of the study; at an initial stage in an inductive form, to acquire information and derive automotive field understandings; at a middle stage to specify the concepts and propose a new approach to engine manufacturing; and in the last stages to confirm the predictions related to the overall performance of the new approach. Experimental research was used during model simulation. The case study was designed and used to show the applicability of all related concepts and tools. A survey strategy was also considered, and even initiated, but subsequently abandoned. This was because automotive companies were not willing to share engine related information, which was considered to be highly proprietary and confidential.

3.4.4 Purpose of research

Research studies can be classified in terms of their purpose as well as by the research strategy used. Relating purpose often research has a combined exploratory, descriptive and explanatory nature. As with strategies, the research may have one or more purposes during the conduct of the research studies, especially at different stages of the study.

Exploratory research

Exploratory research is particularly useful when attempting to clarify understandings about a problem. It aims to find out "what is happening; to seek new insights; to ask questions and to assess the phenomena in a new light" (Robson 2002).

Saunders et al. (2003) point out the three main ways of conducting exploratory research, namely:

1. a search of the literature;
2. talking to experts on the subject;
3. conducting focused group interviews.

Exploratory research is intrinsically adaptable to change. The direction taken during research studies may have to vary as a result of new data discovery, or new insights that occur. The focus of the study is initially broad and becomes progressively narrower as the research progresses.

Descriptive research

The intention of descriptive research is to accurately represent a phenomenon (Robson 2002; Sekaran 2003), this may include profiles of persons, events or situations. These types of studies normally follow up an exploratory study. Descriptive research is an attempt to have a clear picture of the phenomenon and research focus, before proceding with the data acquisition on the relevant issues.

Explanatory research

Explanatory research is focused on studying a situation or a problem, building up from the gathered data, and reasoning about it, in order to explain the relationships between the variables. It essentially uses 'why' questions that spontaneously or more formally emerged from the exploratory and descriptive studies.

These three forms of research were used during the study and through most of its stages. Namely: talks with experts, literature review and visits to some UK based engine plants; author descriptions and representations of several phenomena, directly or more indirectly affecting the performance of engine manufacturing industry; and finally explaining the use of current approaches to engine machining systems and the implications of changes in external factors on the efficiency of such industry.

3.4.5 Research credibility

A sound research design is important to prevent misleading research findings. Saunders et al. (2003) and Yin (2003) emphasize that particular attention should be put into:

Construct Validity: the validity of the constructs can be improved by establishing correct operational measures for the concepts being studied and by avoiding subjective judgements when collecting data. The use of multiple sources of evidence and the establishment of chains of evidence might help.

Internal Validity: the internal validity is only a concern for explanatory studies (since exploratory and descriptive studies are not concerned with causal claims). It seeks to validate causal relationships, e.g. if a causal relationship is correct and does not omit independent variables.

External Validity or Generalisability: generalisabity is the extent to which the research results are generalisable, i.e. whether the findings may be generically applicable to other research settings, such as other organisations.

Reliability: the objective of reliability is to grant that if a later investigator followed the same procedures as described by an earlier investigator, it should arrive at the same findings and conclusions. Good documentation on procedures is essential. The goal of reliability is to minimize errors and biases in a study.

The construct validity and internal validity were a permanent concern of the author along the study. Doubts about their validity were slowly removed through an ongoing review of literature, access to multiple institutional reports, talks with experts from both academia and industry, and a process of consolidation and maturation of the concepts and approach being proposed. Chapter 9 will discuss the extent to which the new approach might be applied to automotive companies and to other industries. Relating the reliability of the research study and the research process, it is the author's conviction that given the present thesis and the software applications developed, any person is able to reach similar findings.

3.5 RESEARCH METHODOLOGIES SELECTED

In the present study it was determined that several general research methodologies discussed in section 3.4 could be utilised to achieve the objectives stated in section 3.3, along with a suitable set of methods for gathering relevant data and know-how from the automotive industry. Table 3.1 summarises the primary research methodologies adopted during each study phase. Overall however the research methodology followed can best be described as being applied research of both inductive and deductive forms.

Table 3.1 Research methodologies adopted during different phases of the research

Research phase	Description	Primary methodologies selected
Phase 1	General review of relevant literature on the automotive industry, about present trends, fuel efficient vehicles and emissions, global energy demand, oil resources and fuel prices.	Grounded theory; Exploratory studies.
Phase 2	Critical review of specific literature on: dedicated transfer lines and their use for engine machining; manufacturing flexibility and agility; and vehicle propulsion technologies.	Grounded theory; Exploratory studies.
	Understand best practice in: engine manufacturing practice; and engine machining systems engineering.	Exploratory studies; Descriptive studies; Counselling interviews Unstructured interviews Conversations and visits to automotive plants, engine plants and manufacturers of engine machining facilities
Phase 3	Development of Quantum Agile Manufacturing concepts	Grounded theory. Explanatory research.
Phase 4	Design of tools and experiments to enable the operation of Q'@gile systems to be simulated and compared with best practice DTL systems. Tool development for hypothetical scenario generation.	Experimental study (simulation). Explanatory research.
Phase 5	Create an investment model to compare DTL *vs* Agile *vs* Q'@gile systems.	Grounded theory; Explanatory research.
	Develop and review case study results for 36 alternative future scenarios centred on powertrain share. Critically discuss results.	Case study research.

CHAPTER 4

Q'@GILE SYSTEM CONCEPT

4.1 INTRODUCTION

The automotive industry evolved significantly following the development and application of dedicated transfer line (DTL) concepts. DTLs impacted not only with respect to vehicle assembly plants but also for engine plants. The concept of DTL was developed to implement a mass production paradigm, which essentially supported operating conditions characterised by a steady and high volume demand, with limited part variants.

Since the first half of the 20th century, dedicated transfer lines became a traditional symbol of automation. These early automotive production systems provided successful examples of DTL in action. More recently however, customisation and smaller batch production requirements has impacted on needs of automotive manufacturing which in turn has promoted vendors of car engine machining systems to develop what they term *Agile Systems*. The launch of so called *Agile Systems* in the engine machining area is a concerted attempt to satisfy domain requirements for agility i.e., to enable manufacturing systems to react promptly to frequent changes in engine volumes and variants without incurring prohibitive change costs.

Potentially today engine manufacturers face significant financial risks should they choose to deploy new hard[21] automated systems and fail to plan to use flexibly automated systems, because they may not then be able to support needed engine innovation or needed changes in production conditions. Indeed currently frequent changes are made to engine parts so that on average there has been a substantial reduction in the number of years that particular engines stay in production (Harrison 1996; Artzner et al. 1997a; England et al. 2002). Naturally a reduction in product lifetimes necessitates more frequent change to the machining and other production facilities and associated systems. It follows that increasingly automotive manufacturers need to be aware of (1) potential penalties incurred from decommissioning part or all of production facilities prior to the end of their planned and/or useful lifespan and (2) potential benefits that could accrue from adopting more agile production technologies. Bearing this general operating context in mind and its inherent need for (a) change capable production systems that perform competitively in automotive (particularly car engine) production scenarios and (b) an ability to quantify risks associated with the deployment of production systems in given scenarios, the **Quantum Agile Manufacturing** concept (which will be referred to as **Q'@gile**) was conceived by the author of this thesis. Q'@gile concepts are introduced in this chapter and the underlying rationale for their development is described.

4.2 DEDICATED TRANSFER LINES

4.2.1 The concept of dedicated transfer lines in automotive engine machining

Nowadays the dominant car engine manufacturers focus their in-house product machining on the following engine parts: the **engine block**[22], the **cylinder head** and the **crankshaft** (Whitney et al. 1997; Cox 2003). These engine parts are illustrated in Figure 4.1. Some engine manufacturers also machine camshafts, connecting rods and a few other parts in-house; but there has been a distinct trend to outsourcing the manufacture of 'lesser' engine elements, i.e. those parts that have lower piece part costs or are of little strategic importance. A modern engine is quite a complex system and contains from around 350 to 450 parts (Whitney et al. 1997; Moreira 2003).

[21] The term 'hard automated' has been used widely to imply lack of capability to cope with change outside the design scope of a system.

[22] 'Engine block' is also known as 'cylinder block' or 'crankcase'.

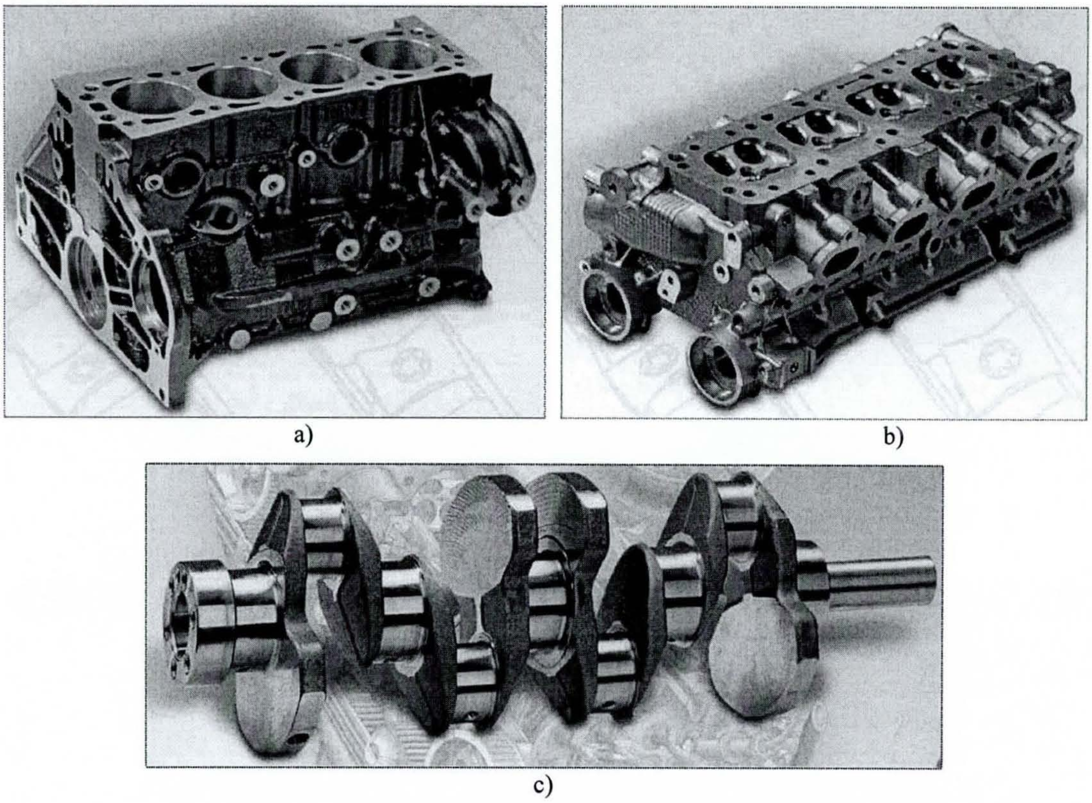


Figure 4.1 Prime engine parts: a) engine block; b) cylinder head; c) crankshaft. Source: IscarINauto catalogue of Iscar Ltd. company (ISCAR 2002).

The engine machining area of an engine plant is focused on three independent DTLs which respectively produce the three primary engine parts. Each DTL makes the part via a well defined sequence of machining operations performed by hard automated machines, that are located at so called 'DTL stations'. Figure 4.2 illustrates conceptually the layout of the plant machining area.

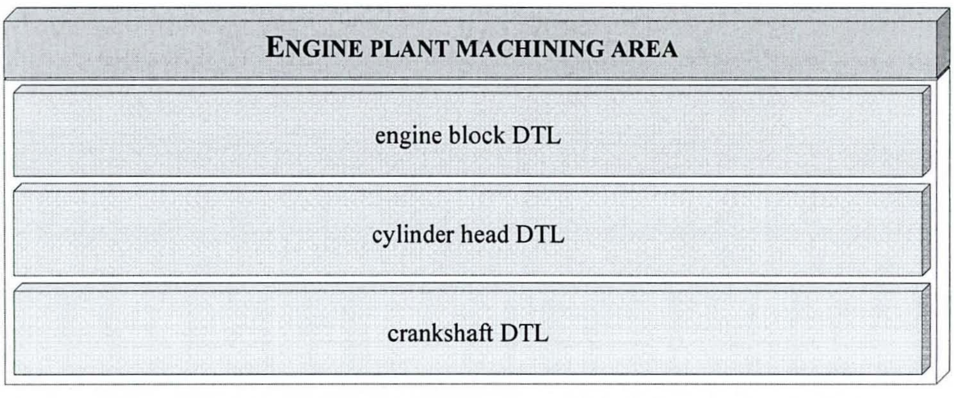
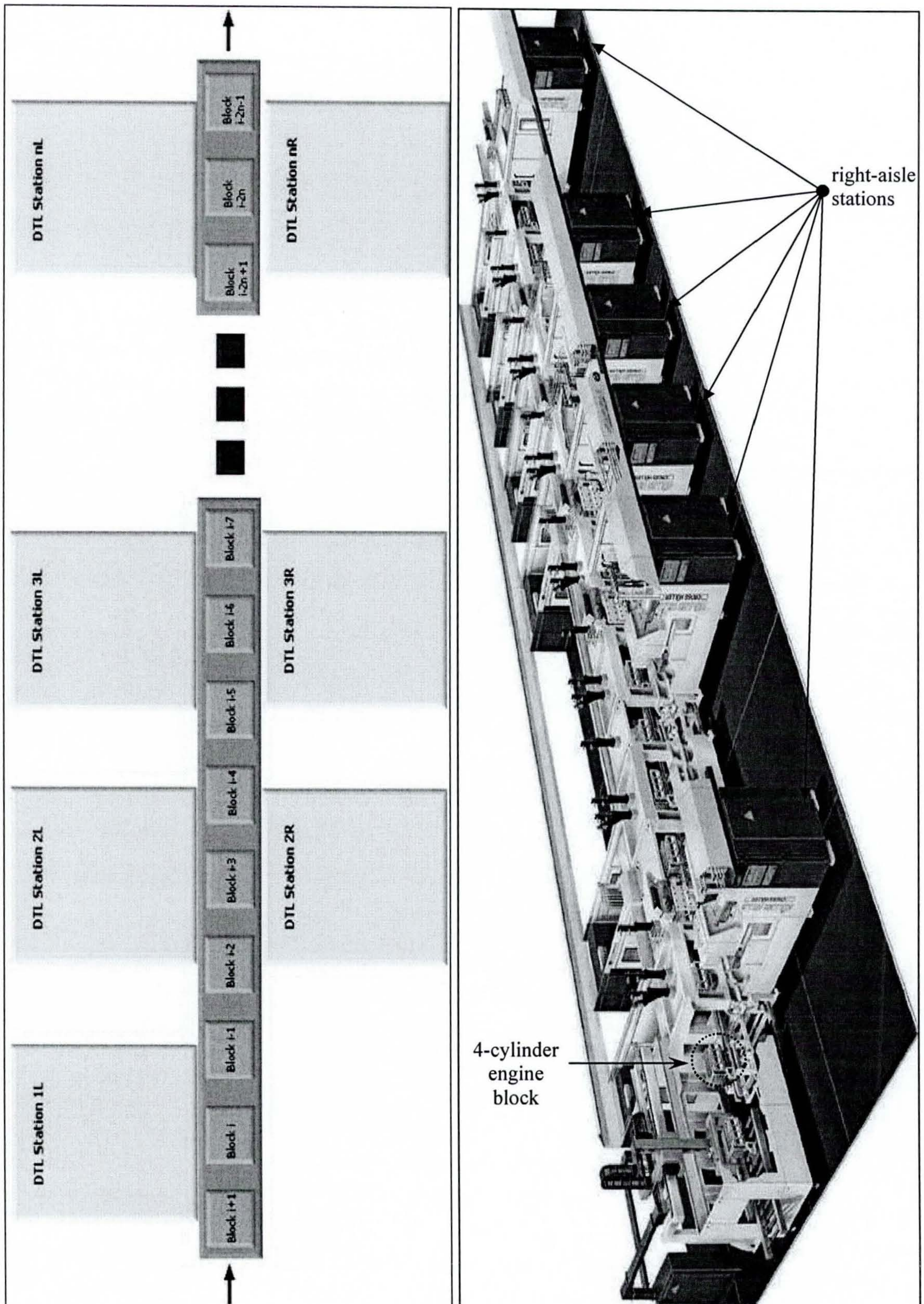


Figure 4.2 Representation of the engine machining area of an engine plant.

A single DTL comprises a number of stations sequentially organised into a flow-line layout. The stations are typically arranged into two aisles physically located either side of the transport automation. There are also fixtures and automation devices which locate and clamp the parts prior to the machining process. A DTL incorporates normally between 12 and 22 stations (plus a device which automatically rotates the part). The exact number of machines per DTL varies according to the engine part and engine type.

The transfer line is synchronised, i.e. after clamping the parts, each station starts machining processes needed for a particular feature of the part. When all stations have finished machining, the parts are unclamped and moved forward to the next station. The parts are then clamped again so that the next machining process can follow. From the viewpoint of a single engine part, this process is repeated until all operations have been done and the part is fully machined. However, from the viewpoint of needing to produce many engines, comprising many, many parts, once started, DTL operation is continuous so that many, many parts are sequentially moved and machined, one after another, until sufficient volumes have been produced that meet production scheduling requirements. Figure 4.3 a) and b), depict a generic representation of a conceptual DTL and a specific commercial DTL, respectively.

A DTL is well designed, well engineered and built well for a high volume, single engine part production. This advantageous capability of DTL manufacturing systems can itself be constrained though because of dependencies between individual stations, which means that degradation of performance at one station can impose significant degradation of the whole system performance. When individual stations need to be stopped (e.g. due to part faults, tool breakdowns or machine breakdowns), the whole system must be halted, compromising the overall system productivity. Thus inherent synchronicity constraints arise because of concepts embedded into DTL designs.



a) b)

Figure 4.3 a) Conceptual diagram of a generic engine block DTL. b) Cross-Huller's 4-cylinder engine block 12 station DTL, source: Cross Huller website (Cross-Huller 2004d).

Arguably DTLs have been the most popular production systems used by the automotive industry, particularly with respect to main engine part machining. DTLs are the traditional solution wherever volume production is required. This type of automation is justified by Cross Huller (a major vendor of DTL production systems) where demand exceeds 350,000 to 450,000 parts per year (Cross-Huller 2004b). DTLs require substantial initial capital investments (e.g. a 1989 Zeta cylinder head DTL required USD 77 million, and a 1993 Sigma cylinder head DTL required USD 40 million investments (Harrison 1996)) and are expected to have a long production life-span.

The machines comprising each DTL station are hard automated machine tools. Each one of these machines is designed to perform a specific, well defined, metal removing operations (which might comprise a set of more elemental machining operations) at an exact location on a single part of a particular engine make and model. The machine tools are highly constrained in terms of number of axes (many of them possess one axis only) and usually do not have an automatic tool changer.

Normally, the possibility that a DTL station might be used to machine part variants or new parts (e.g. for new engines) is not taken into consideration at the machine design stage. Therefore, in general, a DTL will not possess capabilities to deal with changes in parts, and in this respect the full DTL system can be viewed as being an inflexible (hard automated) machine system.

Inherently therefore the flexibility of DTLs is significantly constrained, even though some stations may include a multi-head, that has several spindles which perform a complete pattern of machining operations simultaneously.

Figure 4.4 depicts left and right aisles of a station, along with the transfer bar which moves the engine blocks along the line and across the stations. Also visible is the automation located at the top central part of the station, which is used to clamp the part in position. The reader should also note the simplicity of the machine which enables one axis of movement only.

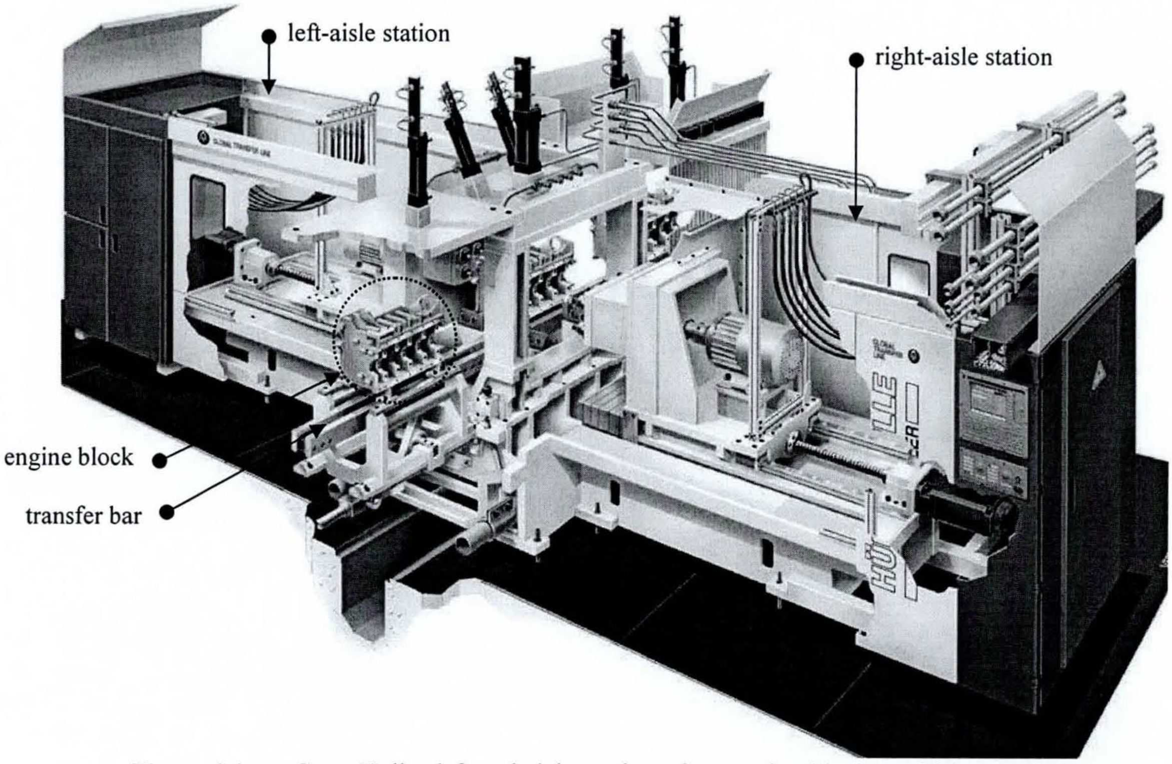


Figure 4.4 Cross-Huller left and right station of an engine block machining DTL. Source: Cross Huller website (Cross-Huller 2004c)

Modern transfer lines producing 4 cylinder engines have a cycle time of around 20 to 40 seconds; during which individual machining operations are performed at each station and the parts are moved to the next station, ready for the cycle to recommence. For a 30 seconds cycle time this means that 1 engine part will be produced at the output of the transfer line every 30 seconds; hence such a DTL would produce 120 engine parts per hour unless it were interrupted for some reason. However the actual cycle time of DTLs used in practice can vary marginally depending on the engine material, the performance of the machines used at each station, type of tools used, complexity and number of features in the part, etc. The three machining lines depicted in Figure 4.2 would normally have balanced cycle times, i.e. have approximately the same cycle time. For the example DTL cycle time considered above, this would mean that roughly 120 engine blocks, 120 cylinder heads and 120 crankshafts would be the issue of the three lines every hour.

Machines used at stations are designed for minimum time deviation relative to the overall DTL cycle time, which will be dictated by the slowest of the stations. However there are always some time differences between the stations which dictates the need for a waiting period for the fastest ones. The waiting time period varies from station to station. In general the line cycle time ($\mathbf{t}_{cycle}$) is determined by the sum of: the time to clamp the part

(t_{clamp}); the (machining or part orientation) time taken by the slowest of the stations ($Max(t_i)$); the time to unclamp the part ($t_{unclamp}$) and the time taken by the transport system to take the part from $station_{(i)}$ to $station_{(i+1)}$ (t_{transp}). Hence

$$t_{cycle} = t_{clamp} + Max(t_i) + t_{unclamp} + t_{transp}$$

Assume for instance, that: clamping the part takes 3 seconds, unclamping another 2 seconds, the transport system takes 6 seconds from any two successive stations, and the slowest of stations takes 26 seconds to carry out its designated machining tasks. Then the cycle time will be 37 seconds. On the assumption that all three lines for blocks, heads and crankshafts have a similar cycle time, then all three lines would output around 97.3 parts per hour, which, without any defective production would enable 97.3 engines per hour to be produced by the plant.

It follows that DTL cycle times directly affect the engine production rate and therefore determine the maximum engine production capacity of an engine plant. However it is also observed that engine machining DTLs have a fixed capacity (under the same work-time model). Should a company plan to build a new engine plant based on DTL concepts and technology then "what is the required DTL capacity?" is one of the first questions to be addressed. In general though it is not a trivial matter to provide an answer to this question since the capacity utilisation is likely to vary significantly over the years to come. Nevertheless the answer has to be given, normally 2 to 3 years before production starts, so that maximum cycle time can be fixed and machine builders can start the design processes of the particular DTL stations. As an example, if the production capacity for a new engine plant is established at 400,000 engines a year, accomplished through a single engine machining facility, then (under a working regime of 16 hours a day and 235 days a year) each one of the three DTLs will require a cycle time that never exceeds 33.84 seconds.

Although there is no worldwide consensus view of such matters, there is a common measure used to determine the percentage capacity utilisation of automotive plants which is commonly quoted in literature and is frequently referred to by the automotive industry in North America (to a lesser extent in Europe). This measure is the so called Harbour capacity utilisation index, which is based upon the norm of 100 percent capacity utilisation being equated to operating for 16 working hours per day (2 shifts of 8 hours each) and 235 working days per year. This measure has been used in this study as a reference. When deploying this measure it is observed that it is possible for an engine plant to work at greater than 100 percent of capacity, such as by: working 3 shifts per day, working on Saturdays, keeping the plant open during the annual holiday period, etc. In fact in recent years some companies have taken strategic decisions to increase productivity in vehicle assembly plants by achieving greater than 100% capacity utilisation. As an example, the PSA group has strategically increased their vehicle assembly plants capacity utilisation rate from an average of 69 percent in 1997 to 114 percent in 2001 (PSA 2002) and 117 percent in 2002 (PSA 2003) (as measured by the Harbour index:100%=hourly production capacity x 16 hours x 235 days). Another example comes from BMW plants, including the Hams Hall-UK engine plant. BMW has implemented so called flexible work-time models, named "*BMW's formula for work*". This enables use of production facilities for between 60 and 140 hours per week. Hence there have been cases where installed automotive plant capacity has been exceeded by up to 40 percent above what might be perceived to be the maximum available capacity (BMW 2004).

Because an engine plant is a capital intensive asset, companies do not build them frequently. In fact, companies have to plan their development very carefully, by forecasting market demand for the vehicles they will make, estimating sales volumes and fluctuations for each model and the customers' choices of engine variants associated with each model. Such predictions are difficult to make because a multitude of variables might influence the customers' choice, including: the relative success of models from competing automotive companies; the effect of global oil prices and national taxes on fuels (which might influence customers choice on the car segment or fuel type, e.g. petrol, diesel, LPG, hybrid); the impact of tax incentives offered by local governments for fuel efficient cars; possible stagnations or growths in national economies; impacts of global conflicts; and relativities of competitive commercial and marketing strategies. Whereas DTL based plants have a fixed capacity it is a fact that customer choice will dictate required volumes of engine types. Hence ultimately it is customers that will drive plant capacity utilisation given a particular plant, operating policy and given a set of political, economic and social environmental conditions.

It follows that in principle DTL technology is a good choice when there is a steady demand for engines and little change in engine variants over long periods of time. When frequent changes in **engine volumes** occur necessarily the use of DTLs will generate waste in some form, due to its fixed installed capacity. Moreover if new **engine variants** are required more frequently, then the use of DTLs alone can be expected to give rise to inefficiency (due to excessive downtime for retooling). It is likely also to prove a very expensive solution, since it involves time consuming engineering activities and significant engine variation will invariably necessitate additional investment in new machinery, as well as long lead times.

4.2.2 Major limitations of dedicated transfer lines

Despite evident limitations, most engine machining system vendors continue to recommend the use of DTL technology to machine prime engine parts. For example the BMW Hams Hall engine plant in UK (which uses transfer lines to machine engine blocks, cylinder heads and crankshafts) is referenced by some automotive field experts as being the most advanced engine plant in the world. Unfortunately the use of the installed capacity at Hams Hall engine plant, since production started in 2001, has continued to be lower than 35% during its first three year period of operation.

To summarise therefore, DTL based engine plants have the following limitations:

- Production capacity is not scalable, i.e. is fixed;
- Production capacity estimates need to be made 3 years in advance of production start;
- A complete DTL system has to be designed, engineered, built and tested prior to production start;
- Part quality faults, tool breakdowns or single machine breakdowns necessarily result in complete transfer line halts, restricting the system uptime and overall productivity of the system;
- Each machine deploys hard automation which makes it technically difficult, time consuming and costly, to adapt to changes in engine parts;
- A complete DTL system may need to be decommissioned (and possibly scrapped) prior to the end of its planned useful lifespan, such as in the event of major unexpected changes;
- In general DTL systems do not possess functional capabilities to produce a mix of engine part variants.

These limitations can impact negatively on performance related issues, as follows:

1. Limited efficiency can result in respect to the production of engine parts, particularly because single machine breakdowns require the whole system to halt;
2. Considerable time will be lost, and financial penalties will be incurred, should significant machining systems redesign, reconfiguration or substitution be needed when engine part changes are required;
3. Significant waste of installed capacity will occur where demand varies over time, simply because the production capacity is fixed. There is also a significant risk of over sizing the capacity of a plant because of the desire to satisfy demands which are difficult to accurately predict over several years into the future. Predicted increase in demand may not occur;
4. Serious difficulties can occur with respect to rationalising the global production of engines. This problem is exacerbated when an engine plant has to be stopped to enable the reconfiguration or substitution of a DTL.

Apparently the limitations of DTL technology listed in the foregoing, and consequent business related problems, are widely recognised in the automotive industry. But previously a quantitive analysis of their impact has not been reported in public domain literature. It follows that public domain (technical and business) justifications for using alternative (possibly more flexible) technologies have not been made.

4.3 Modular Transfer Lines & Flexible Transfer Lines

With a view to overcoming some of the limitations of DTLs, engine manufacturers and the machine vendors have proposed and realised a number of significant technological developments so that the design, building and commissioning of engine machining systems can better cope with engine part variation. Two distinctive approaches have been taken leading to so called: 'modular transfer lines' and 'flexible transfer lines'.

4.3.1 Modular transfer lines

Modular transfer lines constitute a recent development of DTLs which is based on the notion that standard DTL modules can be usefully applied. Potentially the approach enables an economic construction and reconfiguration of differentiated stations, over shorter periods of time than possible using conventional DTL system design and construction techniques. Over several years, researchers in the Manufacturing Systems

Integration Research Institute (MSI/RI) at Loughborough University, have studied the application of modular concepts to DTL machining. Many of their proposals were conceived as part of a research programme, centred on the COMPAG[23] project which was jointly sponsored by EPSRC and the automotive industry. The COMPAG project involved co-operative activities amongst an international consortium of companies including the Ford Motor Company Ltd., Jaguar cars Ltd and Mazda Motor Corporation (end users); Lamb Technicon, Johann A Krause UK Ltd and Cross Huller (machine builders); Mannesmann Rexroth Group and Parker Hannifin Ltd (part suppliers); Echelon UK Ltd, FDS Ltd and Hopkinson Computing Ltd (technology vendors). The COMPAG project aimed to provide:

- a comparison of current DTL best practice with component-based DTL system;
- the implementation of a component-based control system for use on engine machining and assembly transfer lines;
- a study of related business issues; and
- a generalisation of project results to enable wider exploitation of the approach.

Modular control techniques were used to enable each modular element of a production machine to be tested separately, prior to the assembly of a specific machine. It was anticipated that this would facilitate the commissioning of machining and assembly systems, and thereby significantly reduce the elapsed time between system design and production ready. Although the use of MSI specified machine modules and component-based controls remains promising, component-based manufacturing systems of the type conceived and prototyped within the COMPAG project have yet to impact as was expected in the area of engine machining. Detailed information on these projects can be found in (Weston 1999; Harrison and West 2000; Harrison et al. 2000; Harrison et al. 2001; Weston et al. 2002; Ong 2004).

Potentially modular transfer lines can address some limitations of DTLs because they can benefit from reduced system ready lead-time and reduced retooling costs. This can lead to flexibility improvements from some points of view but does not address other flexibility constraints, because modular transfer lines are still composed of individual machines developed for a specific machining operation and machining capacity. It also follows that modular transfer lines (like in conventional DTLs) have a fixed capacity

[23] COMPAG: COMponent based Paradigm for AGile automation

which necessarily generates waste. Synchronicity constraints between essentially fixed machines will also limit overall system performance.

4.3.2 Flexible transfer lines

An alternative way of improving the flexibility of DTLs, which has been investigated and developed, has been to (1) introduce general purpose single-spindle CNC stations and multi-head changers into DTL stations and (2) to integrate their operation and use with traditional transfer line machines and positioning systems. CNC machine tools are able to perform various metal cutting operations, by automatically exchanging programmable tools. Indeed the working regime, namely the spindle speed and feed rate, the spatial positioning of tools and tool trajectory, the cutting lubricant and the coolant, is automatically controlled by an NC program. The cutting trajectories can also be automatically optimized in order to minimize the time needed to complete the whole machining cycle. Benefits arising from these options have been argued. However, their use significantly increases the level of complexity and cost of the system, and can result in lower overall system reliability. None the less some machine system vendors supplying the automotive industry propose this type of hybrid system solution as a future technology for car engine producers.

However inherently flexible they may be themselves, a set of CNC machines working in the constrained context of a transfer line must inherit certain DTL constraints and problems, as previously described in section 4.2. Particularly, when a machine breakdown or a part quality fault occurs, it is necessary for the related single CNC machine to become inactive, which means that the whole system has to be shut down. Consequently the overall system downtime increases. Indeed if the CNC elements introduced are less reliable than hard automated elements, their use may significantly deteriorate overall DTL system efficiency levels. Flexible transfer lines also inherit the overall constraint of fixed production capacity. What is more, as a result of having increased idle times during tool changes, the cycle time is likely to be higher. In some cases though, the use of a single tool (when compared to that of a multi-head) can also add to the cycle time, lowering the productivity. The prime flexibility benefit of flexible transfer lines arises when a system reconfiguration has to take place. In such cases almost instantaneous exchange of NC programs and tool magazines can substantially decrease change cycle times and financial penalties when compared with DTLs requiring a similar reconfiguration.

4.4 AGILE SYSTEMS

Discussions with an academic researcher working along with major vendors of engine machining automation (Harrison, 2003, private communication) and with an engine manufacturer (Cox 2003), confirmed a shift towards systems based in the deployment of general purpose CNC machines so that more flexible production strategies can be implemented.

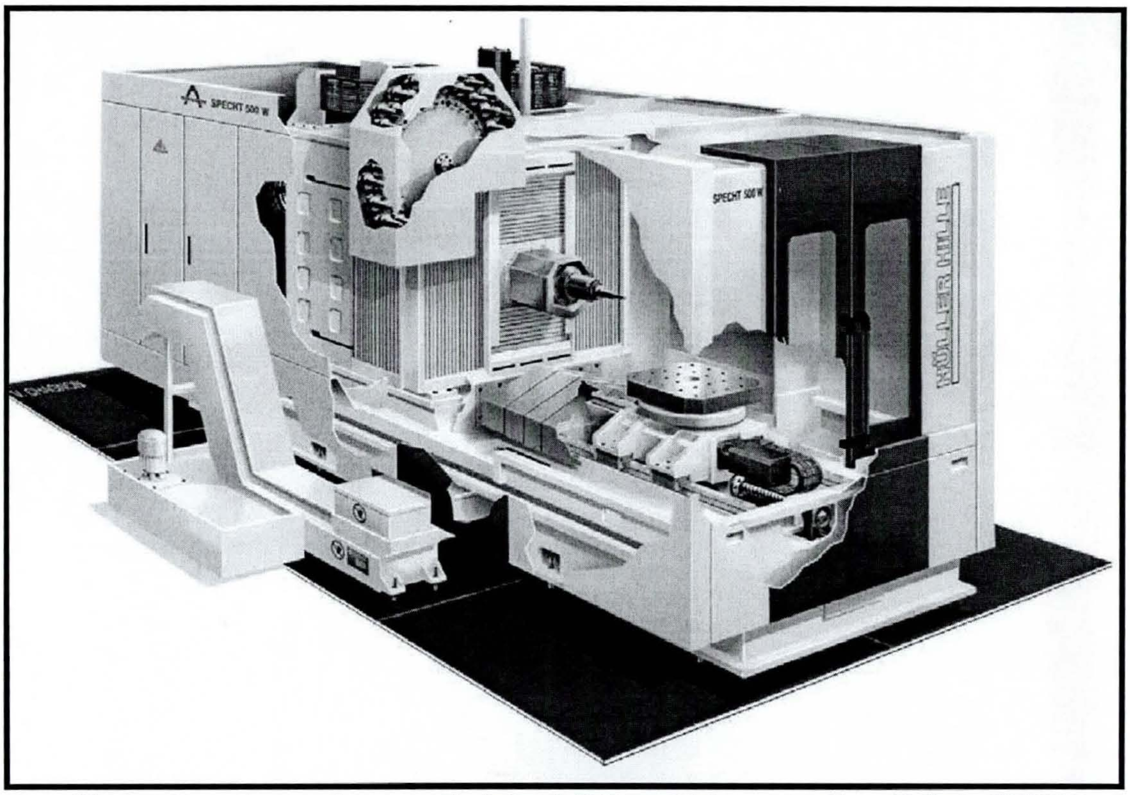


Figure 4.5 A general purpose single-head CNC machining centre Cross-Huller's SPECHT 500W Agile System Station. Source: Cross-Huller website (Cross-Huller 2004a).

Some vendors of engine machining systems are already offering what they refer to as *Agile Systems*. The agile systems they offer incorporate a number of identical general purpose single-head CNC machining centres that can be grouped and operated within cells. For example, the Cross Huller agile system station comprises a machining centre with 3 axes, an automatic tool changer and sufficient capability to accomplish needed engine machining operations. As an optional feature the stations can be fitted with a device which incorporates a linear axis and a rotational plate. Such a rotational plate enables access to 4 faces of engine parts by rotating the plate through steps of 90 degrees. The linear axis enables a translational movement which loads or removes engine parts to and from the machining area. The Cross Huller agile system station also has a large tool magazine, which enables access to all the tools required for the machining operations to be accomplished by a particular cell. It also includes spare tools for tool replacement, in the case of tool wear or tool breakdown, so that production downtime is kept to a minimum level. A new engine block machining facility recently installed at Ford Dagenham in Essex and an engine block and cylinder head machining facility recently installed at Ford Bridgend in Wales, are based in this type of technology.

These emerging kinds of *agile system* typically comprise a number of cells, each consisting of a maximum of 6 general purpose CNC machining centres. Each cell is programmed and tooled to carry out a small number of different machining operations. Within a given cell all the machines execute exactly the same machining operations. Also each cell has a double gantry robot which loads the cylinder head into the machine and unloads it when an operation is complete. The gantry robot takes the cylinder head from the transport automation and places it inside the machine. After finishing the operation the robot removes the cylinder head from the machine and places it in the transport automation of the next machining cell.

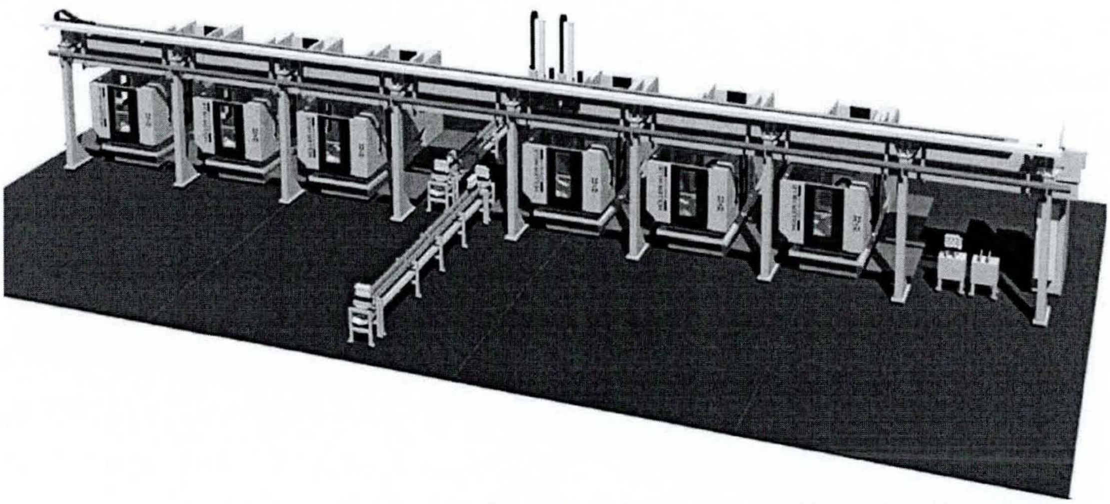


Figure 4.6 A Cross-Huller's cylinder head Agile System SPECHT cell, with 6 stations, transport automation and gantry robots. Source: Cross-Huller website: (Cross-Huller 2004b)

A single CNC machining centre costs around USD 500,000. The double gantry robot costs around another USD 500,000 (Price 2003a).

Since: (1) each CNC machining centre belonging to the same cell executes exactly the same operations; and (2) the number of machines can vary from one to six machines per cell; the production capacity of the system can vary, starting in 1/6 of the full system capacity. New capacity can be added in lumps of 1/6 of full capacity (by installing one more machine in each cell) in short periods of time and theoretically without interrupting machining activities being carried out by the remaining production facilities. At full capacity some cells may require less than 6 machines, since the individual cycle times inside each independent cell can be different.

Part quality faults, tool breakdowns or single machine breakdowns do not necessarily impose a whole system shutdown as is the case with DTLs. However the production capacity will be affected in the inverse proportion to the number of machines installed per cell. If a single machine is installed in a particular cell and that machine has to be stopped then the full system is halted. At the other extreme, if there are 6 machines installed in a particular cell and one of those machines has a breakdown then only 16,7% (1/6) of the installed capacity is affected.

Figure 4.7 illustrates an 8 cell agile system designed for cylinder head machining. In total this comprises 31 general purpose and similar machining centres, transport automation in between the cells and gantry robots for loading and unloading parts.

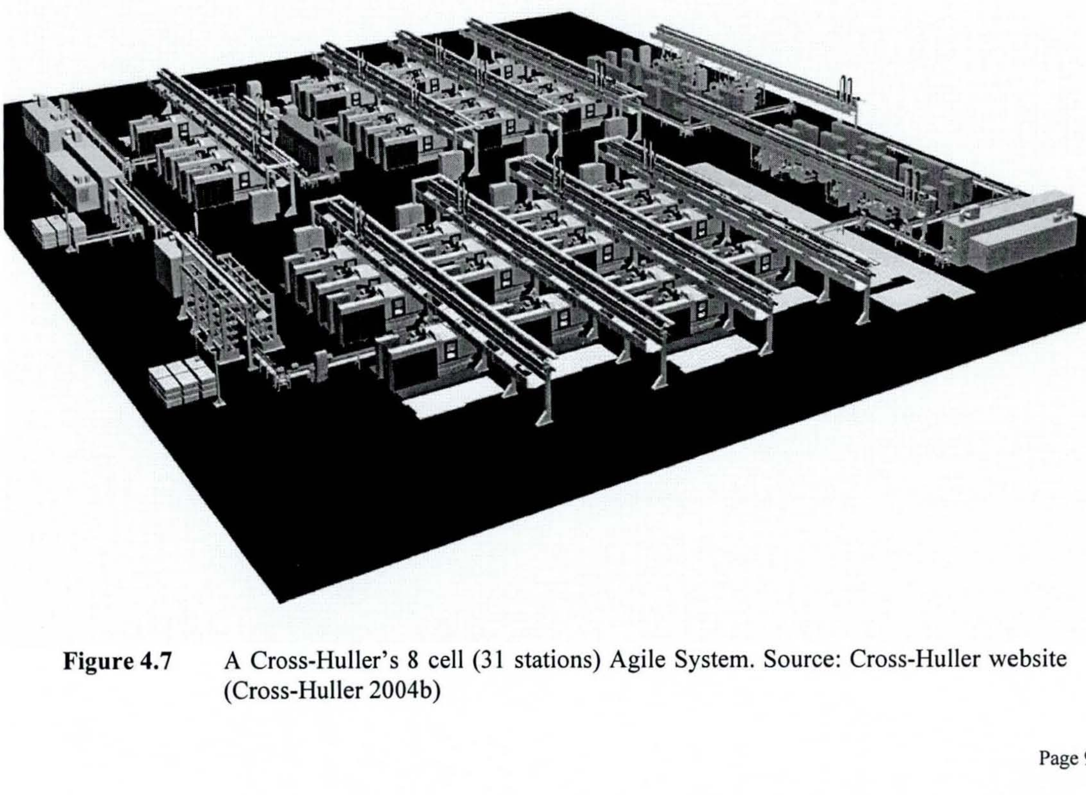


Figure 4.7 A Cross-Huller's 8 cell (31 stations) Agile System. Source: Cross-Huller website (Cross-Huller 2004b)

Advantages of this kind of *agile system*:

- The minimum set-up for production start is one machine per cell, plus the full transport automation system and all gantry robots, therefore enabling a phased investment.
- Production capacity is scalable, in lumps of 1/6 of the full system capacity.
- Effective production capacity can be determined less than 1 year in advance of production start. However, space considerations may need to be finalised up to 2 years in advance.
- Each machine is based on the use of flexible automation which makes it technically feasible, significantly less time consuming and cheaper, to adapt to engine part change.
- Since the system is made of replicated general purpose single-spindle CNC machines (even though they accomplish differentiated operations) the process of system design, systems engineering, and test is facilitated;
- Lower level of dependency between machines imposes a partial degradation of the system performance when individual machines are halted. This contrasts with full degradation of performance in the DTL case.
- This kind of *agile system* allows a mixed production of engine part variants in batches of one unit, however this practice is not common in the industry.
- CNC machines can be moved around the globe to engine plants that require additional capacity.

The major limitations of this approach are:

1. Although equipped with faster machines the overall time required to execute the same machining operations takes longer to accomplish. This is due to the use of a single-head when compared to the use of multi-head stations in DTLs.

2. Significantly more space is required to achieve the equivalent production capacity of DTLs.

3. The machines used in this kind of *agile system* are more complicated devices than ones used in DTLs.

4. A higher level of initial financial investment is required for equivalent DTL production capacity. Studies have pointed out however (Price 2003b), that the total cost of this kind of *agile system* can be up to 5% lower than DTLs, depending on the flexibility scenario. Total costs include costly and time consuming processes associated with minor and major changes of DTLs during their planned useful lifespan.

4.5 Q'@GILE SYSTEM

The author's research provided an understanding of the strengths and weaknesses of previous and emerging technologies developed to produce main engine parts (head, block and crankshaft). Those understandings have been described in chapter 2 and in foregoing sections of this chapter. This knowledge helped to identify a set of concepts that were incorporated into the design of a newly proposed **Quantum Agile Manufacturing System.** For brevity the system proposed will be referred to as a ***Q'@gile system.***

Q'@gile was conceived as a theoretical approach to main engine part production which in principle has, at an appropriate level of granularity, an inherent capability to address current and emerging automotive industry problems arising from **lack of engine manufacturing agility;** and associated problems of having an installed base of **excess capacity.** *Q'@gile* is designed to provide manufacturers with freedom to modify their production capacity, via systemic processes of plant instalment, dismantlement or reallocation, at a defined ***Quantum*** level. Further, the proposed *Q'@gile* paradigm enables engine production capacity to be moved around the globe between plants that have an installed *Q'@gile* engine machining facility. In theory the proposed solution promises improved agility in terms of being able to make fast and cost effective responses to market changes, that might for example arise from significant competitors initiatives (such as those arising from advances in the ICE and alternative vehicle propulsion technologies) and/or significant changes in customers requirements. In theory also, Q'@gile can reduce risks associated with large investments in engine production capacity, in two main aspects: a) smaller and phased investments are required to adjust a scalable capacity to market demand; b) by decreasing time based uncertainty factors through a major shortening of the look-ahead time period for plant capacity decision making. Currently automotive manufacturers forecast engine volume demands, and therefore their need for plant capacity. Engine production capacity decision making is apparently constrained by the order of a 2 year lag prior to production start (for a new DTL machining facility). In theory the adoption of Q'@gile systems can reduce this lag to around 12 months or even shorter timeframes.

4.5.1 Q'@gile cells

The central element of the proposed Q'@gile system is a **high-speed general purpose CNC machining centre.** Suitable transport automation, plus a working table with several servo driven axes, is required to complement use of this machining centre element. Collectively these three main system parts form a **Q'@gile cell.** The minimum setup for production start, i.e. be able to produce cylinder heads or engine blocks, equates to a single Q'@gile cell per engine part. Thus a **quantum** level of production capacity that can be deployed when adopting the Q'@gile engine production approach is set by the collective capacity of the three main parts used to realise a single Q'@gile cell. Installing (or removing) capacity by a *quanta* is accomplished by installing (or removing) an integer number of Q'@gile cells[24]. This approach contrasts markedly with the traditional DTL approach which requires a full engine production system to be installed prior to the start of any production run. In the case of Agile Systems the minimum set-up would be one machine per cell (this equates to 8 machines, under a 8-cell system), plus the full transport automation system and all gantry robots, for each prime engine part .

Thus any given Q'@gile system will comprise an integer number of replicated general purpose single-spindle CNC machines and it therefore follows that the process of system design, systems engineering and test will largely be linked with the activities in a single cell design, engineering and test. Since general purpose CNC machine technology is well established, in principle quantum changes to Q'@gile production capacity should be accomplished in significantly compressed time frames relative to the deployment of DTLs.

[24] V-type engines require one block, one crankshaft and two heads per engine. Therefore, in this case, a Quantum of capacity is achieved through one Q'@gile cell for blocks, one Q'@gile cell for crankshafts, and two Q'@gile cells for heads (assuming that the cycle times for the 3 prime parts Q'@gile cells are balanced).

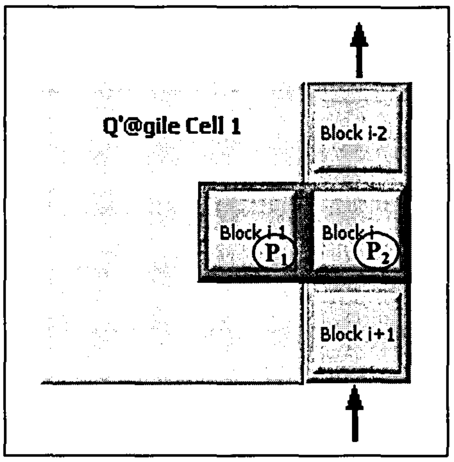


Figure 4.8 Representation of a Q'@gile engine block machining cell.

Hence this study proposes use of Q'@agile cells for engine block machining, where each cell should be composed of:

(A) *A high speed general purpose CNC machining centre* with a minimum of 3 axes (XYZ), a tool magazine and an automatic tool changing device.

(B) *A working table device with several axes*, which incorporates:

B.1) *a double pallet exchange device* which rotates in steps of 180 degrees taking the engine part from P_2 (a pre and post machining position) to the machining area. and *vice-versa*; plus a W-axis which moves interchangeably to and from P_1 (the machining position).

B.2) *a device with a 2 axes holding the pallet* which incorporates fixtures and a pallet clamping device. The B-Axis, which rotates the block, thereby enabling access to 4 faces (for an inline-type engine block) or 5 faces (for a V-type engine block), and the A-axis, which tilts at least 90 degrees enabling access to the remaining part face. As an alternative to this tilting movement (A-axis), tilt of the head of the CNC machine could be enabled (by up to at least 90 degrees), thereby providing a 4^{th} axis of movement.

(C) *Transport automation* (e.g. a gantry robot and a roller conveyor) with capabilities to take engine blocks to and from the cell and to deliver the blocks into position P_2 and to enable their removal following machining operations at that cell.

There is similar evidence about the nature of the machining processes used to machine cylinder heads to those of engine blocks. Furthermore Cross-Huller SPECHT machines used in Agile Systems to machine engine blocks are the same as the ones used to machine cylinder heads. Therefore, since Q'@agile cells use CNC machines similar to those SPECHT CNCs used in Agile Systems, the author envisages that Q'@agile cells could be used for cylinder head machining in a similar manner as previously described for engine block machining. However cylinder head specifics may require a slightly modified CNC machining centre (e.g. with a lower machining power), transport automation and working table multi-axis device. This is due to differences in physical dimensions, part weight, material type, type of metal removing operations and machining positions. Given timeframe constraints associated with this research study the author considered it impractical to investigate further the extent to which cylinder head specifics requires change to Q'@gile systems. There is little doubt about the general applicability of Q'@gile systems for machining cylinder heads, given the widespread current industrial application of similar technology. With regard to crankshafts the author assumes that it is possible to use Q'@gile systems for machining but there is little grounded evidence to support this assumption. It would require further studies to obtain such evidence and this was considered to be outside the scope of the present study.

4.5.2 Q'@gile cells installation, removal and reallocation

Q'@gile cells should be: (1) added to an existing engine production facility (to increase the available production capacity by integer quantum steps), (2) removed from an existing production facility (to decrease capacity by quantum steps) or (3) transported and installed at some other engine plant around the globe so as to balance engine production more equitably with respect to geographical locations where parts are assembled into complete engines or where complete engines are assembled into cars. Figure 4.9 depicts a representation of an engine block Q'@gile system, where the number of cells can vary from 1 to K, therefore adjusting capacity to part demand. The production capacity can be adjusted from a minimum of *1 x Quantum* to a maximum of *K x Quantum* parts.

Given the widespread use of general purpose CNC Machining centres, and the replicative nature of Q'@gile cells within production systems, it is envisaged that very short periods of time may be feasible to install or remove cells from the system. The infrastructure facilities needed, such as a power and coolant drainage system, should be carefully planned in order to allow the installation and removal of cells without significantly disrupting engine production or at least to minimise any disruptions.

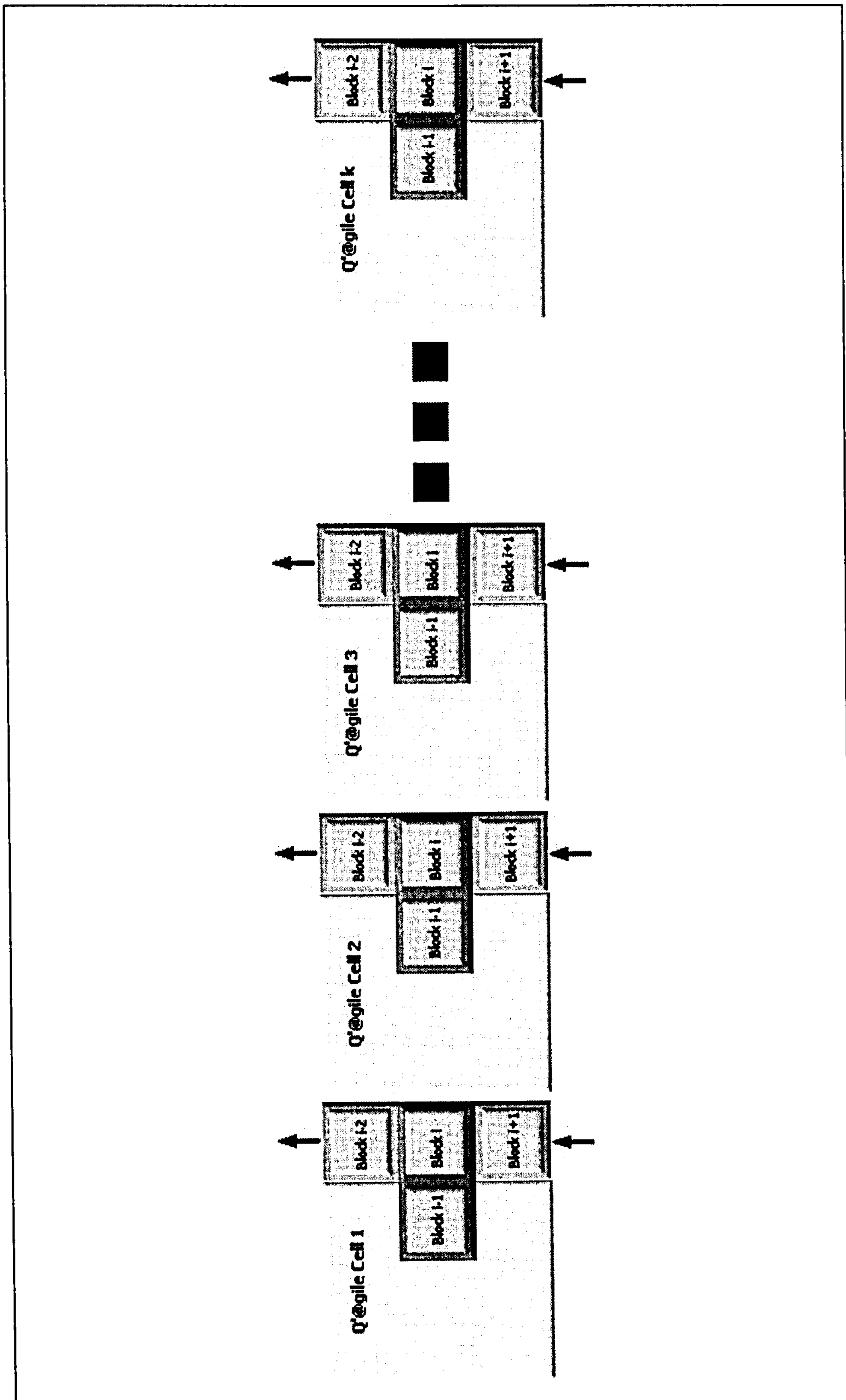


Figure 4.9 Representation of an engine block Q'@gile manufacturing system configured from a variable number of Q'@gile cells.

In comparison to DTL production systems, in theory Q'@gile systems will require significantly lower initial capital expenditure prior to production start. In theory, capacity additions (and deletions) should be phased in as demand develops. In a typical manufacturing scenario where a primary engine manufacturer decides to produce in house the three main engine parts (block, heads and crankshafts) and subcontract the manufacture of the other engine parts, initial expenditure could typically be centred on three Q'@gile cells only: this being determined as being the theoretical minimum configuration to get engine production started. This minimum of three is set because one Q'@agile cell is required to machine each main part. This contrasts with three full DTL production lines, one for machining each main engine part.

As an example, suppose that actual demand for a particular engine type over a 10 year period varies as shown in Table 4.1.

Table 4.1 Annual demand over a 10 year period.

Year	Annual demand (engines)
Year 1	70,000
Year 2	153,000
Year 3	140,000
Year 4	145,000
Year 5	237,000
Year 6	255,000
Year 7	210,000
Year 8	235,000
Year 9	150,000
Year 10	145,000

Assume also that initial forecasting of demand predicted that around 440,000 engines per year would be required in the year 5^{th} and 6^{th} of production. Assume also that following revised forecasts that indicate that initial predictions were too optimistic for that particular engine. In such a case, with conventional practice three DTLs would have been installed and production started as planned. In such a scenario the use of DTL production capacity would be fixed at a maximum of 440,000 engines per year and the "global" waste (in terms of installed capacity) would be slightly above 60% (an equivalent waste of capacity of 266,000 engines per year) of the installed production capacity. This is illustrated by Figure 4.10. The dark (blue) bars represent yearly engine demand. The light (white) bars represent yearly waste of production capacity. The combined bars (dark plus light bars) show the maximum engine parts production capacity.

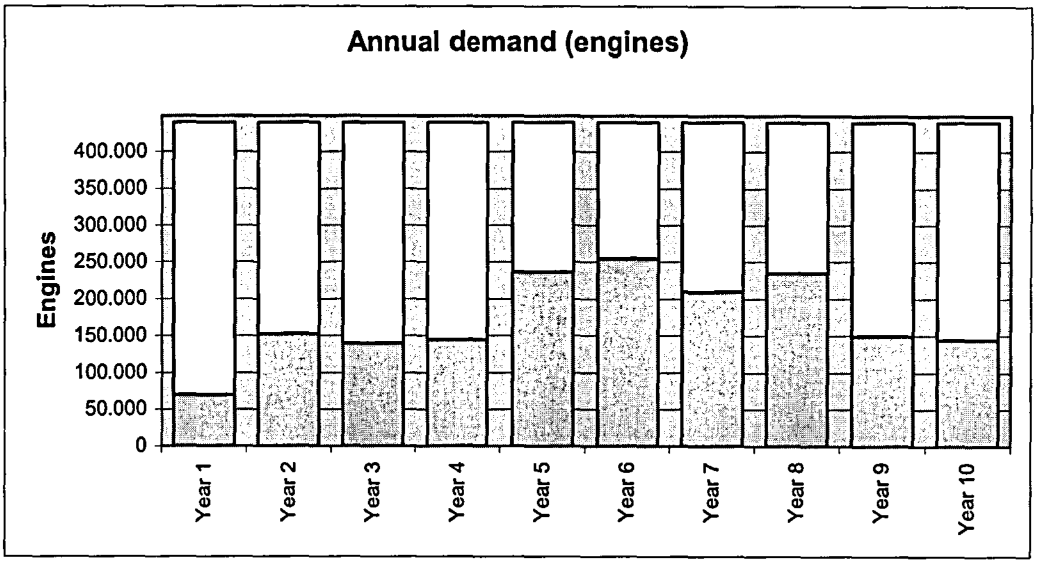


Figure 4.10 Graphical representation of annual demands of an engine over a 10 year period.

In a similar set of circumstances, consider the use of a Q'@gile system with a quantum capacity of 20,000 engines per year.

Table 4.2 Annual production capacity and number of cells to install yearly.

Year	*Annual demand (engines)*	*Annual Q'@gile system capacity (engines)*	*Number of Q'@gile cells*	*Install/release*
Year 1	70,000	80,000	4	4
Year 2	153,000	160,000	8	4
Year 3	140,000	140,000	7	-1
Year 4	145,000	160,000	8	1
Year 5	237,000	240,000	12	4
Year 6	255,000	260,000	13	1
Year 7	210,000	220,000	11	-2
Year 8	235,000	240,000	12	1
Year 9	150,000	160,000	8	-4
Year 10	145,000	160,000	8	0

To meet the actual demand it is observed that an initial installation of 4 cells (per main engine part) would be required to produce all needed main engine parts during the first year. Following which a further 4 cells would be needed in year 2, minus 1 cell in year 3, and so on, as depicted in Table 4.2. In such a case, the global waste of installed capacity would be less than 5% (an average capacity waste of 8,000 engines per year) as depicted by figure 4.11. In figure 4.11 the dark (blue) bars represent the yearly engine demand. The light (white) bars represent the respective yearly excess of capacity. While the combined bars (dark plus light bars) represent the total engine parts production capacity.

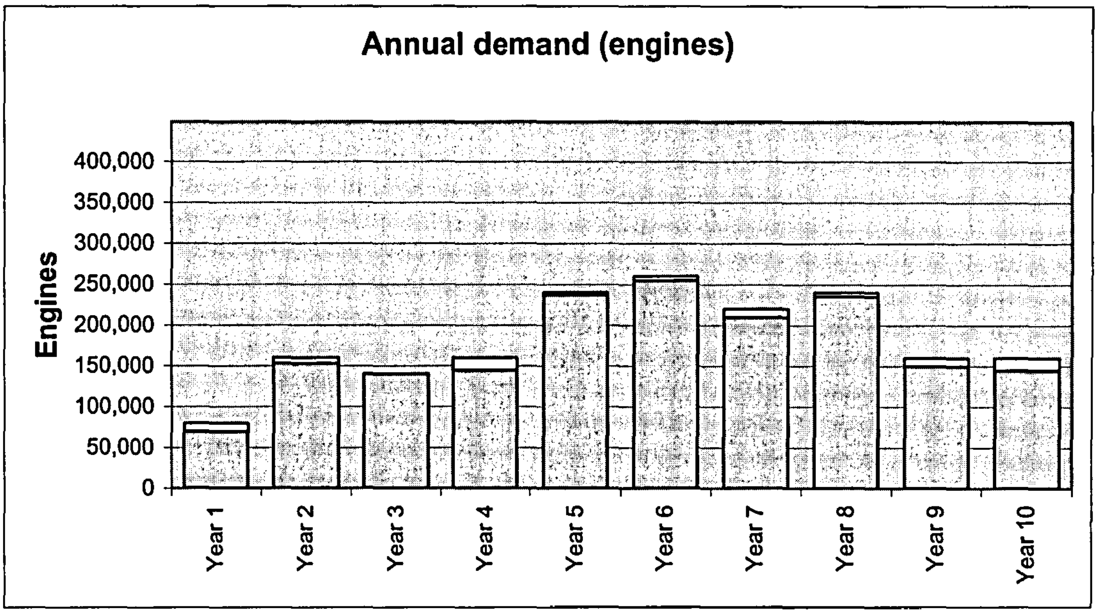


Figure 4.11 Graphical representations of annual demands and respective production capacity of an engine over a 10 year period.

The example scenarios discussed illustrates tremendous potential for Q'@gile systems, in terms of their relative utilisation of installed capacity. The given example is in fact based on a real engine plant, which currently uses DTLs to machine three main engine parts. The specified capacity for the DTLs is real and the demand for the first three years is also real. However the fourth year demand is a company forecast. The engine demands for the remaining years are the author's forecasts.

Regarding production volume, Q'@gile production systems can incrementally expand as market confidence increases and vehicle orders arise. A quantum in capacity is the integer increment enabled, or "volume grain". In fact the production capacity is scalable in increments of 1/K of the full system capacity (where K is the maximum number of Q'@gile cells that can be incorporated into the system; which primarily will be constrained by the plant space and the capabilities of the workflow and infrastructure of the system originally selected and installed). In principle, new capacity can be added in increments of 1/K in very short periods of time, possibly even without interrupting ongoing machining activities in the remaining production facilities. As discussed previously this inherent ability of Q'@gile systems improves their utilisation and match to market demand patterns. It also reduces production overcapacity and investment risks.

4.5.3 Tool and working table requirements for Q'@gile cells

The Q'@gile concept was conceived based on the assumption that Q'@gile systems would deploy commercially available, well proven single-head machine tools and this should enable their acceptance and adoption by the automotive industry. However in the Q'@gile system schema it is proposed that each cell (i.e. grain in production volume) should be capable of performing all needed operations on one of the three main engine parts (e.g. block, head or crankshaft). This also implies a common requirement for generic tool exchangers and engine part face changes. A study by the author of machining operations carried out by DTLs led to the observation that each cell should have:

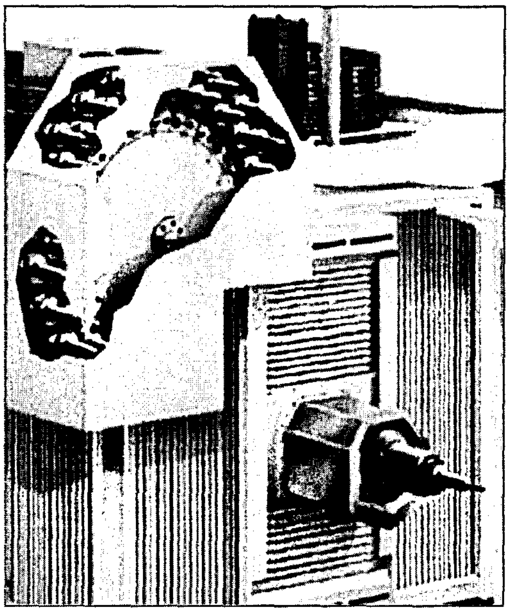
1. a tool magazine with enough space to store all required tools;

2. exceptionally low chip-to-chip automatic tool exchange time;

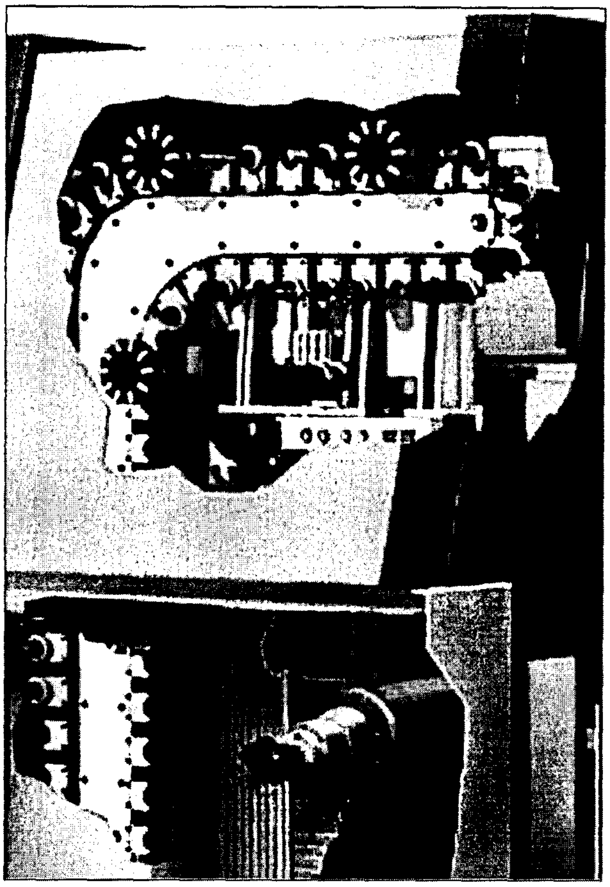
3. a multi-axis working table with : a) a double pallet exchange table with a W-axis; and b) an A and B axis device with needed fixtures and clamping.

As explained previously a DTL traditionally comprises between 12 and 22 stations. Each station performs a distinct machining operation using a different tool. Consequently tool magazines for Q'@gile cells should have sufficient storage space for at least 22 tools so that all the required operations can be accomplished by a single cell. It should also have replicated tools for those tools subject to significant wear. This should not present any practical problems since current CNC machines can have large tool magazines. Figure 4.12 illustrates example tool magazines that are commercially available for use with contemporary CNC machines that apparently possess the various tool changing capabilities required.

Q'@gile systems will require replicated sets of tools at each Q'@gile cell, or at least very similar toolsets that can cater for all needed machining operations for a prime engine part. This is a necessary requirement because each cell needs to perform all required machining operations. Therefore, with respect to tool costs, when compared to DTLs, Q'@gile systems will incur a several fold increase to realise a similar production capacity. Compared to emerging Agile Systems of types described in section 4.4 there will be an increase in tool costs, but this will be a relatively less significant disadvantage than is the case for DTLs.



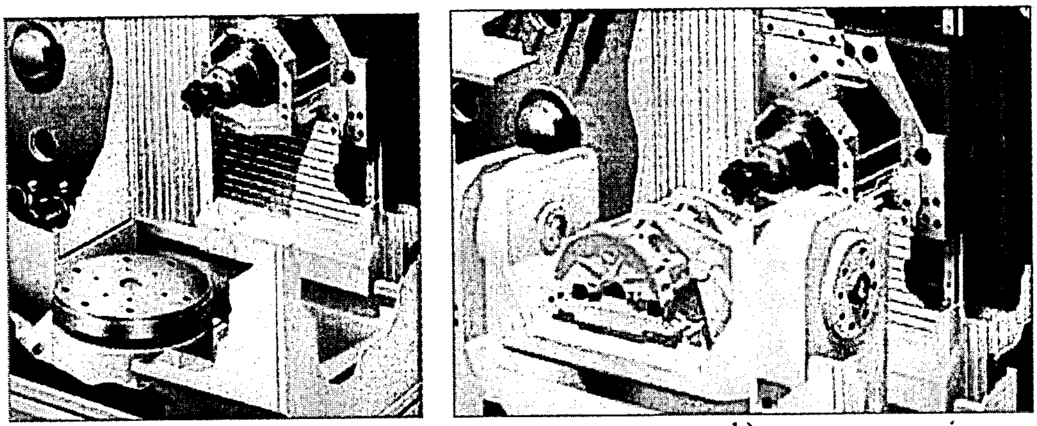
a)



b)

Figure 4.12 a) a 24/36 tool magazine, for CNC machine SPECHT 500W (4.4 seconds chip-to-chip time); b) 57 tool magazine, for CNC machine GENIUS 500 (2.5 seconds chip-to-chip time). Source: Cross Huller website (Cross-Huller 2004a; Cross-Huller 2004h)

Regarding the working table requirement for a combined A-axis and B-axis device, plus a pallet exchange mechanism and a W-axis, the author has yet to identify a commercial device which fulfils these requirements. However independent mechanisms were found which individually satisfy the need identified. Hence it is presumed that the construction of such an integrated mechanism should prove a realistic possibility, albeit that the cost of such a combined device is difficult to estimate. Figure 4.13 shows known devices that realise a B and A-axis movement. The author suggests that the B-axis device could be installed on the A-Axis device. This would enable rotational (B-axis) and tilt (A-axis) movement of engine parts.



a) b)

Figure 4.13 a) Working table with a B-axis, used in SPECHT 500T; b) Working table with an A-axis, used in SPECHT 500D. Source: Cross Huller website (Cross-Huller 2004a)

Suitable pallet exchange devices along with a W-axis device, are available commercially, see figure 4.14.

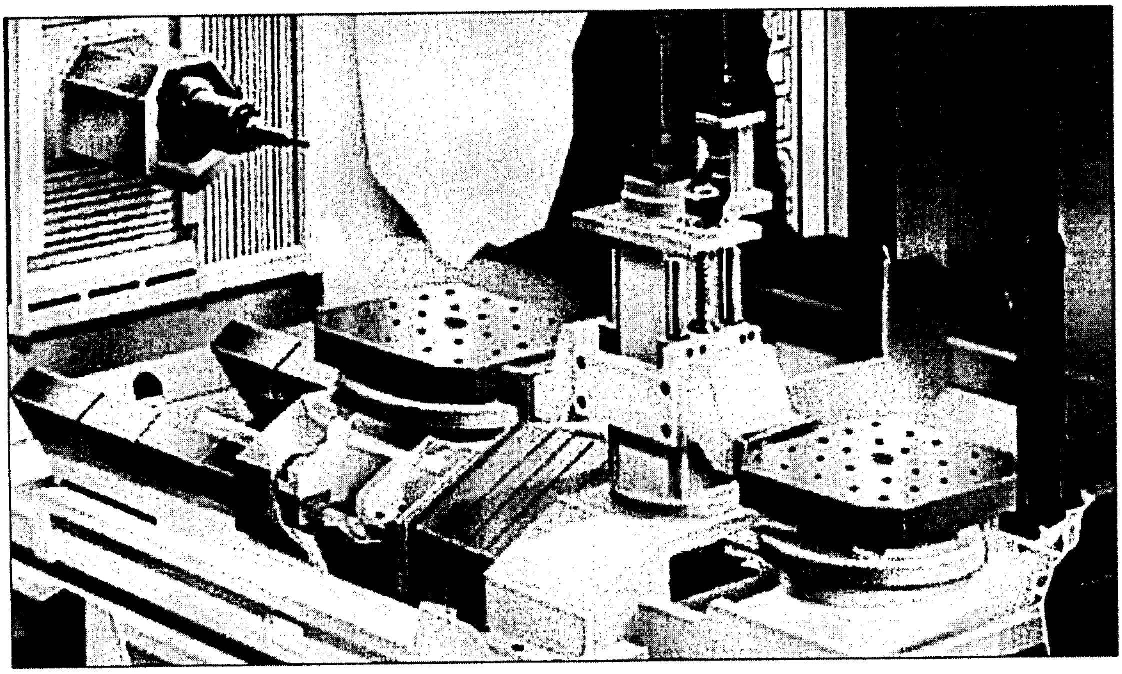


Figure 4.14 Working table with 180 degrees pallet rotating device and a W-axis, which takes the part to and from the machine spindle. Used in the SPECHT 500WP machine. Source: Cross Huller website (Cross-Huller 2004a)

4.5.4 Q'@gile system transport automation

A Q'@gile system does not require cell interlinking transport automation devices since individual cells will not be physically connected to each other. However two forms of transport device are required, namely:

1. a roller conveyor, at each cell
2. a double gantry robot, with capability to serve a number of cells

The envisaged purpose of the roller conveyor is to take a part (such as an engine block) from a temporary storage area which lies inside the main engine part machining plant sector, to position $\mathbf{P_{in}}$. The part will remain at that place until the gantry robot collects it and moves it to position $\mathbf{P_2}$. Subsequently the part will be transferred by the double pallet exchange device to position $\mathbf{P_1}$ where it will be machined. After machining, the part is returned to position $\mathbf{P_2}$ and then the gantry robot collects it and puts it in position $\mathbf{P_{out}}$. The roller conveyor then functions to take the engine out of the machining area so that it can be inspected and redirected to the assembly area or put into temporary stock before being used in the local (or some remote) assembly area. It is estimated that a single gantry robot should possess sufficient capability to serve a number of cells, i.e. between 6 and 10 cells. This is possible because the full machining process from machining start to the end is expected to take more than 480 seconds, thereby enabling a single robot to pick and place the parts required to and from a number of cells.

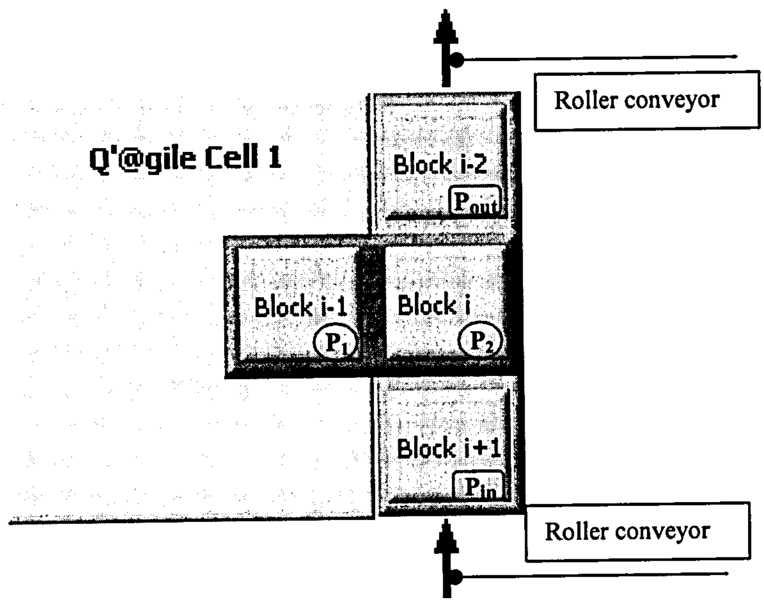


Figure 4.15 Transport automation of a Q'@gile engine block machining cell.

4.5.5 Q'@gile system: introduction of new engines

In terms of agility, changes in engine types should be readily reprogrammed in a Q'@gile production system, without necessarily incurring production losses during closure and/or start up periods. If a cell is reprogrammed offline and any additional tools required (which do not belong to the set of tools needed by the previous engine type) are added to the tool magazine during maintenance time periods or non-productive time periods, very litle productive time will be wasted in transition processes. Moreover such transitions can be phased in time so that a progressive number of Q'@gile cells are adapted to the production of the new engine part. Theoretically this can be done without production disruptions impacting on the remaining cells of the system. This contrasts very significantly with a typical several month period over which production losses occur due to DTL retooling or full substitution of the DTL. Because each Q'@gile cell will be based on flexible automation, it becomes technically feasible, less time consuming and cheaper, to adapt to changes in engine parts.

Attention should be paid to design and choice of fixtures and clamping devices which will be responsible for guaranteeing that exact machining positions are assumed during all machining processes, along with the mechanical interfaces to engine parts so that the transition from one engine part type to another does not requires the addition of special features on the pallet, fixtures or clamping devices.

Special attention should also be paid if the engines are made of a different material, such as aluminium alloy, cast iron, CGI cast iron, etc. This is because a different material may require quite different tools and machine power requirements.

A standardization process should be undertaken across all the mass produced engines (namely I3, I4 and V6 engine types), in order to minimize the changes required with respect to: (a) types of tools used for one engine to another and (b) types of machining operations. Major benefits can be expected during engine parts machining if at design time this issue is adequately taken into consideration. However, the author considers that these detailed engine design concerns are out of the scope of the present studies, and, therefore will not be subjected to further consideration.

4.5.6 Q'@gile system mixed engines manufacturing

In terms of engine variant flexibility, in principle a Q'@gile system has potential to enable the simultaneous production of mixed engine types by different Q'@gile cells, since they are essentially independent production units. When designing a cell for mixed engine manufacture certain considerations should be addressed regarding: maximum metric dimensions for the engine blocks and cylinder heads; allowed weight for the parts; modular fixtures and clamping devices. However needed differences in tool dimensions, interface and weight, along with machine power requirements, shouldn't constitute a problem, except if special materials are used to cast the parts, such as CGI iron.

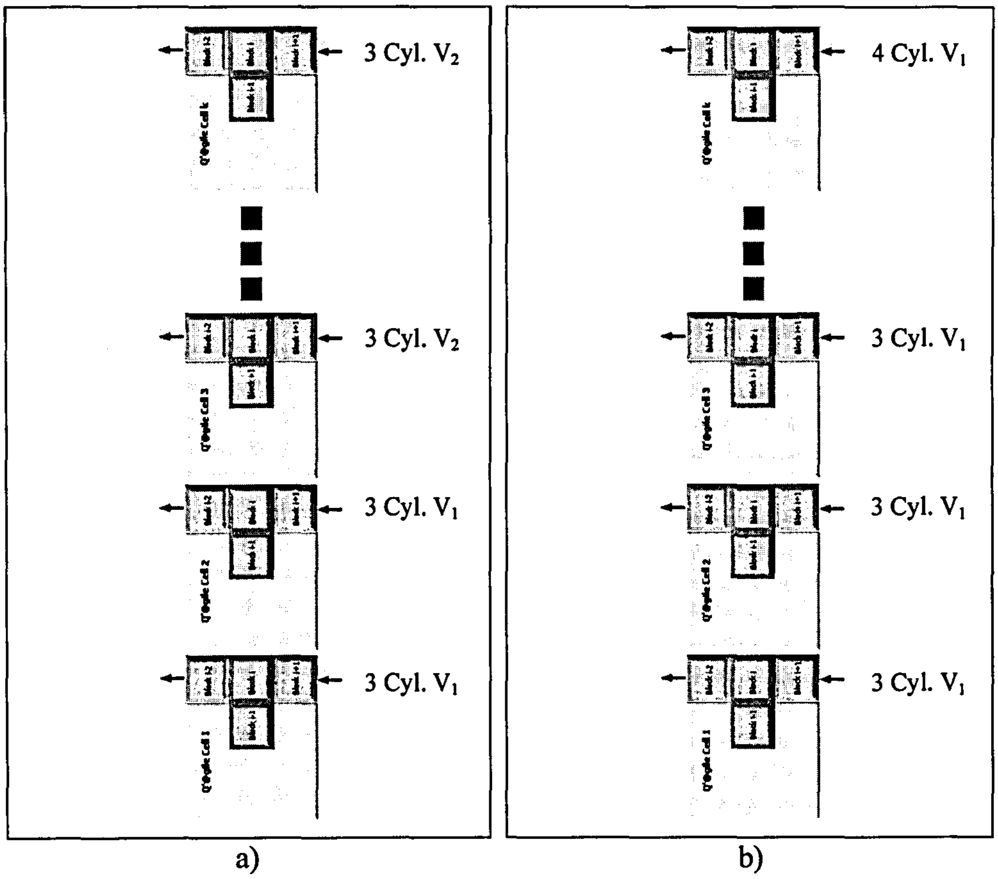


Figure 4.16 Two illustrative representations of a mix of engine blocks being machined simultaneously in a Q'@gile system.

As represented by figure 4.16 a) two cells might be allocated to the production of a 3 cylinder engine part of a particular engine series (3 cylinders V_1), while the remaining cells might be assigned production of another version of the same part type of a different engine (3 cylinders V_2). The number of cells allocated to each engine series part could be varied readily over time, to closely match changes in demand for both engine configurations. Figure 4.16 b) presents a similar situation with at least 3 cells machining parts for 3 cylinder engines (V_1) and the remaining cells machining parts for 4 cylinder engines (V_1). Triggered by customer demand, a Q'@gile system should be able to be incrementally developed in a responsive way, and with minimum costs penalties, to situations like the ones presented in Figure 4.16.

In theory, it may even prove feasible to have a mix of engines types flowing through each unitary Q'@gile cell. However, this is a strategy that might best be avoided (if possible), because it would increase further the cost of replicated tools. It would also require bigger tool magazines. This last option might be feasible however for engine part variants characterized by very low series and highly priced engines, such as: V8, V10, V12, W12 or special purpose engine configurations. The present study has focused most attention on mass produced series, such as the I3, I4 and V6 engines.

In principle Q'@gile systems have potential to allow fully mixed production of engine part variants in batches of one unit. This is due not only to the use of highly flexible machines and transport automation, but also due to the independent nature of each Q'@gile cell, which behaves as a fully independent production unit. Therefore it is expected an overall improvement in the engine manufacturing agility, by achieving faster response to engine variants change and by enabling mixed production of engine part models.

4.5.7 Q'@gile system uptime and engine part traceability

Part quality faults, tool breakdowns or single machine breakdowns occurring in a single cell can in general be expected to impact only on a single Q'@gile cell. Therefore production losses due to a cell production halt are of the order of 1/N of the installed capacity[25] (N being the effective number of Q'@gile cells installed and running at the time the breakdown occurs). However the general robustness and reliability of the machines deployed will also directly influence the system uptime. Overall however it is probable that because the uptime of *Agile Systems* is significantly higher than DTLs, i.e. 80% to 90% uptime against 60% to 75% uptime respectively (Price 2003b), then Q'@gile systems

[25] - Maximum production capacity is achieved with K cells installed in the system, K being the maximum number of cells that can be installed (N varies in integer steps from 1 to K).

should inherit such benefits. In fact potentially the uptimes of Q'@gile systems should be better than *Agile Systems* given that they have comparatively improved production flow dependency between system elements.

A capability that is highly valued in the automotive engine manufacturing industry is that of traceability. Traceability implies ready ability to establish where and when a particular engine (and its respective machining operations) was made. This kind of information is required when quality faults are detected, so that prompt measures can be taken to correct the original process or system. Since an engine can be traced immediately to the machine that made it (because each engine part is made by one Q'@gile cell only), in principle the process of traceability is simplified.

4.5.8 Q'@gile System financial requirements

It is expected that significantly lower initial investment in machining facilities will be made for Q'@gile system, relative to DTLs. Although progressive investments may follow, it is expected that lower overall capital expenditure will be needed during the lifespan of an engine plant. The difference will be particularly marked where engine variation needs to be catered for, because with Q'@gile systems changeover cost should be very significantly lower. In fact the author considers that maximum production capacity is not a good reference base to compare both solutions, since production capacity is very commonly under utilised. Instead a reference demand pattern for engine volume and engine variants should be used. Such a demand pattern can be used to help specify technological requirements in both DTLs and Q'@gile systems, and can realistically compare both alternatives in investment terms.

Because Q'@gile systems can facilitate dynamic change to capacity, according to the market demands, risky financial investment need not be linked to uncertain long term engine demand forecasts. The investment is protected in two main respects, viz: (1) the technology is highly flexible therefore its reuse can be promoted when new engine machining requirements emerge; and (2) short term investment levels will be proportional to short term (more predictable) engine demands so as to minimize risk of over investment.

A Q'@gile system investment model will be presented in chapter 7.

4.5.9 Q'@gile system advantages and limitations

The expected main advantages of Q'@gile systems are as follows (Moreira and Weston 2005):

- A scalable production capacity in incremental quanta, namely a single Q'@gile cell.
- Progressive investment and lower overall capital expenditure during the lifespan of an engine plant. Protection of the investment by selecting reusable technology.
- Initial production capacity is expected to be realised in under 6 months, hence planning can be delayed, and be much closer to production start relative to DTLs. However, space considerations may have to be made up to 2 years in advance.
- Because "standard" Q'@gile cells can be replicated (based on well established CNC technology) system design, engineering, test and commissioning activities can be carried out in a relatively small fraction of the periods taken for traditional approaches.
- Improved overall system uptime and "immunity" to "process coupling" problems should be achieved.
- Q'@gile systems are expected to be highly flexible and responsive to engine part changes and new engine part introduction.
- Q'@gile systems should allow fully mixed production of engine part variants, possibly even in batches of one unit.
- Q'@gile cells can be relocated around the globe at other engine plants that either: (1) also use Q'@gile systems but require additional capacity; or (2) require an initial production capability for a new engine variant.

Anticipated major limitations of the Q'@gile approach are as follows (Moreira and Weston 2005):

- Although equipped with high speed machines, when compared to DTLs the overall time required to execute the same machining operations is expected to be longer. Primarily this will be due to the recommended use of a single-head when compared to the use of multi-head stations in Dedicated Transfer Lines. Tool changes and engine part face changes are also expected to add to the cycle time. However, some tool changes and face changes may be made in parallel.

- More space will be required to achieve an equivalent production capacity to a Dedicated Transfer Line. However, as explained in section 4.5.8 production capacity is not a good base to compare both approaches.
- Q'@gile cells constitute more complex devices than ones used in Dedicated Transfer Lines and are slightly more elaborate than emerging solutions proposed in *Agile Systems.*
- Additional costs relating to the replication of a full set of tools will be required to accomplish all needed machining operations within each Q'@gile cell.
- Additional costs will be required relating the multi-axis working table and pallet exchanger device.
- Additional costs for a global Q'@gile control system which networks all the control units of the Q'@gile cells, enables the downloading of new NC programs into the machines (in the event of new engine phase in), and acquires and monitors production data from individual cells.

CHAPTER 5

Q'@GILE SIMULATION MODEL

5.1 INTRODUCTION

To enable initial validation of likely benefits and limitations arising from use of the Q'@gile system concept, the author created a computer based tool which concurrently executes 'equivalent' models of Dedicated Transfer Lines and Q'@gile systems. The tool was developed by using the general purpose programming environment Labview (version 6.1) from National Instruments. Appendix C briefly describes relevant aspects of Labview which provides a graphical language interface, named 'G' language to create user specified computer programs. Labview was chosen because of the author's previous experience of its successful use as a development tool where it had proven to enable easy construction of user interfaces.

5.2 Q'@GILE SIMULATION TOOL

Therefore the author determined to design and create a simulation model which can visually and analytically compare the operation of traditional engine making approaches (based on DTLs) with Q'@gile production systems: in application scenarios that are representative of known historical patterns of DTL deployment and predicted future patterns of DTL and Q'@gile deployments. The simulation model so created and its underlying Labview software was designed to provide a user friendly interface which enables users to rapidly visualise (1) the ways each system behaves when subject to the occurrence of programmed production events; and (2) of how Q'@gile systems and unitary cells can be deployed to enable equivalent DTL production output levels. The model was also designed to output numerical data which enables in depth analysis and subsequent reasoning about comparative systems performance and limitations. Figure 5.1 illustrates the user interface created for the simulation model. The interface has three main parts, namely:

A. The Q'@gile: Quantum Agile System simulation panel on the left;

B. The DTL: Dedicated Transfer Line panel in the centre;

C. The simulation controls and indicators, i.e. the right hand panel group.

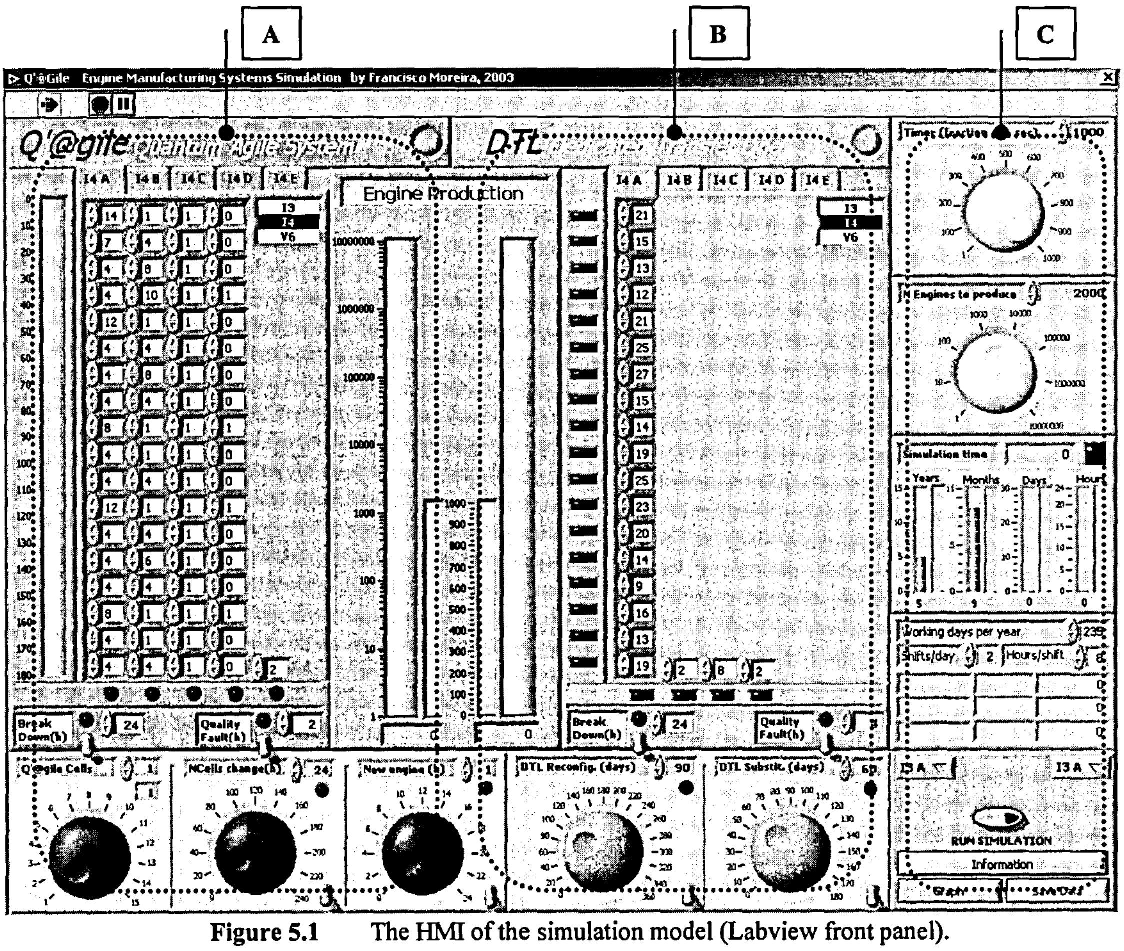


Figure 5.1 The HMI of the simulation model (Labview front panel).

To facilitate comparison between DTL and Q'@gile production systems, initially the model user selects the engine block configuration functions, as illustrated by figure 5.2. Three alternative engine configurations were made available: **I3**: 3 inline-cylinders; **I4**: 4 inline cylinders; and **V6**: 6 cylinders in V-type configuration. Collectively these three engine configurations constitute the primary share of all manufactured engines in recent years. For example more than 95% of all Audi branded vehicles sold in 2003 use I3, I4 or V6 engines.

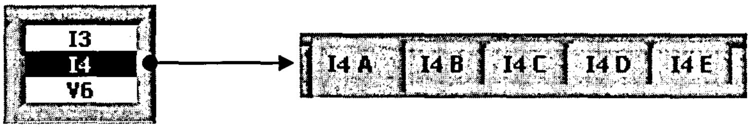


Figure 5.2 Selection of engine configurations and engine types.

When the model user has chosen a required engine configuration the simulation tool enables choice to be made from a predefined set of engine models. Figure 5.2 shows engine models made available with respect to the **I4** engine configuration. The simulation tool can be used to define new engine types and operation times, or change the operation times for the existing engines.

After selecting a suitable simulation speed and simulation mode (time based or number of parts to be made) the model user can trigger the RUN SIMULATION button which initiates simulation. During execution of the simulation model the user can trigger events which impact on the simulated operation of defined DTL and Q'@gile system configurations.

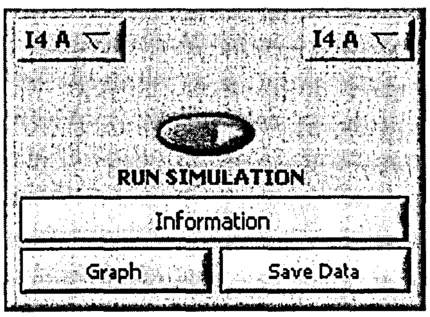


Figure 5.3 Selection of an engine type.

Users are given the option to separately execute models by DTL and Q'@gile systems or they can operate both systems together to enable contrasts and comparisons to be drawn.

Relevant specifics about the G language code and key implementation details are described in Appendix D.

5.2.1 Dedicated transfer lines

To simulate the production of a prime engine part (such as engine blocks) by a dedicated transfer line (DTL) it was decided that each station would be coded as a single process which runs concurrently with all other DTL processes that constitute stations of the line. It was assumed that when simulations are initiated the line is fully loaded with engine blocks and they are already clamped. Under such conditions the repetitive sequence of operations at each line station is as follows:

1. **machine the part** (concurrently at each station);
2. **unclamp** the part;
3. **transfer** the part to the next station;
4. **clamp** the part;
5. repeat point 1 above.

At time instant zero, all the stations begin their respective machining operation. Following which each station will run until the time delay for the respective operation has elapsed. Then the station will wait for others to complete their running cycle. When all stations have finished, the parts are unclamped and transferred to the next station where they are clamped again so that the next operation of the processing sequence at each station can take place.

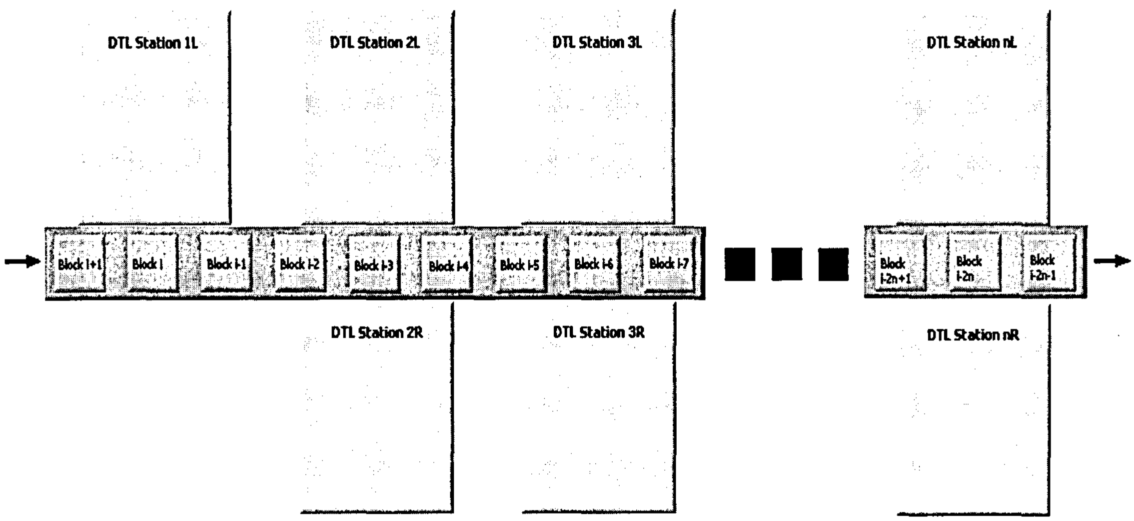


Figure 5.4 Conceptual representation of an engine blocks Dedicated Transfer Line.

Representative data was encoded within the simulation model about the time duration for each machining operation and its variation with engine configuration and engine model. Table 5.1 presents the operation timings for a model 'A' 4-cylinder engine block. These timings are based on real data obtained from an engine machine builder based in the UK (private communication). Other engine part operation timings were inserted as illustrative examples, they are similar to type 'A' operation timings but are not real industrial data. This kind of data is generally regarded as being confidential by the engine manufacturing industry.

Table 5.1 DTL operation times for type 'A', 4-cylinder engine block

Station	Operation ID	Time (seconds)
Station 1 Left (1L)	Op. 10	21
Station 2 Left (2L)	Op. 20	15
Station 2 Right (2R)	Op. 30	13
Station 3 Left (3L)	Op. 40	12
Station 3 Right (3R)	Op. 50	21
Station 4 Left (4L)	Op. 60	25
Station 4 Right (4R)	Op. 70	27
Station 5 Left (5L)	Op. 80	15
Station 6 Left (6L)	Op. 90	14
Station 6 Right (6R)	Op. 100	19
Station 7 Right (7L)	Op. 110	25
Station 8 Left (8L)	Op. 120	23
Station 8 Right (8R)	Op. 130	20
Station 9 Left (9L)	Op. 140	14
Station 9 Right (9R)	Op. 150	9
Station 10 Left (10L)	Op. 160	16
Station 11 Left (11L)	Op. 170	13
Station 11 Right (11R)	Op. 180	19

The reader can observe from Table 5.1 that the "slowest" of the stations is Station 4 Right (4R) which requires 27 seconds to complete its operation. After this time the parts will be unclamped (which takes 2 seconds) and transferred to the next station (which takes a further 8 seconds). The parts are clamped again (2 more seconds) and a new machining cycle starts.

During execution of each machining operation the LED used in the simulation tool to represent respective operations is turned ON. When not in the machining state the respective LED is OFF. The same happens for the LEDs used to represent the states of the unclamp operation, transfer operation and clamp operation. This means that the **Operation**

LED is ON for 27 seconds while at other stations the LEDs will reach the OFF state earlier, namely as soon as each station finishes machining. The relevant HMI is presented in Figure 5.5.

As a convention in the automotive industry, operations are named sequentially: **Op 10, Op 20,...Op X.**

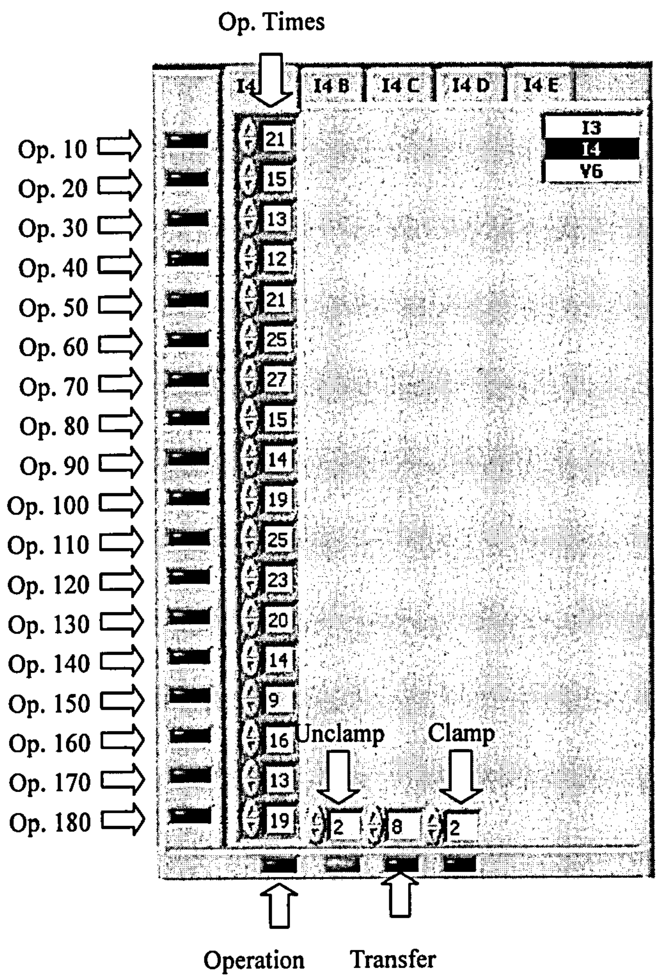


Figure 5.5 HMI of the DTL time duration of machining operations

The cycle time for the model 'A' engine block is 39 seconds. After each cycle an engine block will output from the line. The model user can receive information about the performance of the DTL by watching the number of parts finished in the front panel (HMI). Figure 5.6 shows HMI scales for both Q'@gile (left most scales) and DTL (right most scales). There are 2 DTL scales: a) the smaller one, a linear scale, which measures up to 1000 finished parts; this enables representation and analysis of short term DTL performance; and b) the tallest one, a logarithmic scale, which measures up to 10 million finished parts, and thereby encodes long term performance.

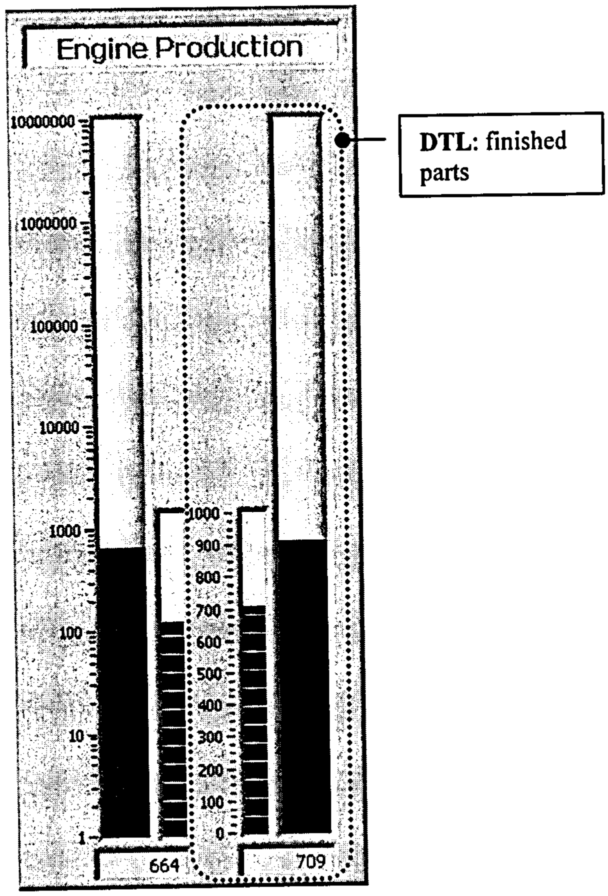


Figure 5.6 Finished parts counting (DTL).

The performance of the DTL depends not only on machining processes, unclamping, transferring and clamping operations, but also on several events that occur during the system lifespan: such as machine breakdowns, part quality faults and system retoolings. These events will be the subject of further discussion in section 5.2.5.

5.2.2 Q'@gile system

To simulate the production of prime engine parts using a Q'@gile system approach the minimum required is a single Q'@gile cell. The simulation model describes each cell as a process which executes a sequence of tasks. It was assumed that, at the initiation of each simulation run, each cell (or group of cells) is loaded with an engine block ready to start machining processes. From this point in time the sequence of operations in the cell was modelled as follows:

1. **machine the part** (machining operation);
2. **repeat 'n' times the machining operation** as required;
3. **exchange tool or/and change the part face;**
4. if the part is finished proceed in point 5 below otherwise repeat point 1 above (for the remaining operations);
5. **exchange the pallet holding the part** (part exchange device);
6. repeat point 1. above.

Clamping the pallet (which holds the engine block in place) is assumed to be done while the previous part is being machined. Unclamping the pallet which holds the finished engine block assumed to be carried out while the next engine part is already being machined.

As explained previously the number of cells installed in the system will dictate the real throughput of a Q'@gile system. If all cells machine the same engine part, the throughput will equate to the number of cells times the throughput of a single cell. This is illustrated by Figure 5.7.

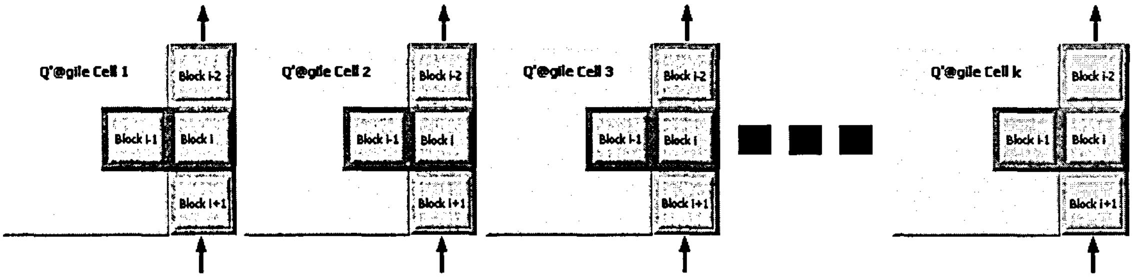


Figure 5.7 Representation of the Q'@gile approach with 'K' cells to machine engine blocks.

The time interval for each operation will vary according to the engine configuration and engine model. The number of times a single operation needs to repeat varies essentially according to the engine configuration (it might also vary with the engine model). Table 5.2 presents the operation timings for a model 'A' 4-cylinder engine block. These timings are author estimates since it is not possible to obtain real world operation timings because

Q'@gile systems are still a concept conceived to machine engine parts in the future.

Table 5.2 Q'@gile estimated operation times for type 'A', 4-cylinder engine block

Operation ID	Time (seconds)	Number of times to repeat	Tool exchange	Block face change
Op. 10	14	1	1	0
Op. 20	7	4	1	0
Op. 30	4	8	1	0
Op. 40	4	10	1	1
Op. 50	12	1	1	0
Op. 60	4	4	1	0
Op. 70	4	8	1	0
Op. 80	4	4	1	0
Op. 90	8	1	1	1
Op. 100	4	1	1	0
Op. 110	4	4	1	0
Op. 120	12	1	1	1
Op. 130	4	4	1	0
Op. 140	4	6	1	0
Op. 150	4	4	1	0
Op. 160	8	1	1	1
Op. 170	4	1	1	0
Op. 180	4	4	1	0

Each engine, e.g. I4 model 'A', is characterized by a sequence of machining operations, change part face, exchange tool, etc. Each of these has a specific operation time (described in seconds), such as those indicated in Figure 5.8 for the I4 'A' engine. From left to right, column 1 of figure 5.8 represents the machining operation time, column 2 represents the number of times that particular operation has to be repeated, column 3 is the time taken to change the tool, column 4 is the time taken to exchange the face of the engine block, and the remaining indicator on the right-bottom corner of the picture is the time taken to exchange the engine block with a new one. At the design stage for the simulation tool, it was considered that it is possible to simultaneously execute the tool exchange and to exchange the face of the block.

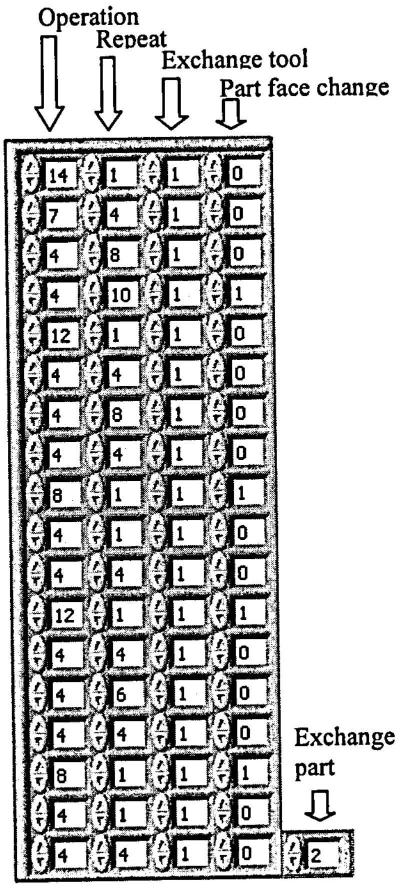


Figure 5.8 Operation timings for an I4-A type engine.

The cycle time for a single Q'@gile cell producing model 'A' engine blocks is 344 seconds, i.e. 5 minutes and 44 seconds. After each cycle an engine block will be output from each cell. Hence the throughput from a multi-cell Q'@gile system will vary according to the actual number of cells installed in the system. The number of cells installed in the system can vary with time. The user can access visual and analytical information about the performance of simulated Q'@gile systems by observing the number of parts finished in the front panel (HMI). Figure 5.9 shows HMI scales for the Q'@gile system. There are 2 Q'@gile scales: a) the smaller one is a linear scale, which measures up to 1000 finished parts and enables short term Q'@gile performance measurements; and b) the tallest one is a logarithmic scale, which measures up to 10 million finished parts, and gives long term performance indications. These scales, along with the DTL ones enable almost instantaneous perceptions to be drawn as to how well each system is performing in terms of the production of engine parts.

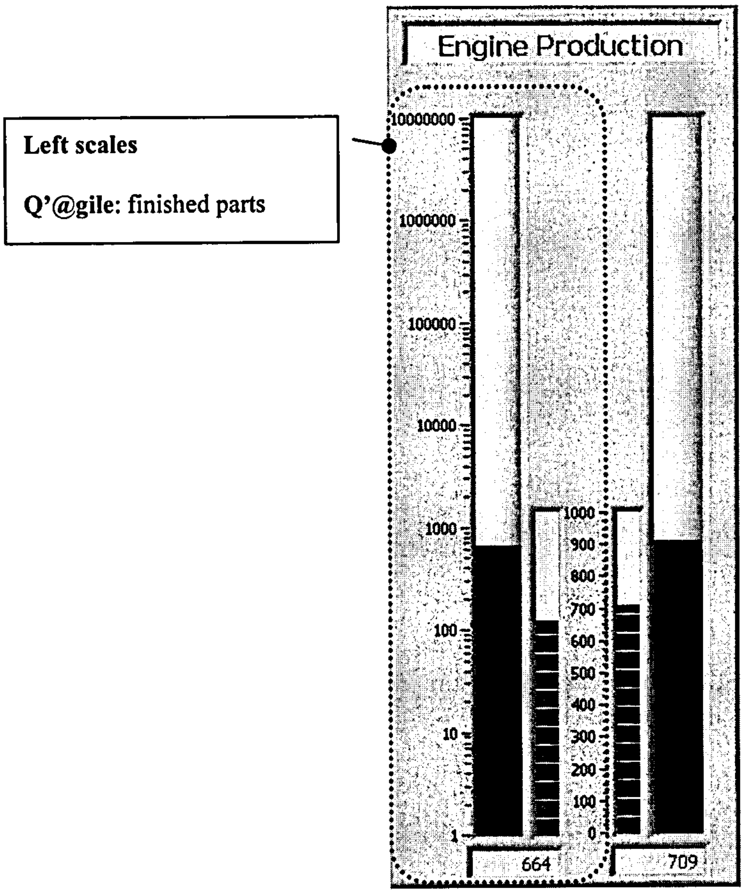


Figure 5.9 Finished parts counting (Q'@gile).

The performance of Q'@giles is dependent on the machining processes and also on several events that occur during the system lifespan, such as machine breakdown, part quality faults, change in the number of installed cells or engine changeovers. The impact of these events is subject to further discussion in sections 5.2.5 and 5.2.6.

5.2.3 Time control concept

The simulation model is based on the execution of software processes which use:

1. **real time**, i.e. the time used in the processes (simulation) are equal to the time the processes would take in real life, or;

2. **a fraction of the real time**, i.e. the time used in the processes (simulation) are a fraction of the time the processes would take in real life. The maximum fraction is 1/1000 of the real time, i.e. what would be executed in 1 second in real life can be executed in 1 milisecond.

The real time option (and also low time ratios, e.g. ½; 1/5; 1/10) was found to be useful to understand how the system behaves at the operations level. Normally, using this option the user wants to check in detail those events which take place over timeframes of the order of seconds or minutes. This excludes the simulation of DTL retooling, machine breakdowns, etc. since these events normally take place over hours, days or even weeks. Therefore it was found less practical to use low time ratios to simulate these kind of events. Low time ratios are also useful to confirm that the system is making what is supposed to make, before "speeding up" the simulation model to observe how it behaves over a longer period of time.

The second option (at higher ratios, such as 1/100 and 1/1000) was found to be useful to simulate the behaviour of systems in the long term. Operations over a week's duration, months or even years can be simulated in this way. This is used to gain important data on events that occur and greatly impact on system performance. It is also very useful to compare long term runs of the systems.

Once a given timer setup is chosen and execution of the model is started it is not possible to change the simulation speed. The current model run has to finish or be stopped by the user before the simulation speed is changed.

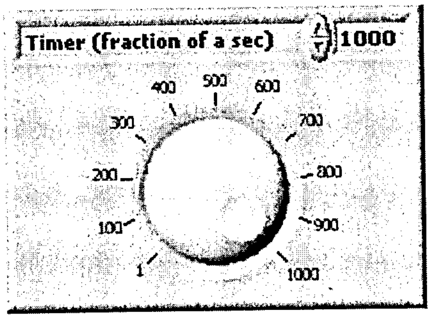


Figure 5.10 Simulation speed timer: time ratio.

Simulation can be executed under two different modes:

A. Time based;

B. Parts to be made.

By default the tool uses the parts to be made mode. Under this choice the user specifies the number of parts to be made and the model runs until the number of parts has been accomplished.

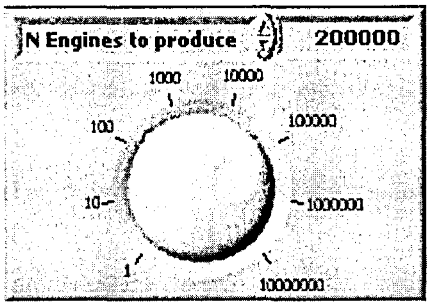


Figure 5.11 Simulation mode: parts to be made.

Under the time based mode, the user specifies the simulation time before running the model and activating this mode. During execution the user has a visual display of the total simulation time, and at any time, the elapsed time. Figure 5.12 illustrates a simulation which has run over 4 years and 6 months. The figure also shows the simulation elapsed time, in the present case the elapsed time (at the time the image was captured) was 3 years, 5 months, 22 days and 8 hours.

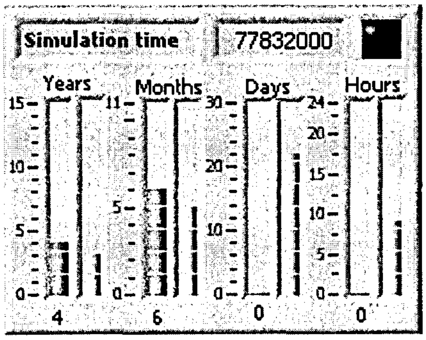


Figure 5.12 Simulation mode: time based.

The simulation model uses a working regime setup to build up the available working time. For example, if the user wants to simulate 1 year of production of engine parts, the available working time will be: **Working days per year** X **Shifts per day** X **working hours per shift.** The working regime philosophy varies from company to company.

The working regime is specified by the user before the start of the simulation model. The working days per year, shifts per day and hours per shift, can be input in the manner shown in figure 5.13

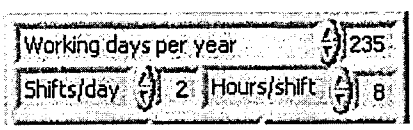


Figure 5.13 Specification of the working regime.

5.2.4 Engine type changeovers

Given that the Q'@gile approach intrinsically enables the replacement of engine parts by different ones, the process is expected to be much simplified and incomparably less costly than the DTL process. Engine replacement likely requires exchange of NC part programs, exchange of tools and eventually also the need to introduce some changes to the pallet adapter. The required halt in production can be introduced by choosing the required time (production loss) and turn ON the respective switch so that changes take effect. Figures 5.14 illustrates the procedure defined to switch engines.

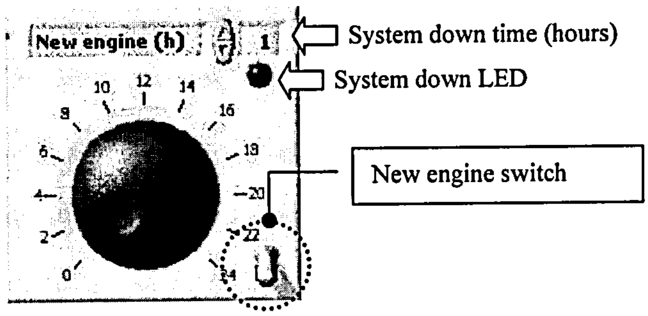


Figure 5.14 Q'@gile introduction of a new engine.

After the time has elapsed the simulation will resume operation.

It is normally possible to retool an existing DTL in order to produce a slightly different engine, such as a new version of an I4 model 'A' petrol engine. These types of change require:

1. additional investments for retooling part of the existing facilities;

2. production losses since production has to be halted for some time period.

The lost production during the retooling period, was implemented by halting all DTL processes for the time period stipulated by the user. To start the reconfiguration process the user has to activate the reconfiguration switch. Figure 5.15 illustrates the reconfiguration HMI.

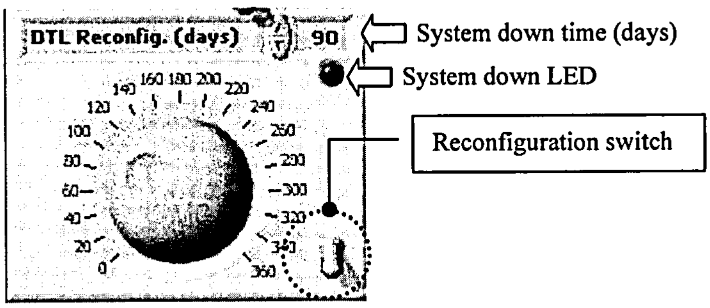


Figure 5.15 DTL reconfiguration knob.

Retooling is not always an option however. In some cases, under major changes, e.g. the introduction of a new generation of engines, the substitution of an engine configuration by a different one, etc., might require the full facility to be scrapped and substituted by all new machinery.

Both cases imply losses since production has to be halted. These losses can be simulated by using the simulation tool developed. To start the reconfiguration process the user has to activate the DTL substitution switch. Figure 5.16 shows the substitution knob.

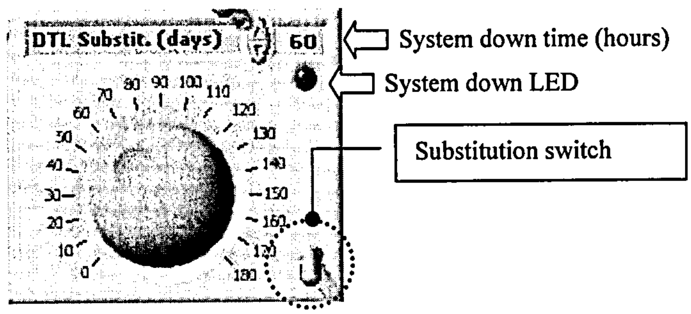
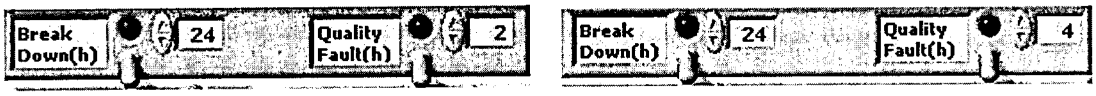


Figure 5.16 DTL substitution knob.

5.2.5 Machine breakdown and quality fault machine stop

The result of single DTL station breakdowns are complete transfer line halts. In the case of a part quality fault, a single station halt to repair the problem also implies a complete line halt. Therefore a system composed of many stations, which depends on the proper operation of each single station, may exhibit poor system uptime and consequently lower overall productivity.

The user can simulate station breakdown events and quality fault events by specifying the respective downtime and triggering the respective switch. Figure 5.17 a) shows the Q'@gile HMI for breakdown events and quality faults; b) shows the DTL HMI for the same events. After event completion the simulation run will resume from the prior state.



a) b)

Figure 5.17 a) Q'@gile breakdowns and quality faults; b) DTL breakdowns and quality faults.

5.2.6 Adding/removing Q'@gile cells to the system

As explained in section 4.5.2 it is possible to add a number of cells to a Q'@gile system in order to increase the available production capacity by integer quantum steps. Adding Q'@gile cells to a system may require temporary halts to the remaining cells currently involved in the manufacturing activities. Removing a number of cells from a Q'@gile system to decrease the available production capacity by integer quantum steps is also possible and may also require temporary system downtime. During execution of the simulation model the user can simulate such occurrences by specifying:

1. The number of cells required;

2. The amount of time the Q'@gile system will be offline;

and by activating:

3. The Add/Remove switch.

To select the total number of cells that the system will have after installing or removing cells the user rotates the knob accordingly, or keys in the respective value. Figure 5.18 shows the number of cells knob.

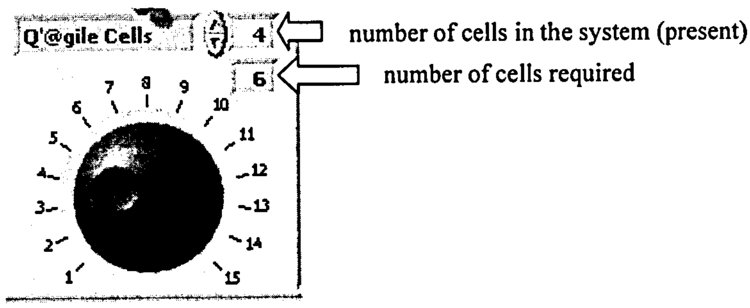


Figure 5.18 Number of cells knob.

To insert the amount of time that the system will be off, the user rotates the respective knob, or alternatively, keys in the respective value. To execute these changes the user has to activate the **Add/Remove cells switch.** By doing that the Q'@gile system halts its operation and resumes only after the time duration has elapsed. During that time the **System down LED** will be on, indicating that the full system is off. After resuming operation the system will run with the number of cells now specified. Figure 5.19 Shows the add or remove cells knob.

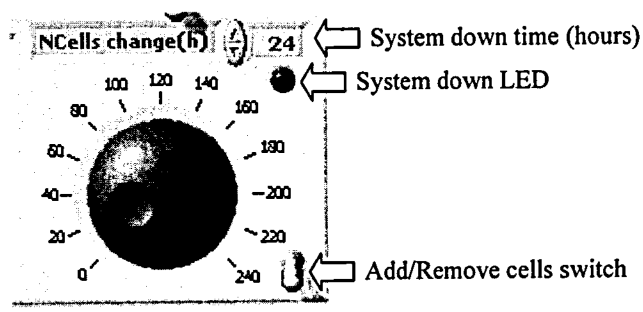


Figure 5.19 Cells installation or removal knob.

5.2.7 Simulation tool testing and experiments

A number of simulations have been exercised and the model was improved in terms of its reflecting real situations more precisely. A significant part of the data used to run the simulation model has necessarily been estimated by the author. Particular estimation has been needed with respect to machining operation timings within hypothetical Q'@gile cells.

A set of validity tests for the simulation model was conducted. These tests had different natures and were conducted in different manners.

- Type 1: Testing the functionality of the tool
- Type 2: Testing the validity of the simulation philosophy
- Type 3: Testing the validity of the simulation results

Type 1 tests included the testing of the controls and indicators of the HMI and the respective outcomes of the functionalities expected from the tool. These tests were conducted in a non systematic manner by the author and have resulted in successive improvements of the simulation tool. Therefore there is no quantitative evaluation of this type of aspects of the tool. There is however a very positive qualitative opinion relating the tool HMI expressed by John Ladbrook[26] in December 2003, during a demonstration session by the author of the Q'@gile simulation tool at Ford Dunton Engineering Center. In terms of personal opinion the author of the study considers that in terms of available functionalities, respective operation and HMI, the tool has reached a very satisfactory level.

Relating type 2 tests the author has conducted a set of experiments which support the validity of the simulation tool. These experiments have shown that the execution of the simulation model has time overheads (i.e. simulation time deviation when compared to the theoretical time) below +1.5% for long term simulations using 1/1000 timer rate over stable and meaningful runs for DTL only simulations and Q'@gile only simulations. For DTL plus Q'@gile combined simulations the time overheads were below 1.75% and below 2.33% for DTL and Q'@gile systems, respectively. A resume of these tests can be found in table 5.3. Detailed results from type 2 tests for DTL only simulations can be found in Table E.1 of Appendix E; results from Q'@gile only simulations type 2 tests can be found in Table E.2 of Appendix E; and results from the combined DTL and Q'@gile simulations type 2 tests can be found in Table E.3 of Appendix E.

[26] - John Ladbrook works for the Ford Motor Company where he holds a position as an European simulation technical specialist. He is also chair of the WITNESS Automotive Special Interest Group. Witness simulation tool is used by Ford to design their engine manufacturing facilities.

Table 5.3 Simulation tool type 2 tests (time overhead in percent)

Simulation	Timer (1/1000)	Timer (1/100)	Timer (1/10)	Timer (1/1)
DTL only	$\leq 1.49\%$	$\leq 0.56\%$	$\leq 0.08\%$	$\leq 0.02\%$
Q'@gile only	$\leq 1.38\%$	$\leq 0.49\%$	$\leq 0.04\%$	$\leq 0.01\%$
DTL (combined DTL + Q'@gile simulation)	$\leq 1.74\%$	$\leq 0.56\%$	$\leq 0.15\%$	$\leq 0.00\%$
Q'@gile (combined DTL + Q'@gile simulation)	$\leq 2.32\%$	$\leq 0.44\%$	$\leq 0.07\%$	$\leq 0.00\%$

As an example of such tests (extracted from table E.1 of Appendix E), the model was executed in order to produce 1,000 engines of model 'A' I4 engines (39 seconds cycle time) using the DTL only simulation without any production halt events. This would require (theoretically) 39000 seconds of real time (i.e. 10 hours and 50 minutes of production time). The model was executed with the timer at a thousandth of a second. The simulation model gave a result of 39,516 seconds (i.e. 10 hours and 59 minutes of production time) to make the 1,000 engines. The computer executing the model took 39.52 seconds to make the simulation. The time overhead (computational time) was 516 seconds, about 1.32%, of the theoretical time. The same setup was done with the timer at a hundredth of a second and a tenth of a second. These have resulted in time overheads of 159 seconds (0.41%) and 22 seconds (0.06%) respectively.

These results were considered acceptable given the magnitude of the time deviation and the purpose of the tool (stated in the first paragraph of section 5.2), which is to compare the relative performance of the DTL and Q'@gile systems (both systems are affected by the time deviation of the simulation runs in similar manners), and to acknowledge the number of Q'@gile cells for equivalent DTL performance. Details about these tests can be found in Appendix E. The tests were made in Pentium 4, 3Ghz CPU personal computers running Windows XP (some computers had 512 Mbytes of RAM and others 1 Gbyte of RAM) with similar results.

The author considers that the validity of the simulation philosophy (type 2 tests) has been confirmed since: 1) the time overhead produced by the simulation model is negligible and can be quantified; 2) at similar timer definitions the simulation tool gives very consistent results. The simulation model will give slightly different results when executed in computers with very different performance characteristics. It is reasonable to think that machines similar or with better characteristics than the ones used to test the simulation tool will provide similar or better results than the ones obtained by the author. Low performance computers are expected to produce poorer results than the ones reported in this study, and therefore should be avoided when trying to replicate the work hereby described.

The author also considers that for the specified purpose the simulation tool developed has produced acceptable results while being extremely easy to use. The tool also produces immediate visual results relating the comparable performances of the systems. The tool has a good HMI which enables a very short learning period for the execution of simulation runs.

Relating type 3 tests the major issue here is the validity of data used in the model. DTL I4 model 'A' engine is based in real data from industry, provided by researchers at MSI involved in industrial projects. Other engine configurations are author estimates since it proved an extremely difficult task to gain access to other engines' data. Manufacturers were reluctant to provide data for other engines, even after the author assuring confidentiality over the source of the data. Q'@gile timings were necessarily author estimates. The author has however taken into account likely gains in the processing speed and the need for replicating the operations over a single engine face, among other reasonable issues. Access to additional real industrial data would however be highly desirable. The author considers that the data and the estimates do not change the general results found during the simulations. For precaution however, and since a particular study is necessarily required for each industrial case, in case a similar study is required in the future, the author suggests that real data from that specific engine manufacturer should be used. If the methodology and tools hereby described is used by people belonging to a specific organization, the access to internal data should not be a problem.

5.3 SIMULATION RESULTS

The DTL and Q'@gile system models were run concurrently over a simulation period of 15 years. Here simulation model parameters corresponded to the production of an E-type I-4 engine were used. The respective operation times of DTL and Q'@gile system elements are listed in table F.1 and F.2 of Appendix F. The DTL had a cycle time of 39 seconds. This figure corresponds to a theoretical production capacity of **347,077 engines per year** and was calculated using the Harbour Report productivity index which assumes system working over 16 hours per day for 235 days per year.

The Q'@gile system cells had a cycle time of 1,199 seconds, i.e. 19 minutes and 59 seconds. This equates to a production capacity for each cell of 11,289 engines per year. Hence the theoretical quantum of capacity for Q'@gile systems proposed in this study is 11,289 engines. It follows that the theoretical number of cells required to match the capacity of the simulated DTL system is 31 (or more exactly 30.7).

Results obtained by running the DTL and Q'@gile models show that:

(1) The DTL is able to produce a maximum of 5,122,110 engines over the 15-year period, with an average yearly production capacity of 341,474 engines. This corresponds to 98.4% of the theoretical capacity and the difference can be accounted for by the time overhead introduced by the simulation tool, explained in section 5.2.7.

(2) A Q'@gile system with 20 cells installed was observed to be able to produce 3,361,020 engines over the 15-year period, with an average yearly production capacity of 224,068 engines. This corresponds to 99.2% of the theoretical capacity and the difference can again be explained as being due to a time overhead introduced by the Labview tool.

It remains the case, however, that the theoretical figures will not correspond exactly to the practical (realisable) production capacity of real DTL and Q'@gile systems. This is because a number of factors will impact negatively on the performance of real systems run under production conditions. The most important impacts are listed in table 5.4:

Table 5.4 Factors impacting on the performance of the engine machining systems.

DTL systems:	Q'@gile systems:
1. major retooling	1. introduction of a new engine
2. minor retooling	2. introduction of a number of cells to the system
3. engine part with a quality fault	3. engine part with a quality fault
4. machine breakdown	4. machine breakdown

The author determined to estimate the likely impacts such factors produce on the performance of real, in production systems, by introducing simulated events during simulation runs of the DTL and Q'@gile models. Tables 5.5 and 5.7 show a list of such events with likely frequency of occurrences and respective estimated time durations.

Table 5.5 Production halts affecting the manufacture of prime engine parts in DTL based production systems.

Production Halts (DTL)	Occurrences	In 1 year	In 15 years	Average duration of Production halt time			
1. Major retooling	1 in 15 years		1	A	B	C	D
				9 months	6 months	3 months	1 month
2. Minor retooling	2 in 15 years		2	E	F	G	H
				2 months	1 month	2 weeks	1 week
3. Engine part Quality Fault	5 per year	5	75	I	J	K	L
				3 days	2 days	2 shifts	1 shift
4. Breakdown of a single machine	1 per year	18	270	M	N	O	P
(assuming a 18 M/Cs based DTL)	(per machine)			2 shifts	1 shift	4h	2h

From the data provided in Table 5.5 it can be deduced that theoretically 256 possible combinations of production halt scenarios can occur in DTL based systems. The author decided that it was feasible and could be informative and representative to test 8 combinations out of the 256 possible. For each one of the 8 combinations data were input into the simulation tool and the model was executed. To enable direct performance comparisons to be drawn the execution was made with DTL and Q'@gile models running in parallel. The decision to focus on only 8 combinations was taken for practicality reasons only, since each simulation run (for a 15-year period) takes more than 2 days to execute.

Results from the series of 8 simulation runs shown that the average yearly capacity of a DTL system varied from 277,662 engines (80.0% of the theoretical capacity) to 332,800 engines (95.9% of the theoretical capacity). The average capacity being **307,925 engines per year** (88.7% of the theoretical capacity). Table 5.6 presents these results.

Table 5.6 Simulation results for the 8 combinations of production halts occurring in the DTL lifespan.

Number	Combination	DTL Capacity (engines)	Percentage of the theoretical Capacity of DTL	Average Yearly Capacity (engines)
1	A-E-I-M	4,164,930	80.0%	277,662
2	C-F-I-M	4,310,410	82.8%	287,361
3	D-F-J-M	4,457,330	85.6%	297,155
4	B-F-J-N	4,580,270	88.0%	305,351
5	A-F-K-P	4,766,100	91.5%	317,740
6	B-G-K-P	4,837,570	92.9%	322,505
7	C-G-K-O	4,842,440	93.0%	322,829
8	D-H-L-P	4,992,000	95.9%	332,800
	Average:	4,618,881	88.7%	307,925
	Theoretical:	5,206,154		347,077

The same reasoning was followed with respect to the Q'@gile system. Production halts affecting the Q'@gile system are however slightly different given the general purpose nature of the machines incorporated into the cells (flexible CNCs) and the nature of inherent system dependencies arising from the Q'@gile machining approach. Type 3 production halts (engine part quality faults) and type 4 (breakdown of a single machine) production halts are the same for both DTL and Q'@gile system. However, the systems' productivity is affected in very different ways by these similar events. For instance while the DTL system has to come to a full stop (i.e. all 18 machines have to be stopped) when a breakdown occurs in a single machine (and resumes operation when that machine is again ready for production), in the Q'@gile system when a machine breaks down inside a cell, only that cell has to be stopped. In a similar manner when an engine part quality fault is detected, after identifying the station where the problem firstly occurred, that machine has to be stopped (incurring once again a full DTL stop). In the Q'@gile system this is not necessary, only the cell which constitutes the source of the problem has to be stopped.

Table 5.7 Production halts affecting the manufacturing of prime engine parts in Q'@gile based production systems.

Production Halts (Q'@gile)	Occurrences	In 1 year	In 15 years	Average duration of Production halt time			
1. New engine introduction	1 in 15 years		1	**A**	**B**	**C**	**D**
(disruption of the machining in all cells)				2 weeks	1 week	3 days	1 day
2. Introduction of new cells to the system	1 per year	1	15	**E**	**F**	**G**	**H**
(disruption of the machining in all cells)				1 week	3 days	1 day	1 shift
3. Engine part Quality Fault	5 per year	5	75	**I**	**J**	**K**	**L**
(disruption of the machining in a single cell)				3 days	2 days	2 shifts	1 shift
4. Breakdown of a single Cell	1 per year	20	300	**M**	**N**	**O**	**P**
(assuming a fixed 20 Cells based Q'@gile)	(per cell)			2 shifts	1 shift	4h	2h

Results from a series of 8 simulation runs using 20 Q'@gile cells (i.e. a fixed number of cells) during the 15-year simulation period showed that the average yearly capacity of such a Q'@gile system varied from 222,199 engines (98.4% of the theoretical capacity) to 223,924 engines (99.2% of the theoretical capacity). The average capacity being **223,081 engines per year** (98.8% of the theoretical capacity). Table 5.8 presents these results.

Table 5.8 Production halts affecting the manufacturing of prime engine parts in Q'@gile based production systems.

Number	Combination	Q'@gile capacity: 20 cells (engines)	Percentage of the theoretical capacity of Q'@gile theoretical Capacity	Average Yearly Capacity (engines)
1	A-E-I-M	3,332,980	98.4%	222,199
2	C-F-I-M	3,334,760	98.5%	222,317
3	D-F-J-M	3,336,180	98.5%	222,412
4	B-F-J-N	3,344,100	98.7%	222,940
5	A-F-K-P	3,352,020	99.0%	223,468
6	B-G-K-P	3,356,060	99.1%	223,737
7	C-G-K-O	3,354,800	99.1%	223,653
8	D-H-L-P	3,358,860	99.2%	223,924
	Average:	3,346,220	98.8%	223,081
	Theoretical:	3,386,822		225,788

These results show that major events that will arise in practical in-production situations will impact significantly on the engine machining systems and thereby change significantly their comparative performance. Table 5.9 highlights that phenomenon.

Table 5.9 Type 'E' I4 engine block Theoretical vs. Realistic production capacities

System	Theoretical Capacity (engines)	Realistic avg. capacity (engines)	Difference (%)
DTL (39 secs cycle time)	347,077	307,925	-11.3%
Q'@gile (20 cells, 1199 secs cycle-time)	225,788	223,081	-1.2%

It follows that in practice the Q'@gile quantum capacity can be considered to be 11,154 engine units per year, whilst the equivalent DTL capacity is 307,925 units per year. It follows that 28 cells (or more precisely 27.6) will exhibit an equivalent capacity to the modelled DTL. Because the new approach is more flexible an estimated decrease in the number of required cells from 31 to 28 is required.

Hence the simulation models were found to usefully exercise various production scenarios. However, it was observed that the engine demand patterns impact most on the adequacy of a given choice of machining approach. Indeed, since DTL systems have a fixed capacity that is decided up to 2 years in advance of the first production start, yearly deviations from forecasted demands will result in wasted investment in capacity, i.e. lack of return on money invested. The greater the deviation between actual engine demand and predicted engine demand the lower will be the profitability: because idle machine systems will result or insufficient machining capacity will be available.

On the other hand the Q'@gile system is grounded in the quantum capacity concept. This enables progressive installation of production capacity, in quantum steps as the engine market evolves. Q'@gile also enables decision time frames to be reduced, e.g. relating to the choice of initial production capacity.

Chapter 7 will compare alternative investments in DTL and Q'@gile based production systems. The resultant models of investment in engine machinery are then exercised with reference to alternative patterns of future engine demands which are predicted using a rationale developed in Chapter 6. This rationale is supported in part by published industry data and sets 'bounds' on uncertainties arising from unpredictable variations of many (mainly environmental) factors that lie outside of the control of engine manufacturers.

CHAPTER 6

PREDICTIVE PATTERNS OF ENGINE DEMANDS

6.1 POWERTRAIN ALTERNATIVE FUTURE SCENARIOS

With a view to supporting investment decision-making about future engine production plants, a set of 36 alternative scenarios for powertrain type shares are developed herein. Scenario construction has been made based on the assumption that there will be four powertrain types in the market during the forecast period, namely: petrol engines, diesel engines, hybrid engines and fuel cell powered engines. This implies that other breakthroughs in alternative powertrain technology will not lead to commercial viability during the forecast period. The decision to focus solely on relative shares between the four listed propulsion technologies was made since: (1) internal combustion engines utilise well established and currently dominant propulsion technology; (2) hybrid engines have been successfully developed and deployed in the automotive industry over the last 5 years, and have been the subject of renewed interest recently, especially in Japanese and North American market places; (3) fuel cell propulsion technology has currently been developed for demonstration purposes in most industrialized countries and is widely regarded in the automotive industry as being the most promising propulsion technology (EC 2003).

6.1.1 Scenarios design and available historical data

Each of the 36 alternative scenarios has been developed bearing in mind a 15 year period beginning in 2005, and this forecast period has been subdivided into three periods of five years. The choice of this scenario lifespan was made by the present author because it aligns with a forecast period used by Price (2003), namely a 14 year long lifespan for engine production facilities (Price 2003). Each of the 36 scenarios developed has three phases, e.g. Scenario 1 is composed of Sc 1A, Sc 1B and Sc 1C as illustrated by Figure 6.1.

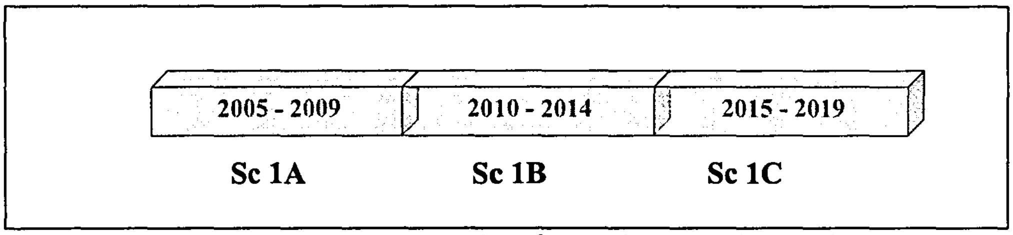


Figure 6.1 Representation of a generic powertrain scenario

The vehicle production base line corresponds to the year 2004. Subsequent respective shares of petrol:diesel:hybrid:fuel cell powered vehicles were forecast by analysing historical statistical data, company reports and observed automotive trends. For each half decade period the average **vehicle production growth** (%), average **hybrid share growth** (%), average **fuel cells share growth** (%), average **petrol share growth** (%) and average **diesel share growth** (%) are estimated. These calculations are used to predict the annual number of engines needed in respect of each powertrain type throughout the forecast period.

Therefore the powertrain scenario's developed as part of this study predict possible yearly demands for engines, corresponding to the four alternative powertrain types. Particular engine configurations, such as 4-cylinder diesel engines or 3-cylinder petrol engines, were subsequently estimated for particular years based on an historical analysis of engine configuration shares. This process, however, necessarily incurs further estimation errors. For example a simple method of calculating the yearly volume demand for I3, I4, V6 petrol engines, and for I3, I4, and V6 diesel engines was used and involved multiplying forecasted annual engine demands for petrol and diesel engines (as predicted by specific scenarios) by the 2004 share values of engine configurations. This approach assumes that the engine configuration shares for petrol and diesel engines will not change over the forecasted period. Clearly this is unlikely to prove to be correct because many market and environmental factors may impact differently on shares of propulsion types, and engine configurations for each type, in different geographical locations around the globe. However no evidence could be found in the literature to support the use of other, more sophisticated, analysis.

The predicted annual volumes for I3, I4, V6 petrol engines and annual volumes for I3, I4 and V6 diesel engine configurations were subsequently used within this author's research study to support decision making regarding the adoption of alternative manufacturing paradigms.

Much of the development of the 36 powertrain scenarios was achieved through making reference to data from a specific vehicle manufacturer. The chosen company was Audi A.G., because the present author had access to vehicle production data from that company and thereby indirect access to data on engine production volumes. Audi A.G. vehicle production volumes over years 2000 to 2003 (VW 2001; VW 2002; VW 2003; VW 2004) are presented in Table 6.1. This table includes an estimate for 2004, where the estimate was made by the present author by extrapolating published first semester production and sales volume (Audi-AG 2004).

Table 6.1 Audi A.G. vehicle production volumes for the years 2000 to 2003. 2004 share estimated. Source: VW group annual reports (2001, 2002, 2003, 2004).

Year	2000	2001	2002	2003	2004 (Author's estimate)
Vehicles produced (units)	**650,559**	**726,753**	**747,809**	**763,273**	**799,790**
Production increment (%)	**+4.0%**	**+11.7%**	**+2.9%**	**+2.1%**	**+4.8%**

Audi A.G. reported (Audi-AG 2002; Audi-AG 2004) powertrain type shares for the corresponding year are presented in Table 6.2. This also includes an estimate made by the present author for 2004 based on Audi first semester production data.

Table 6.2 Audi AG proportion of powertrain types share production volumes for the years 2000 to 2003. 2004 share estimated. Source: Audi AG annual reports (2002, 2004).

Year:	2000	2001	2002	2003	2004 (Author's forecast)
Proportion of petrol engined vehicles	**59.9%**	**55.8%**	**53.7%**	**54.0%**	**52.5%**
Proportion of diesel engined vehicles	**40.1%**	**44.2%**	**46.3%**	**46.0%**	**47.5%**

Over the period 2000 to 2004 Audi did not produce commercial forms of hybrid or fuel cell propelled vehicles, i.e. the proportion of Audi hybrids and fuel cell production was recorded as being zero during the baseline sample period.

6.1.2 Design and implementation of the scenario generator

Bearing in mind the foregoing estimates and data in this study, it was decided to focus on scenarios derived from the data shown in Figure 6.2. Audi vehicle production was estimated to reach 799,790 units by 2004, of which it was projected that 52.5% are to be propelled by petrol engines with the remaining 47.5% by diesel engines. Vehicle production volume for Audi was expected to grow at an average rate of 2% yearly in the period 2005-2009 (following an average growth of around 5% yearly from 2000 to 2003); 0% in the period 2005-2009 and 1% in the period 2015-2019.

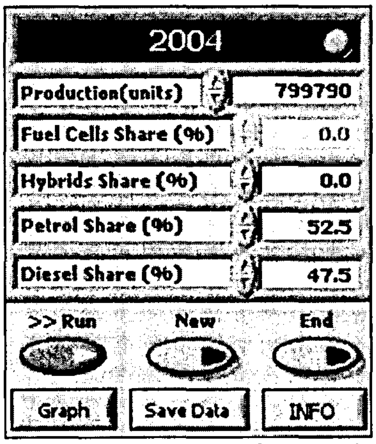


Figure 6.2 Audi 2004 base case for scenarios generation.

It was decided that a number of future scenarios could be generated by varying the increments made in the yearly shares of diesel, petrol, hybrid and fuel cell propelled vehicles. It was observed that the actual values of these share increments would be influenced by many real world variables, such as fuel prices, governmental tax systems, emission legislations, technological advances (such as in respect of fuel cells), etc. However to attempt to handle the unpredictability several of these projected changes were lumped together when generating different increments (positive or negative) in the shares of the propulsion system. However the choices of share increments covered by the scenarios would need to bear in mind the following factors:

1. Introduction of progressively stricter emissions legislation (Euro IV by 2005 and Euro V by 2008 in Europe and similar measures in Japan and the USA);

2. Reported growing interest and advancements in hybrid vehicles. Hybrids being regarded as an intermediary step, ultimately leading to vehicles fully powered by fuel cells.

3. Previous forecasted market introduction of Fuel Cell vehicles by around 2010 (EC 2003; Spencer and Barret 2003);

4. Previous forecasted oil peak production and significant oil prices increase by around 2010 (Aleklett and Campbell 2003).

Likely impacts of these kinds of hypothetical change were translated into specific figures in a systematic way and implemented into the Powertrain-SGen tool, thereby generating each of the 36 scenarios. This number of scenarios was considered to be reasonable essentially for two reasons. (1) This should be sufficient to cover a broad range of possible situations that may occur in reality. (2) The data generated would be extensive but manageable. Nevertheless, it was understood that other forms of investment decision-making might need a different number of scenarios. Table 6.4 shows the selected increments in propulsion system share implemented into the scenario generator, so as to generate the hypothetical volumes required yearly. Table 6.3 provides a 'key' to help interpret the symbols used in Table 6.4. The '--' symbol represents a "strong " decline in the demand for a given propulsion system (from -5.0% to -2.5% over the scenario period); the '-' symbol represents a moderate decline (from -2.5% to -0.5% decline); the '=' symbol represents an insignificant change (from -0.5% to +0.5% change); by the other side a '++' symbol represents a "strong" increment in the demand for a given propulsion system (from +2.5% to +5.0% over the scenario period) and the '+' symbol represents a moderate increment (from +0.5% to +2.5%).

Table 6.3 Increment intervals in percentage.

Symbol	Increment interval (%)
--	[-5.0, -2.5]
-	]-2.5, -0.5[
=	[-0.5, 0.5]
+	]-0.5, 2.5[
++	[2.5, 5.0]

A further implementation assumption made was that full fuel cell propelled cars would not be introduced to any significant extent before 2010. Therefore the symbol "n/a" was introduced in the respective column for the 2005-2009 phase.

Table 6.4 Propulsion systems scenarios.

	Petrol			*Diesel*			*Fuel Cells*			*Hybrids*		
Scenario	*2005-2009*	*2010-2014*	*2015-2019*	*2005-2009*	*2010-2014*	*2015-2019*	*2005-2009*	*2010-2014*	*2015-2019*	*2005-2009*	*2010-2014*	*2015-2019*
1	=	=	=	=	=	=	n/a	=	=	=	=	=
2	-	-	-	+	+	+	n/a	=	=	=	=	=
3	+	+	+	-	-	-	n/a	=	=	=	=	=
4	-	-	+	+	+	-	n/a	=	=	=	=	=
5	=	-	-	=	-	-	n/a	=	=	+	+	+
6	-	--	--	=	+	+	n/a	=	=	+	+	+
7	=	+	+	-	--	--	n/a	=	=	+	+	+
8	-	--	+	=	+	--	n/a	=	=	+	+	+
9	=	-	-	=	-	-	n/a	+	++	=	=	=
10	-	--	--	+	+	=	n/a	+	++	=	=	=
11	+	+	=	-	--	--	n/a	+	++	=	=	=
12	-	--	=	+	+	--	n/a	+	++	=	=	=
13	=	-	-	=	-	-	n/a	+	++	+	+	+
14	-	--	--	=	=	=	n/a	+	++	+	+	+
15	=	=	=	-	--	--	n/a	+	++	+	+	+
16	-	--	=	=	=	--	n/a	+	++	+	+	+
17	-	-	-	-	-	-	n/a	+	++	+	+	=
18	-	--	--	=	=	=	n/a	+	++	+	+	=
19	=	=	=	-	--	--	n/a	+	++	+	+	=
20	-	--	=	=	=	--	n/a	+	++	+	+	=
21	=	-	-	=	-	-	n/a	=	=	+	+	++
22	-	--	--	=	+	=	n/a	=	=	+	+	++
23	=	+	=	-	--	--	n/a	=	=	+	+	++
24	-	--	=	=	+	--	n/a	=	=	+	+	++
25	=	-	-	=	-	-	n/a	+	++	=	=	=
26	-	--	--	+	+	=	n/a	+	++	=	=	=
27	+	+	=	-	--	--	n/a	+	++	=	=	=
28	-	--	=	+	+	--	n/a	+	++	=	=	=
29	=	-	--	=	-	--	n/a	+	++	+	+	+
30	-	--	--	=	=	=	n/a	+	++	+	+	+
31	=	=	=	-	--	--	n/a	+	++	+	+	+
32	-	--	=	=	=	--	n/a	+	++	+	+	+
33	=	-	--	=	-	--	n/a	+	++	+	+	=
34	-	--	--	=	=	=	n/a	+	++	+	+	=
35	=	=	=	-	--	--	n/a	+	++	+	+	=
36	-	--	=	=	=	--	n/a	+	++	+	+	=

A simple computer program was developed by the author in order to generate each scenario and graphically represent the yearly requirements for the propulsion systems. The tool is named Powertrain-SGen (from Powertrain Scenario Generator). The scenario generator was conceived for a single engine manufacturer. To create a new scenario the user selects the first scenario phase (i.e. 2005-2009) and keys in (or rotates the respective knobs) as shown in figure 6.3, to specify: a) average growth in vehicles sales (%); b) average yearly share growth of fuel cells vehicles; c) average yearly share growth of hybrid vehicles; d) average yearly share growth of petrol vehicles, and; e) average yearly share growth of diesel vehicles. Following this, the user selects and keys in the required data for the second and third scenario phases (i.e. 2010-2014 and 2015-2019). The tool limits the input of data to reasonable value ranges and checks for some inconsistency data and then proceeds with the generation of the scenario data. This data can also be represented in a graphical form, enabling immediate perceptions of the main trend in the scenario. The data generated can also be exported to Microsoft Excel to allow further calculations to be made as required.

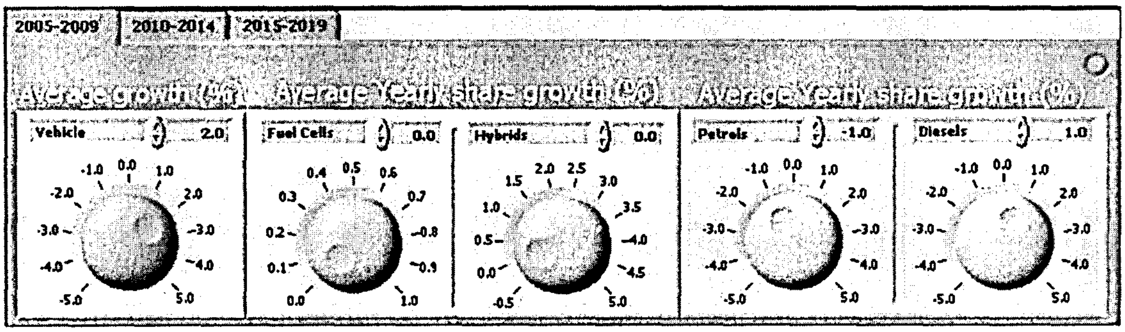


Figure 6.3 Powertrain-SGen 2005-2009 input knobs.

Each one of the 36 scenarios was created by using the Powertrain-SGen tool and the data presented in table 6.4. The reference case for the year 2004, illustrated in Figure 6.2, was used has a scenario baseline. The scenario baseline has been justified in section 6.1.1 and the specific figures presented in table 6.1 and 6.2.

6.1.3 Illustrative scenarios

Here four illustrative scenarios (namely scenarios 2, 6, 14 and 26) are presented in greater detail to aid the readers understanding of their design and purpose. **Appendix G** shows the full set of data for the 36 scenarios developed. Each scenario was generated using the Powertrain-SGen tool.

Scenario 2

1. In this scenario vehicle production volume grows at average rates of 2%; 0%, and 1% in respective periods 2005-2009; 2010-2014; and 2015-2019.

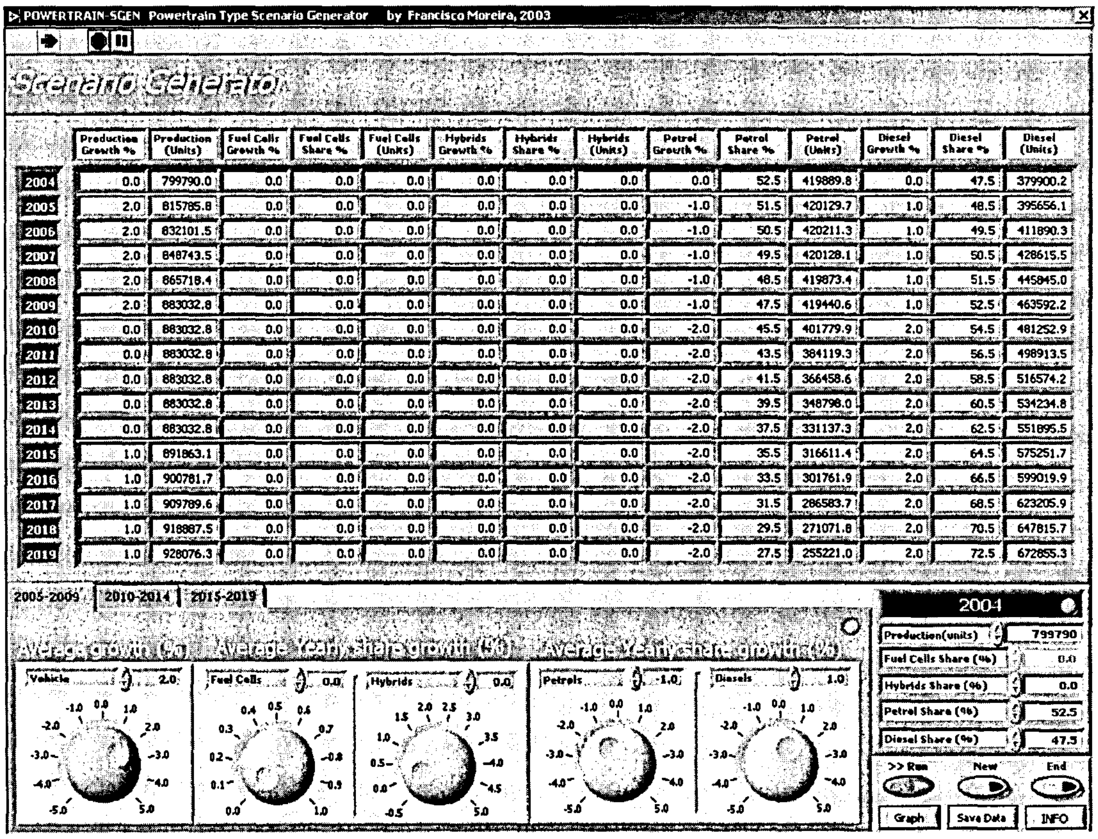
2. **Diesel driven vehicles progressively gain market share relative to petrol driven vehicles (current trend).**

3. Fuel cell driven vehicles fail to gain market share, despite market introduction around 2010

4. Hybrid vehicles fail to gain market share, despite market introduction around 2005

5. Oil price increase is smooth (linear) over the periods 2010-2014 and 2015-2019.

Avg. Yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids Share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**Not relevant**
2010-2014	**0.0**	**-2.0**	**2.0**	**0.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**-2.0**	**2.0**	**0.0**	**0.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	51.5	420129.7	1.0	48.5	395656.1
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	50.5	420211.3	1.0	49.5	411890.3
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	49.5	420128.1	1.0	50.5	428615.5
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	48.5	419873.4	1.0	51.5	445845.0
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	47.5	419440.6	1.0	52.5	463592.2
2010	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	45.5	401779.9	2.0	54.5	481252.9
2011	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	43.5	384119.3	2.0	56.5	498913.5
2012	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	41.5	366458.6	2.0	58.5	516574.2
2013	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	39.5	348798.0	2.0	60.5	534234.8
2014	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	37.5	331137.3	2.0	62.5	551895.5
2015	1.0	891863.1	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	35.5	316611.4	2.0	64.5	575251.7
2016	1.0	900781.7	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	33.5	301761.9	2.0	66.5	599019.9
2017	1.0	909789.6	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	31.5	286583.7	2.0	68.5	623205.9
2018	1.0	918887.5	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	29.5	271071.8	2.0	70.5	647815.7
2019	1.0	928076.3	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	27.5	255221.0	2.0	72.5	672855.3

Figure 6.4 Powertrain-SGen Scenario 2 generation.

As observed from figure 6.5, the impact of combined growth in the total number of vehicles (+2% yearly over 2005-2009) and the loss of petrol vehicle share (-1% yearly over 2005-2009) is that an essentially stable demand for petrol engines arises in the first period. From 2010 onwards however, the demand for petrol engines begins to decline, while diesel engine demand steadily climbs.

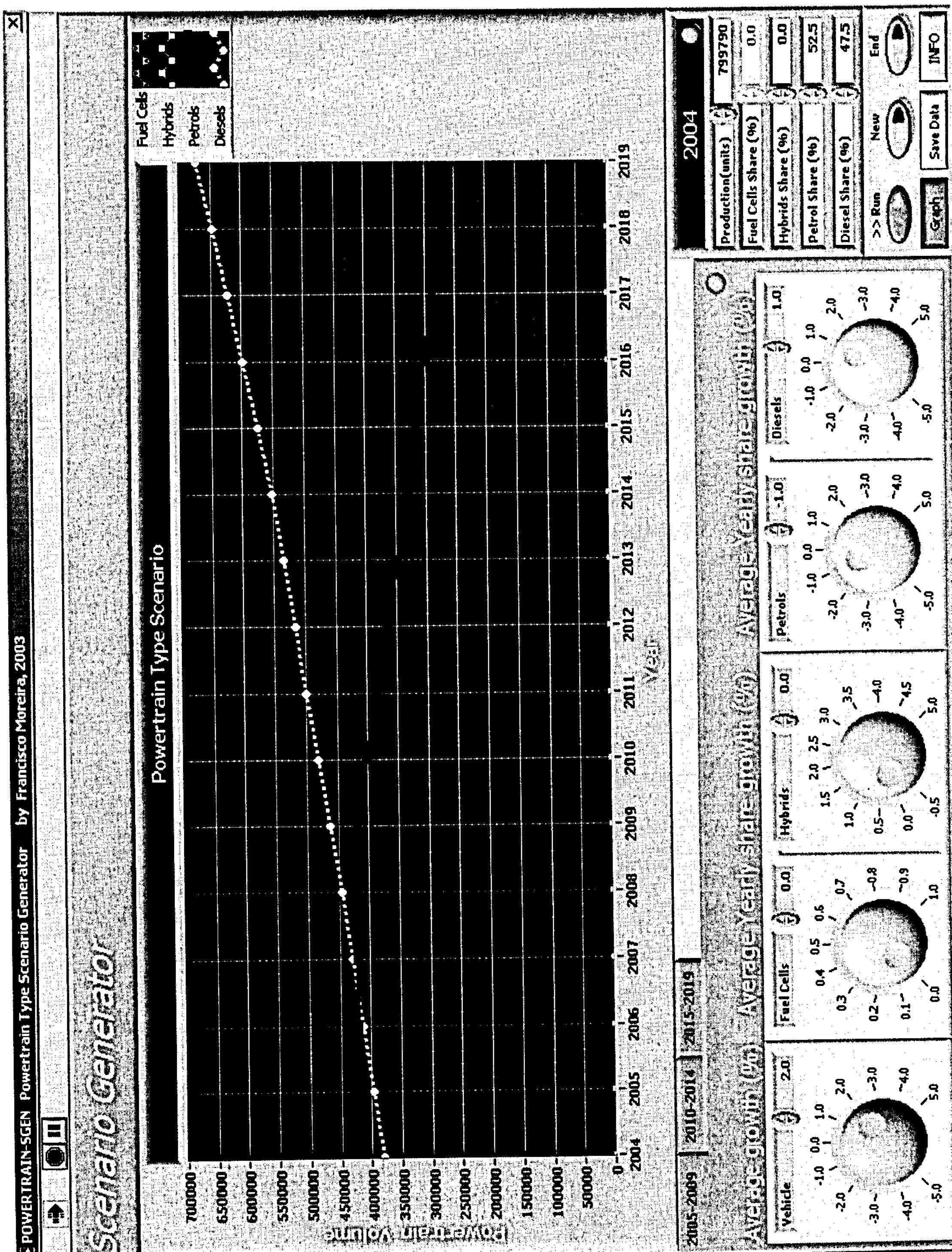


Figure 6.5 Powertrain-SGen Scenario 2 graphical representation.

Scenario 6

1. Vehicle production volume grows at average rates of 2%; 0%; and 1% during respective periods of 2005-2009; 2010-2014; and 2015-2019.

2. **Diesel driven vehicles progressively gain market share relative to petrol driven vehicles (present trend).**

3. Fuel cell vehicles fail to gain market share, following their market introduction around 2010.

4. **Hybrid vehicles gain significant market share following their market introduction around 2005.**

5. Oil price increase is smooth (linear) during the periods 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**-3.0**	**1.0**	**0.0**	**2.0**	**Smooth**

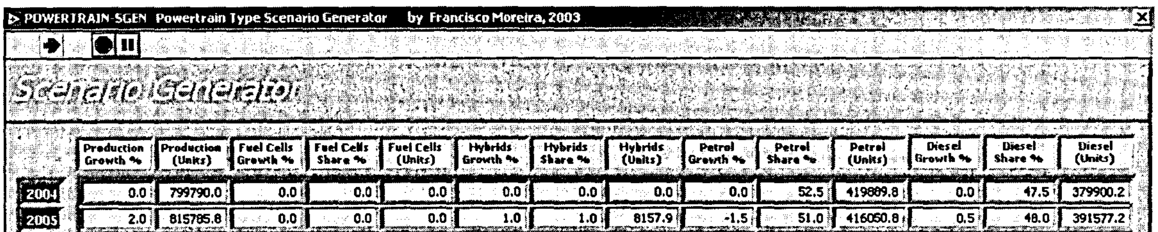


Figure 6.6 Powertrain-SGen Scenario 6 generation.

Figure 6.7 predicts a combined growth in diesel and hybrid vehicles while petrol vehicle share declines. This leads to a significantly reduced volume demand for petrol engines over the period 2015-2019 which may impact significantly on the profitability (and hence investment risk) of petrol engine manufacturing plants.

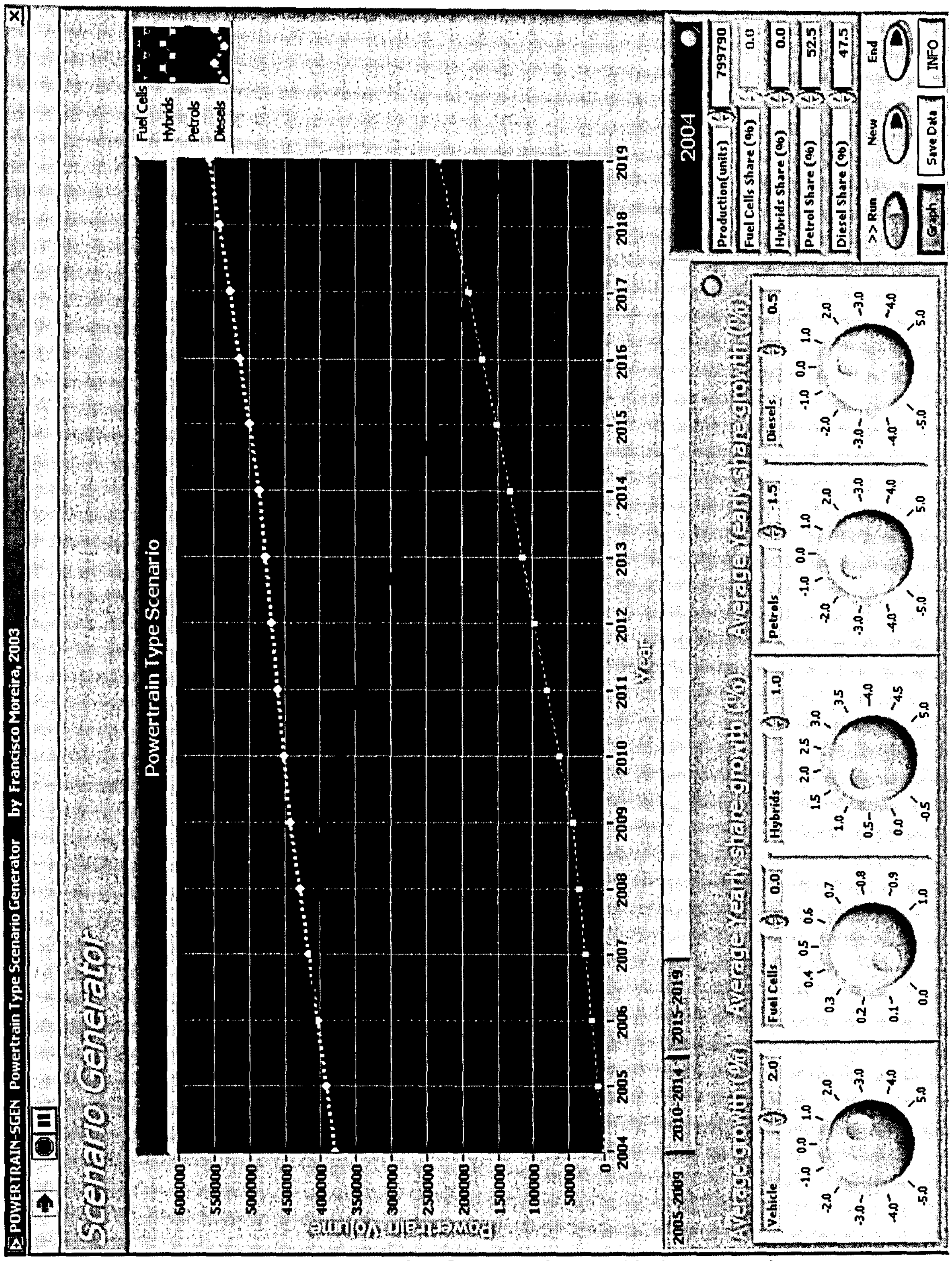


Figure 6.7 Powertrain-SGen Scenario 6 graphical representation.

Scenario 14

1. Vehicle production volume grows at average rates of 2%; 0%; and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

2. **Diesel driven vehicles progressively gain significant market share relative to petrol driven vehicles (present trend).**

3. **Fuel cell vehicles gain significant market share following their market introduction around 2010.**

4. **Hybrid vehicles gain significant market share following their market introduction around 2005.**

5. Oil prices increase is smooth (linear) over the periods 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-4.0**	**0.0**	**2.5**	**1.5**	**Smooth**

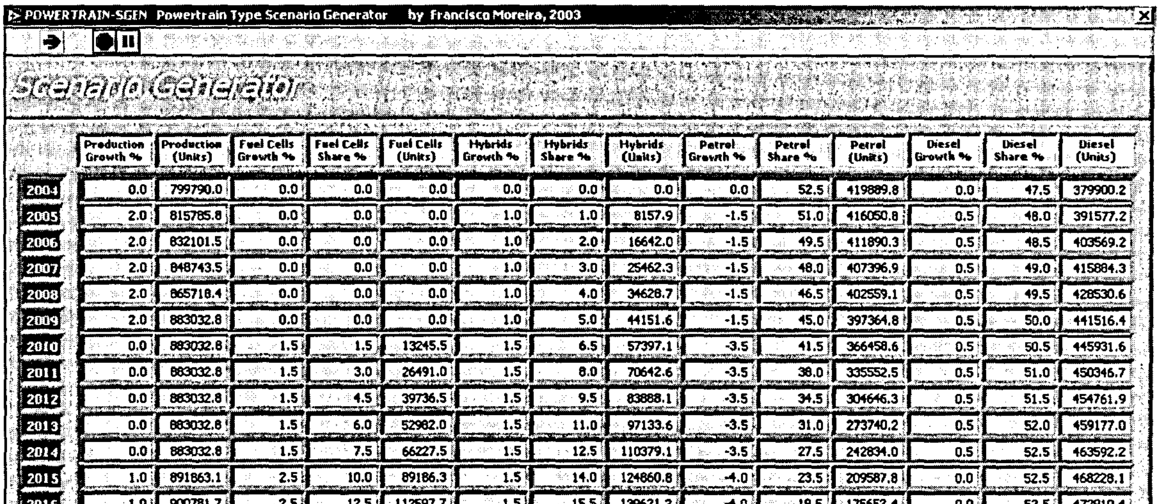


Figure 6.8 Powertrain-SGen Scenario 14 generation.

Scenario 14, which is illustrated by figure 6.9, predicts that the relatively modest but combined successful introduction of hybrid (by 2005) and fuel cell (by 2010) driven vehicles will cause a rapid decline of petrol vehicles posing a major threat to the petrol engine manufacturing business.

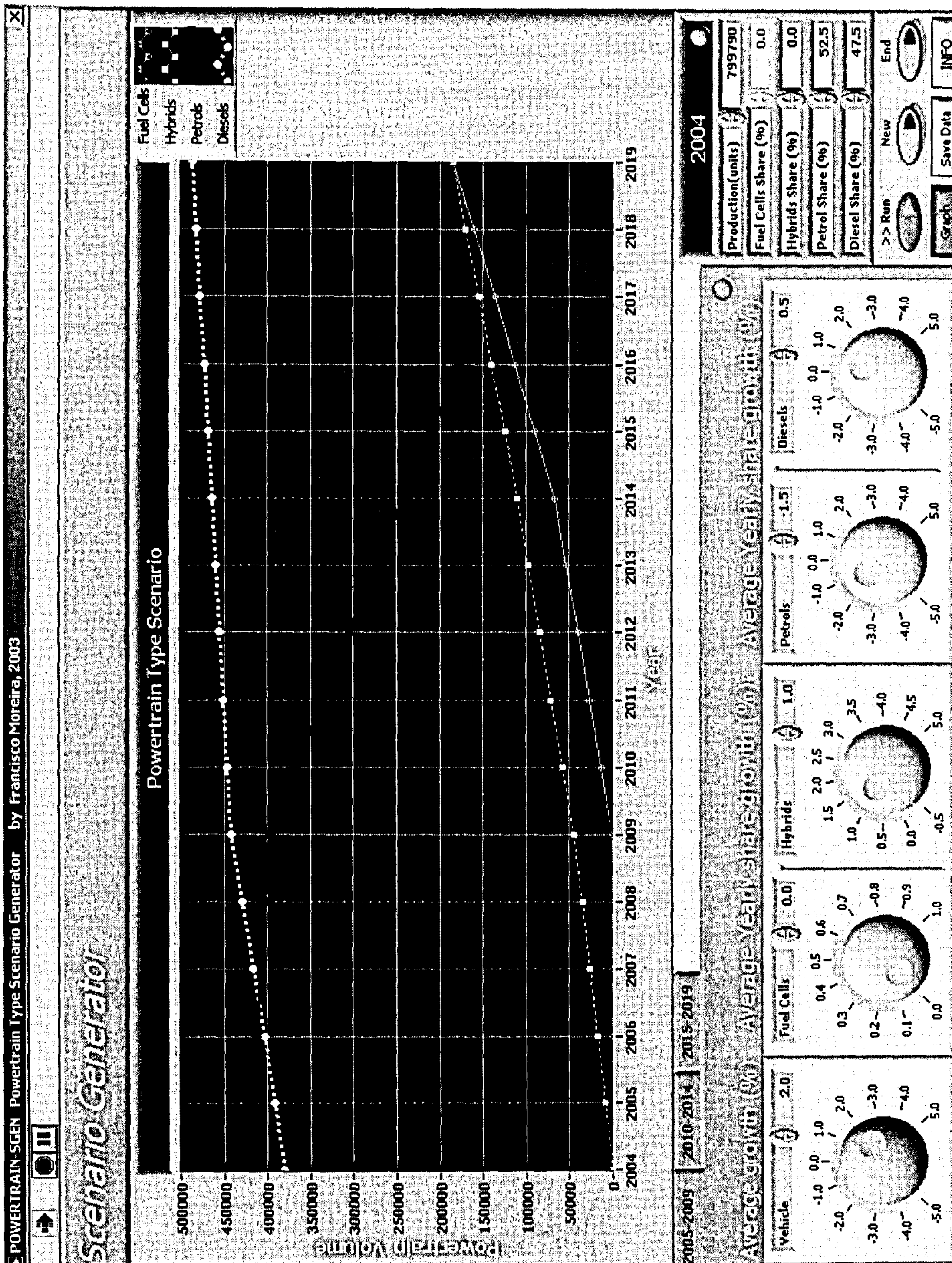


Figure 6.9 Powertrain-SGen Scenario 14 graphical representation.

Scenario 26

1. Vehicle production volume grows at average rates of 2%; 0%; and 1% in respective periods 2005-2009; 2010-2014; and 2015-2019.

2. **Diesel driven vehicles progressively gain market share relative to petrol driven vehicles (present trend).**

3. **Fuel cell driven vehicles gain significant market share following their market introduction around 2010.**

4. Hybrid vehicles fail to gain market share following their market introduction around 2005.

5. **Oil price increase is smooth (linear) in the period 2010-2014 but increases rapidly (possibly unpredictably) in the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**-4.0**	**0**	**4.0**	**0.0**	**Fast**

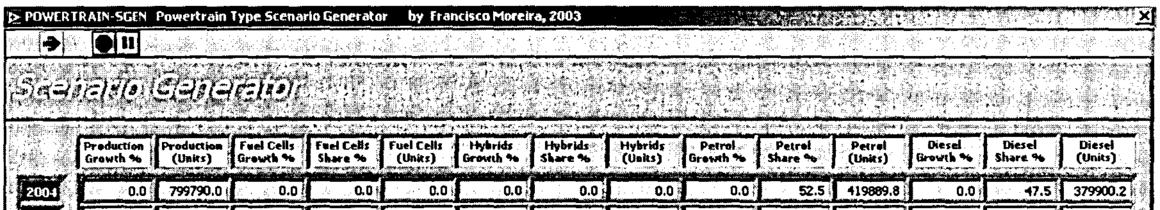


Figure 6.10 Powertrain-SGen Scenario 26 generation.

Following the successful introduction of fuel cell driven vehicles by around 2010 and very significant increases in crude oil prices from 2015 onwards it is expected that fuel cell technology will rapidly gain market share (since price of fuel is currently a main disadvantage of this technology, when compared to ICEs). Figure 6.11 also predicts that in such a scenario petrol vehicles demand will progressively and rapidly decline.

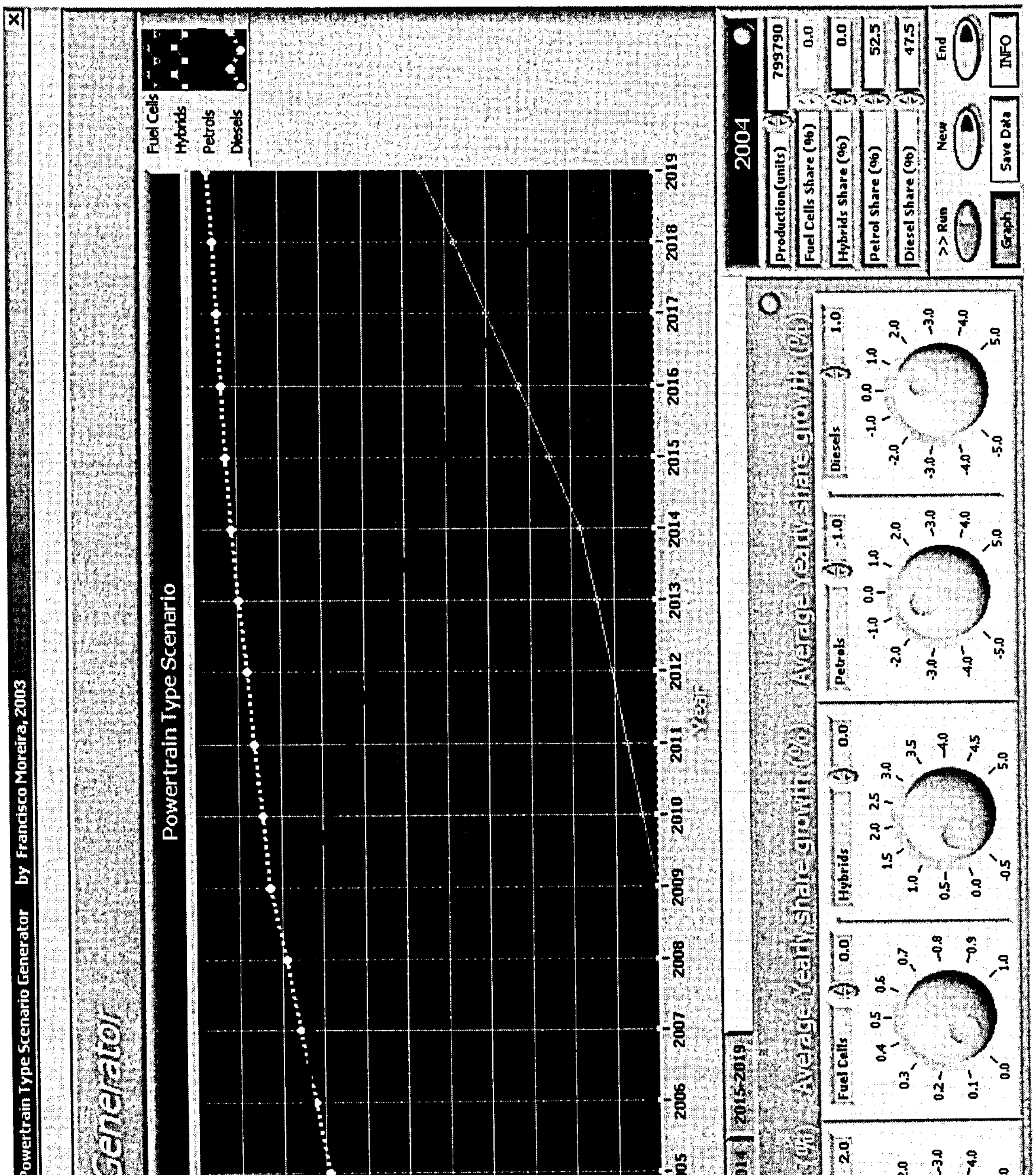


Figure 6.11 Powertrain-SGen Scenario 26 graphical representation.

By using the Powertrain-SGen tool created during this study, simulation modelling for each of the 36 scenarios generated predictions about yearly volume requirements for petrol, diesel, hybrid and fuel cell engines. The complete data set for these scenarios is presented in a spreadsheet format in **Appendix H.** The tool was implemented so that scenario predictions can be exported directly from the Powertrain-SGen tool to a Microsoft Excel file.

6.1.4 Adopted strategy to estimate the particular engine configuration proportions

The 36 future scenarios have resulted in estimated figures for the 4 propulsion systems types, namely: petrol engines, diesel engines, hybrid engines and fuel cells. As explained in section 6.1.1, engine plants using dedicated transfer lines normally require specific engine machining facilities for each engine configuration, such as I3 petrol engines, I3 diesel engines, I4 petrol engines, I4 diesel engines and so on. Therefore the information provided by the set of 36 scenarios does not provide enough detail to support eventual decision making regarding the adoption of a specific machining approach in engine plant investments.

In order to estimate the volumes required for each engine configuration, data is required regarding the respective share of each engine configuration for Audi branded vehicles. Audi annually publicly disseminates data about its global share of petrol and diesel powered vehicles. However, it does not release data regarding its production volumes for specific engine configurations. Therefore, base data was not available about its production volumes requirements for Audi vehicles, namely for 4-cylinder diesel, 4-cylinder petrol, V6 diesel, V6 petrol. However it was known that Audi did not produce 3-cylinder diesel engines during the period 2000 to 2003. Other engine configurations such as the V8 and the W12 were excluded from the study given that their required quantities were very low. Hence the present author devised a strategy to estimate the proportion of engine configurations used in Audi vehicle models line-up, where this strategy is explained in the following paragraphs.

Audi AG has 3 engine plants: Audi Hungaria Motor Kft; Cosworth Technology Limited; and Automobil Lamborghini S.p.A. Yearly production volumes at each of these plants is recorded in table 6.5.

Table 6.5 Audi engine plants production volumes. Source: Audi Facts and Figures 2003 (Audi-AG 2004)

Engine Plant	2002	2003
Audi Hungaria Motor Kft	1,280,067	1,334,985
Cosworth Technology Limited	3,979	6,541
Automobil Lamborghini S.p.A.	442	1,357

Cosworth Technology Limited (UK) produces high performance engines for Audi niche market models. This includes the 4.2 L V8 engine for the Audi RS 6 which is produced using low volume production methods (4,841 units sold in 2003).

Automobil Lamborghini S.p.A. produces high performance engines, including V10 and V12 engines, essentially for the Lamborghini car brand, which belongs to Audi AG group. In 2003 Automobil Lamborghini S.p.A. produced 442 engines.

Table 6.6 Engine configurations manufactured at Audi Hungaria Motor Kft in 2003 and shares.

Engines manufactured at AUDI Hungaria Motor Kft					
2003	I3	I4	V6	V8	Total
Engines	0	1,048,128	238,387	48,470	1,334,985
Percentage share	0.0%	78.5%	17.9%	3.6%	100%

Essentially it was observed that Audi Hungaria Motor Kft produces engines for all mass produced vehicles under the Audi brand. This engine plant produces a massive quantity of engines which actually exceeds Audi customer demands. The excess production volume is sold for use on other vehicles produced by the Volkswagen AG group, namely VW, Seat and Skoda. This engine plant does not produce the 3-cylinder diesel engines used in the Audi A2 model. Since Audi produced 27,323 units of the A2 model in 2003 (Audi-AG 2005), and assuming that the proportion of diesels in 2003 for the A2 model was also 46% (as presented in Table 6.2), it was estimated that in 2003 12,569 A2 diesel vehicles were produced.

Table 6.7 Audi A2 model production in the year 2003 (estimated values).

Engine Type	Percentage Share (2003)	Number of A2 units (2003)
Petrol	54%	14,754
Diesel	46%	12,569

Since the only diesel engines that are fitted into A2 vehicles are I3 engines, and since A2 is the only Audi model equipped with I3 engines, it can be deduced that the number of I3 diesel engines needed during 2003 was 12,569 engines, i.e. about 1.6% of the total number of engines incorporated into Audi cars in 2003.

By adjusting the proportions of engine configurations enumerated in table 6.6 (which did not consider I3 engines, since these engines were not produced at the Audi Hungaria Motor Kft), and applying them to the total number of engines required by Audi in 2003 the results presented in table 6.6 were calculated.

Table 6.8 AUDI engine configuration share requirements (estimation).

2003	I3	I4	V6	V8	Total
engines	12.569	589.396	134.053	27.256	763.273
%	1,647%	77,220%	17,563%	3,571%	100%

Therefore the estimated share of I3 engines for 2003 Audi models was about 1.6%. By following similar lines of reasoning the estimates made for I4 engine share, V6 engine share, and V8 engines share were 77.2%, 17.6% and 3.6% respectively.

By applying the 2003 Audi petrol/diesel share (as presented in Table 6.2) to Audi engine configurations requirements (presented in Table 6.8) the respective figures for particular engine configurations (engine type *vs.* engine model) were calculated. The resultant estimated percentage shares of engine configurations are shown in Table 6.9.

Table 6.9 AUDI engine types and configurations share requirements (estimation).

	Petrol			Diesel			Petrol and Diesel	
2003	I3	I4	V6	I3	I4	V6	Others (V8, ...)	Total
engines	0	319.191	72.597	12.569	270.205	61.456	27.256	763.273
%	0,0%	41,8%	9,5%	1,6%	35,4%	8,1%	3,6%	100%

From previous Audi historical data and estimates it was observed, figure 6.10, that I4 petrol engines represent 81.47% of the petrol engines total (excluding V8 petrol and other petrol engine configurations) and V6 petrol engines represent 18.53%. I3 diesel engines represent 3.65% of the diesel engines total (excluding V8 diesel and other diesel engine configurations), I4 diesel engines represent 78.50%, and V6 diesel engines represent 17.85%.

Table 6.10 a) I3, I4 and V6 shares of petrol engines; b) I3, I4 and V6 shares of diesel engines (estimations).

Petrol Engines				
2003	I3	I4	V6	Total
engines	0	319.191	72.597	391.788
% (Petrol)	0.0%	81.47%	18.53%	100%

a)

Diesel Engines				
2003	I3	I4	V6	Total
engines	12.569	270.205	61.456	344.229
% (Diesel)	3.65%	78.50%	17.85%	100%

b)

Subsequently, the estimated petrol engine configurations share and the estimated diesel engine configurations share are automatically multiplied by the yearly figures (of the respective engine type) from each of the 36 scenarios (found in Appendix H) so that specific quantities for a particular engine type and configuration is obtained. The respective quantities, of the complete data set for all scenarios, of I3, I4 and V6 engines, for both the diesel and the petrol engine configurations, based on share estimations presented in table 6.10 is presented in **Appendix I.**

As an example from Scenario 1, the requirements for petrol engines in 2005 is 428,288 engines (see Scenario 1 of Appendix H). By multiplying 428,288 by the respective shares[27] of petrol engines configurations presented in Table 6.10a), results in requirements for zero I3 petrol engines; 348,927 I4 petrol engines; and 79,360 V6 petrol engines (see Scenario 1 of Appendix I). In a similar manner, the requirements for diesel engines in 2005 is 387,498 engines (see Scenario 1 of Appendix H). By multiplying 387,498 by the respective shares of diesel engines configurations presented in Table 6.10b), results in requirements for 14,149 I3 diesel engines; 304,169 I4 diesel engines; and 69,180 V6 diesel engines (see Scenario 1 of Appendix I).

[27] - The exact share values used to make the calculations use more than 4 decimal points, while the share values presented in table 6.10 were rounded to 4 decimal points. Therefore if the reader attempts to make calculations of the illustrated examples he will get slightly different results than the ones found by the author.

6.2 SCENARIOS CONSIDERATIONS

When building future scenarios key assumptions have to be made bearing in mind identifiable "likely givens" and "important trends" (Hodgson et al. 1998). Chapter 2 has identified trends impacting the engine manufacturing industry. The 36 scenarios characterise key impacts of those trends, covering a range of alternative options over a suitable strategic planning timeframe. It follows however that the 36 cases defined are hypothetical only, even though care has been taken to ensure that they 'envelop' the total range of engine demand shares that are likely, despite the industry's volatility. The key assumptions made when framing the 36 cases are considered to be as follows.

1. That shares of engine configurations are essentially fixed during each 5 year sub-period. In reality it is unlikely that this assumption will prove to be correct. For example it is the author's belief that, given a substantial increase in fuel prices (such as from 2010 onwards, or even at some earlier date) the likely impacts would be as follows:
   a) In Europe, larger volumes of smaller engine configurations (e.g. I3 engines) would be in demand. In the US this might be manifest in a growing share for I4 engines (whereas V6 engines are currently dominant);
   b) Diesel engines (equipped with particulate traps) would likely gain an increased market share. Or alternatively, hybrids would gain a significantly increased market share;
   c) Intensive research in fuel cells and into hydrogen fuels might generate new competitive engine types in shorter than expected timeframes.

2. The share of diesel and petrol engines was assumed to be similar for each engine configuration (i.e. I3, I4 and V6 engines). The Audi shares of I3, I4 and V6 engines used in the study were derived from respective shares produced by a major Audi engine plant. The author did not find any study in literature which co-related relative demands for petrol and diesel vehicles with engine capacity. The author believes however that the choice of fuel type is not co-related with the engine capacity; he admits however that this belief could prove wrong in the future.

3. From a universe of possible engine manufacturing strategies that companies might adopt, any rational justification for one approach relative to another, given a set of future hypothetical scenarios, has previously been made mainly from the viewpoint of an independent engine manufacturing businesses. Only recently has there been a partial exploitation of mixed strategies, such as where a company buys engines from competitors, and designs and makes engines in cooperation with competitors, thereby designing full engine families to be manufactured using similar machining facilities at appropriate geographical locations, etc. Such strategies are beginning to emerge and be adopted in the automotive business. The scenarios do not directly take into account causal effects arising from choice of engine manufacturing strategy.

Most engine manufacturers have highly restricted policies regarding their dissemination of data on engines. To-date each automotive manufacturing business has been considered to be largely autonomous. Lack of data on engine production in specific manufacturing businesses has led the present author to spend much time on searching for relevant data from the literature. As a consequence in some respects it has proven impossible to create a robust case study, since in general the data needed is poorly disseminated, generally scarce and typically only partially complete. After selecting a company which provided the best available 'portfolio' of data, it was still necessary to make assumptions about that data to enable scenario building. Probably many of these difficulties could be overcome if autonomous automotive companies chose to use the tools and methodology conceived by this study, since access to internal data should constitute much less of a problem.

In spite of the underlying assumptions made and limited access to relevant case data, the author believes that the 36 scenarios collectively envelop valuable predictions of automotive industry dynamics over the next 15 years. Hence it is believed that collectively the scenarios built can help predict risks associated with loss (or gain) of engine type shares. More complete understandings of market, environment and autonomous business specific factors would increase the certainty with which most likely (or prevalent) scenarios could be selected. However it is probable that this would effect a refinement rather than a major overhaul to the way in which decisions are made about strategic investments in machining technologies.

6.3 SCENARIOS ANALYSIS

A detailed analysis of the data presented in Appendix I shows that in the first phase of the scenarios lifespan, i.e. the period 2005-2009, there is a mixed change in demands for I4 petrol engines. By the second phase however, i.e. the period 2010-2014, higher rates of change are predicted because of forecasted increase in fuel prices and the introduction of fuel cell powered vehicles. The cumulative loss of share for petrol engines can be expected to increase in general by the end of the third phase (2015-2019). These trends are pictured graphically in Figure 6.12.

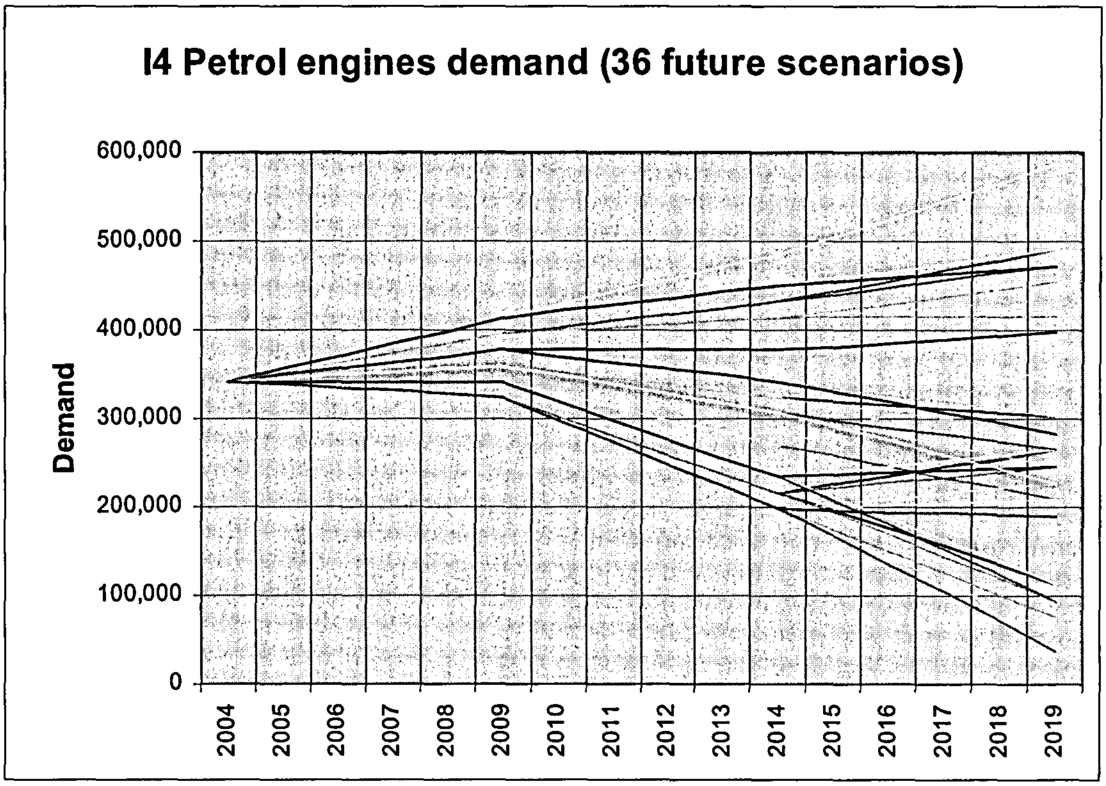


Figure 6.12 I4 petrol engines demand (36 future scenarios).

An equivalent pattern of engine demand was predicted for the case of V6 petrol engines for each of the 36 scenarios. Here the initial volume assumed totalled around 78 thousand engines.

If a DTL approach is selected to realise such an engine demand pattern the resulting average excess capacity is predicted to be 36%. This represents an average (for the 36 scenarios) excess capacity of 153,532 I4 petrol engines per year and 34,919 V6 petrol engines per year. Figure 6.13 illustrates the predicted average yearly excess capacity for I4 petrol engines.

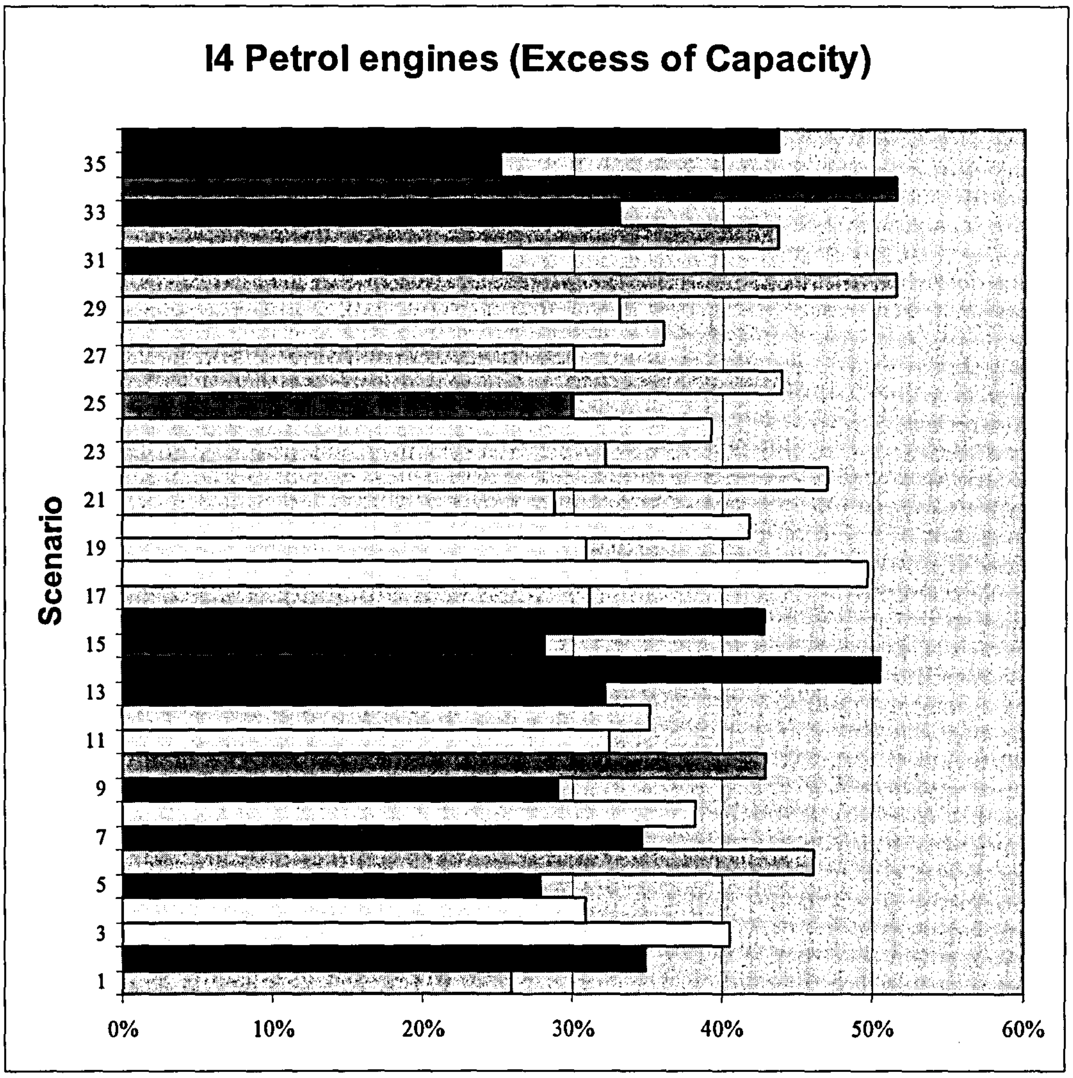


Figure 6.13 I4 petrol engines (excess of capacity using a DTL approach).

With respect to I4 diesel engines, it is likely that the required volumes will grow slightly in most of the scenarios in the first phase of the scenarios lifespan, i.e. the period 2005-2009. This prediction is driven by present trends for a higher share of diesel vehicles in Europe. Overall however no significant change is predicted in the required volumes of I4 diesel engines. By the second phase, i.e. the period 2010-2014, there could be mixed variations. By the third phase (2015-2019), the trend predicted for the greater number of scenarios is one of decline in demand for diesel engines. These trends are pictured graphically in Figure 6.14.

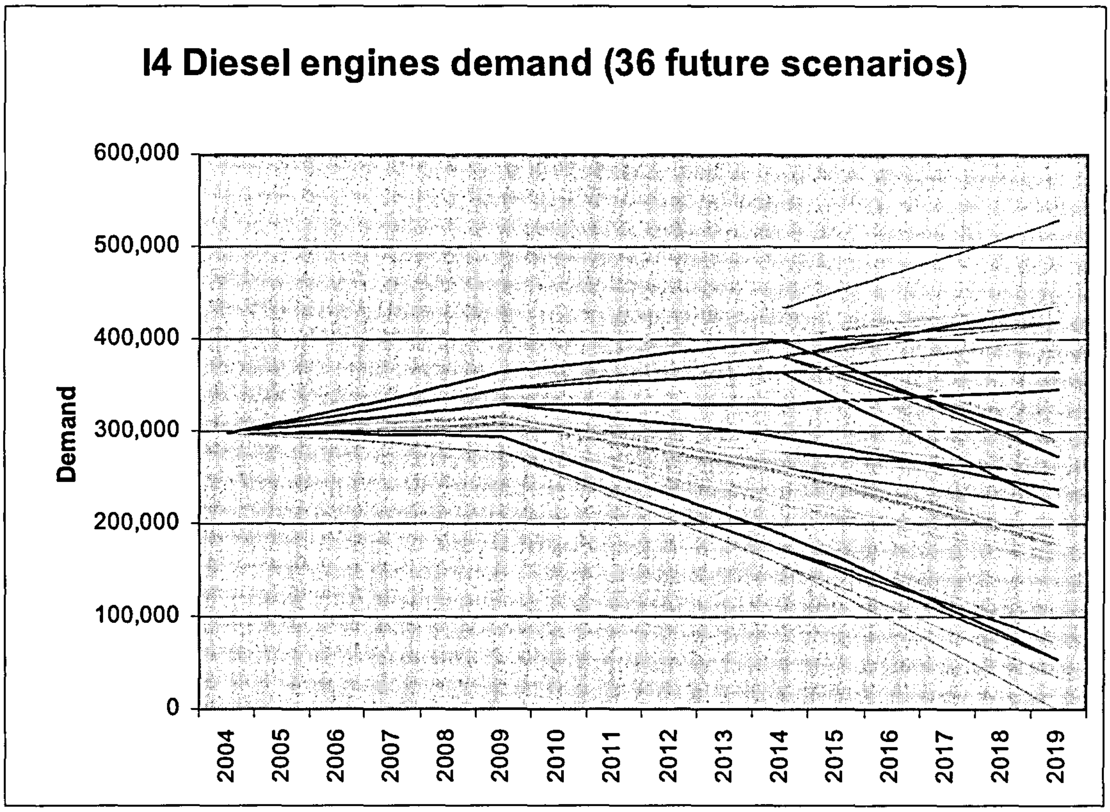


Figure 6.14 I4 diesel engines demand (36 future scenarios).

Equivalent patterns of predicted engine demand have also been obtained for V6 diesel engines for each of the 36 scenarios. Here an initial volume of around 70 thousand engines is assumed.

If a DTL approach is selected to realise the engine demand patterns predicted the resulting average excess capacity will be about 35%. This represents an average (for the 36 scenarios) excess capacity of 139,921 I4 diesel engines per year and 31,824 V6 diesel engines per year. Figure 6.15 illustrates the average yearly excess capacity for I4 diesel engines.

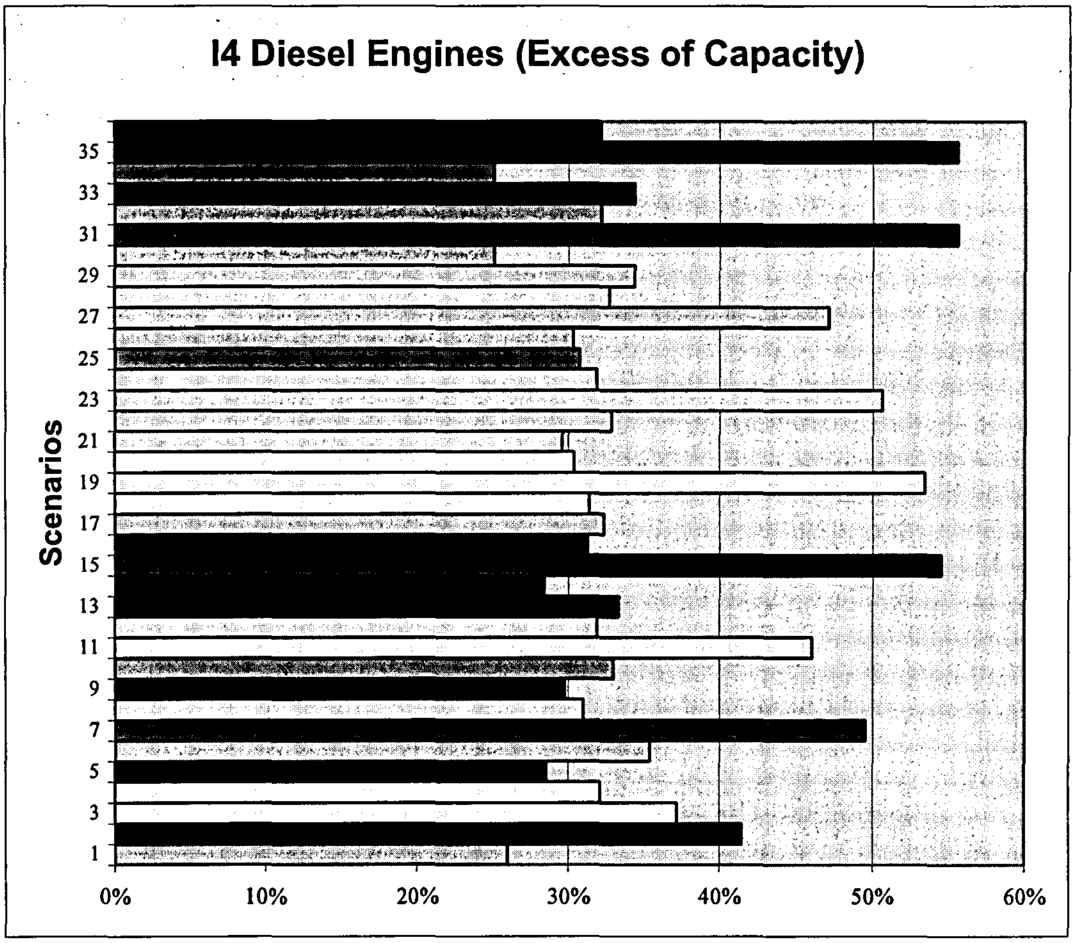


Figure 6.15 I4 diesel engines (excess of capacity using a DTL approach).

Three cylinder petrol engines are not used in AUDI cars. Therefore this engine configuration was excluded from the study. Audi currently use 3-cylinder diesel engines (namely 1.2 and 1.4 litres TDI diesel engines) in their A2 cars, but in very low yearly volumes. This only proves to be economic because Audi outsource the production of these engine models. Since the author had no access to VW Group complementary data (relating the production systems where I3 diesel engines are manufactured) I3 diesel engines were also excluded from the study.

6.4 CONCLUSIONS AND EXTRAPOLATION OF THE RESULTS

The Powertrain-SGen tool has been created and used to predict future propulsion systems type and volume shares with reference to 36 alternative scenarios. Prime reference has been made to historical engine configuration and model shares of a particular automotive company. However this futures prediction approach was designed to be industry rather than company specific. The exercise provides new insights into automotive industry dynamics and thereby into agility requirements for future engine production plants.

As expected in the third scenario period (i.e. 2015-2019) significantly increased uncertainty is predicted within the engine manufacturing business. This derives primarily from projected increases in fuel prices and an increased likelihood that fuel cell powered vehicles will gain a significant increase in market share by 2015.

The study results were generated in respect of specific Audi engine demand data. Therefore direct extrapolation of findings to other companies may be ill advised. Rather it is recommended that each company should itself be subject to detailed analysis and extrapolation of specific engine demands, and should bear in mind their previous predicted trends in their total and specific vehicle production volumes. This should provide baseline settings to enable the building and exercising of scenarios that inform the selection of manufacturing paradigms and engine machining approaches. Therefore, the reader should not presume that the case study observations and conclusions will be directly applicable to other engine manufacturing plants. However they may prove indicative. Whatever the prediction methodology proposed and tested during this study is likely to be reusable by individual (or partnerships of) companies and would likely valuably inform their strategic futures decision making.

Chapter 7 compares investment patterns associated with DTL and Q'@gile systems and proposes a method to compare them from an economic point of view.

CHAPTER 7

INVESTMENT MODEL

7.1 INVESTMENT REQUIREMENTS

In order to contrast and compare investment requirements for DTL and Q'@gile alternatives an investment model was developed. The investment model assumes an equal lifetime for both systems, i.e. a 15-year period. This choice of system lifespan was justified in Section 6.1.1. The cost engineering method used to develop the comparison is the **Net Present Value** method (NPV). The NPV method simply reduces all the cash flows associated with a given investment to a common instant of time. Any instant of time can be chosen for the comparison, but the present time is normally preferred (Humphreys 1991).

The investment pattern required for DTL systems is inherently different from that required for Q'@gile systems. Hence a prime investment differentiator comes from the different time-based cost patterns affecting these systems. By reducing all the cash flows of a DTL based system (initial cost of the DTL system, retooling costs and salvage value of the DTL system at the end of the 15-year period) to present time and reducing all the cash flows of a Q'@gile based system (initial cost of a number of cells and gantry robots, cash flows derived from installing new cells or selling system cells and salvage value of the Q'@gile system at the end of the 15-year period) to present time, it is possible to decide which system offers the most economical solution. It is assumed that the systems have similar performance in terms of actual production of the engine parts, i.e. that the quality, variety and production volumes are equivalent. Therefore comparison will be made on the basis of present values of the cash flows for equal durations, which constitutes a fair comparison (Humphreys 1991).

To bring future values to present time formula 7.1 is used.

$$\textbf{\textit{Present value}} = (\textbf{\textit{future value}}) \times (\textbf{\textit{present-value factor}}) \tag{7.1}$$

The ***present-value factor*** ($F_{SP,\,i,\,n}$) is given by:

$$F_{SP,\,i,\,n} = (1+i)^{-n} \tag{7.2}$$

Where '**i**' is the internal rate of return and '**n**' is the number of years into the future of the '**future value**' formula term.

For simplification and practicality reasons, the following assumptions will be made:

1. the yearly maintenance costs affecting DTL and Q'@gile machinery will be similar. Therefore for comparison purposes yearly maintenance costs will be ignored.

2. the initial cost of a Q'@gile cell remains unchanged for the full time period (i.e the effect of changing inflation rates [presently at 2%, in the UK] will be considered to be negligible or be counterbalanced by a proportional fall in the cost of machining systems).

The internal rate of return adopted in this study is 6.0%, based on recent UK national statistics which put the net return rate for manufacturing companies at 6.0% in the 1st Quarter of 2005 (National_Statistics 2005). For reference purposes the current interest rate in the UK is 4.5% (Bank_of_England 2005).

7.1.1 DTL system investment requirement

The BMW Hams Hall engine machining transfer lines were reported to have required a capital investment of approximately £120 million. This expenditure was apportioned as follows: £30M for the engine block DTL, £50M for the cylinder head DTL and £40M for the Crankshaft DTL (BMW 2003). The installed plant started production in 2001. This study has focused on engine block machining, hence the following analysis will retain that focus. The installed BMW block line only produces 4-cylinder petrol engine blocks with a 30 seconds cycle time and an installed capacity of circa 450,000 engines per year.

In contrast the total machine tool investment made by Ford in their Sigma cylinder head line (which machines I4 petrol Zetec-SE engines) at their Bridgend engine plant (Wales) in 1996 was circa £40 Million (Harrison 1996). At the Dagenham engine plant a recent installation of 3 production systems for machining the same three prime parts of the Lyon V6 diesel engines required a total initial investment of USD 180 Million (Alison Cox, private communication, 2003).

Not surprisingly the availability of this kind of investment information is normally restricted. Also specific details related to these investments are quite limited and therefore some care needs to be exercised with respect to drawing general conclusions. Thus the investment information quoted for the BMW and Ford cases is considered to be relevant and representative of current DTL initial (capital) investments requirements. But the data was not considered sufficiently reliable to accurately characterise a particular DTL investment (in say a specific I4 petrol engine block line) so as to provide a basis for comparison with an equivalent[28] Q'@gile system. Therefore the present author, with advice from field experts, devised an alternative basis for reasoning about DTL and equivalent Q'@gile investments as follows.

(1) From discussions with field experts (Alison Cox, private communication, 2003) and via associated access to key reports (Harrison 1996; Price 2003) it was apparent that a general purpose CNC solution (such as provided by an 'Agile System') would require an initial expenditure which is slightly higher than that required for an equivalent DTL solution.

(2) Since Q'@gile systems proposed in this study embed very similar flexible technology to that used in Agile Systems (but would deploy distinctively different system dependency and production strategies) it was estimated that similar levels of

initial investment in equivalent capacity Q'@gile cells would also be required to that needed for agile machining systems. Therefore it was assumed that any initial investment in a Q'@gile system would also be slightly higher than that of a DTL with equivalent machining capacity.

(3) That machining reinvestments required, in respect of major and minor DTL retoolings, would be some defined percentage of the initial cost of the DTL. Assume that by **year 7** the DTL system requires a major retooling. Assume also that to achieve this retooling a further investment of about **30%** of the initial investment needs to be made around year 7. A major retooling normally involves the replacement of several DTL stations. The actual additional investment needed can however vary significantly from case to case. Field expert advice stated that this can vary from about 10% of the initial investment to 100%, where full replacement of the DTL system is needed. Assume further that two minor retoolings will be required in **year 4** and **year 11** respectively and that a further **8%** of the initial investment will be required for each of these minor retoolings. Both major and minor retoolings investments stated here concern net costs, and assume adjustment from any eventual sale of old stations to offset the cost of acquiring new ones.

Of course in general, at the time that an initial decision is made to invest in a wholly new DTL or Q'@gile machining system, it will not be possible to accurately predict future needs for major or minor retooling. Hence the assumptions outlined above are only indicative of historical patterns of change needed, based on information provided by field experts. It is noted however that DTL retooling may be required more frequently than is currently practicable, because of the significant engineering effort required and prohibitive investment cost in retooling or replacing DTLs. When this is the case evidently the said DTL will operate sub-optimally.

[28] The author definition of a DTL-equivalent Q'@gile system is a system which enables the yearly production of the same number of specific engine parts.

From point (1) and (2) above the author defined 3 levels of investments for DTL vs. Q'@gile systems:

Case 1. The cost of a Q'@gile system is **25% higher** than the cost of an equivalent DTL system (assuming that all the required cells and gantry robots required to achieve DTL-equivalent production capacity are installed at the beginning of the study period). E.g. If a DTL with production capacity of 400,000 engines per year costs initially USD 20,000,000 the equivalent Q'@gile system with the same production capacity from day one costs (100%+25%) x USD 20,000,000 = USD 25,000,000.

Case 2. The cost of a Q'@gile system is **50% higher** than the cost of an equivalent DTL system (assuming that all the required cells and gantry robots required to achieve DTL-equivalent production capacity are installed at the beginning of the study period). E.g. If a DTL with production capacity of 400,000 engines per year costs initially USD 20,000,000 the equivalent Q'@gile system with the same production capacity from day one costs (100%+50%) x USD 20,000,000 = USD 30,000,000.

Case 3. The cost of a Q'@gile system is **75% higher** than the cost of an equivalent DTL system (assuming that all the required cells and gantry robots required to achieve DTL-equivalent production capacity are installed at the beginning of the study period). E.g. If a DTL with production capacity of 400,000 engines per year costs initially USD 20,000,000 the equivalent Q'@gile system with the same production capacity from day one costs (100%+75%) x USD 20,000,000 = USD 35,000,000.

The DTL based approach has a fixed production capacity grounded in foreseeable future demand patterns for specific engine configurations. Figure 7.1 illustrates such an example of an engine demand pattern (in the case of scenario 1, the pattern of engine demand grows progressively from 348,927 engines by 2005 to 396,956 engines by 2019) while production capacity is fixed at 441,812 engines per year, which leads to a pattern of excess of capacity.

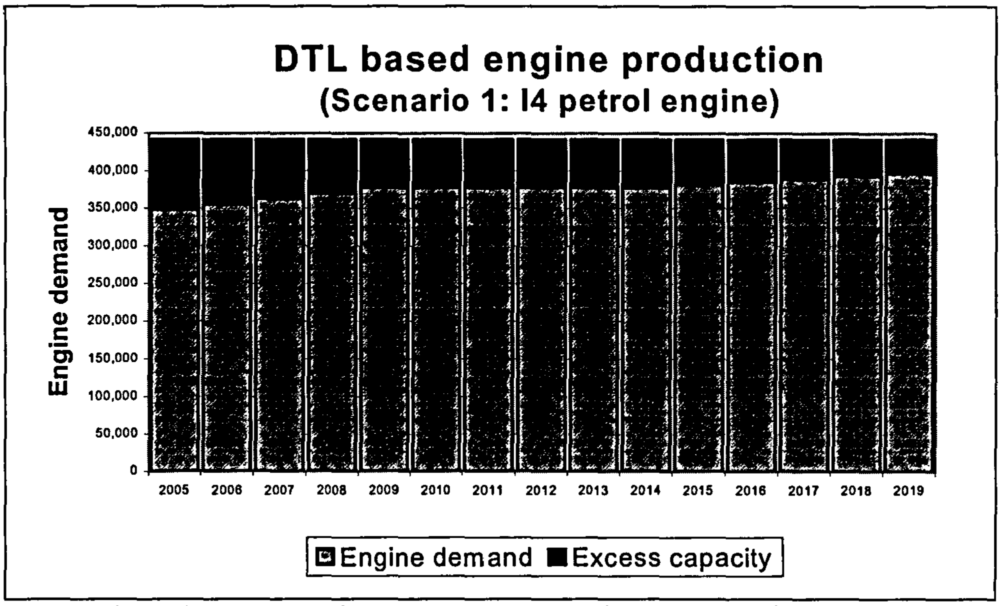


Figure 7.1 Demand patterns *vs.* excess capacity using a DTL based approach.

The Q'@gile based approach has a production capacity which fluctuates with short term future demand patterns of specific engine configurations. Figure 7.2 illustrates such a fluctuation using the same engine demand pattern. Here the production capacity varies from 356,928 engines in 2005 (32 cells), to 368,082 in 2007 (33 cells), 379,236 in 2008 (34 cells), 390,390 in 2015 (35 cells) and 401,544 engines in 2018 (36 cells). The resulting excess capacity is obviously much lower than that for the DTL case.

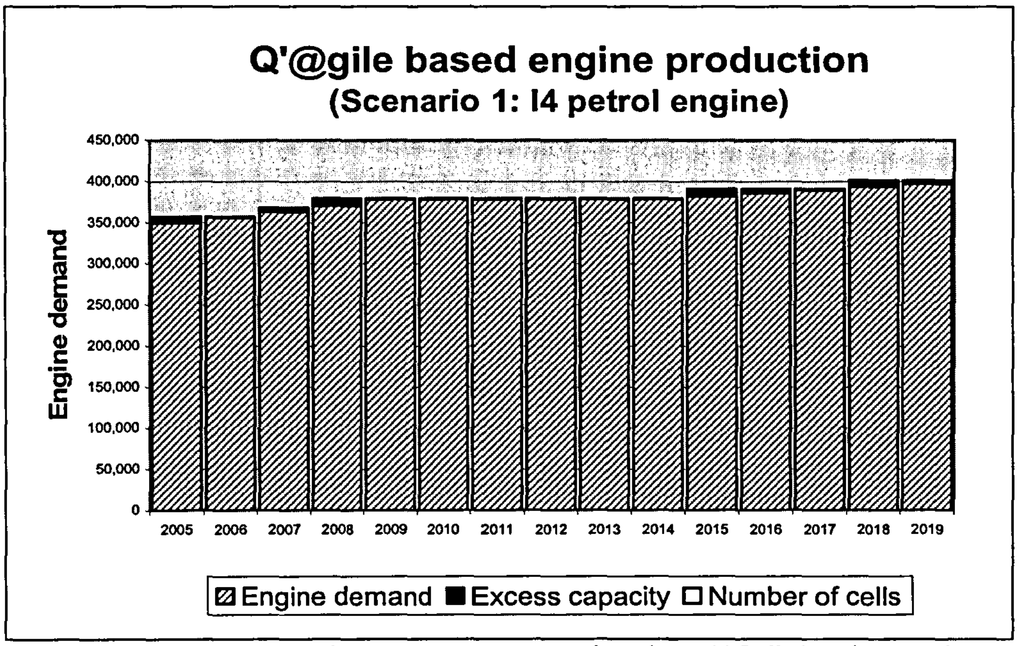


Figure 7.2 Demand patterns *vs.* excess capacity using a Q'@gile based approach.

Salvage value of systems was calculated using the geometric depreciation method (Bank_of_England 2001) with an assumed yearly depreciation rate of 13% (plants and machinery depreciation rate) grounded in a study from the Bank of England dated 2001. Table 7.1 show depreciation rates for several assets in the UK.

Table 7.1 Depreciation rates in UK for several assets. Source: Bank of England (Bank_of_England 2001) pp. 300.

Asset	Depreciation rate (per cent per year)
Buildings	2.5%
Plant and machinery	**13.0%**
Vehicles	25.0%
Intangibles	33.0%
Inventories	0.0%

The depreciation of an asset is geometric when the asset value declines at a constant proportional rate as it ages. For example, suppose that a new DTL costing £20,000,000 has been installed in an engine plant on the 1st of January 2005 and that depreciation of this DTL is 13% yearly. By early 2006 (1-year-old asset) the market value of such a DTL will be £20,000,000 x (100% - 13%) which results in a future value of £17,400,000. By early 2007 (2-year-old asset) the market value of the DTL will be £17,400,000 x (100% - 13%), which is a £15,138,000 future value, and so on. Following the same reasoning, a 15-year-old DTL will be worth £2,476,389.

7.1.2 Estimation of required investments in Q'@gile based systems

Since Q'@gile systems are currently a theoretical approach to main engine parts machining, necessarily the cost of Q'@gile cell main elements have to be estimated. Such an estimate follows, where estimated investments needed for the prime elements of Q'@gile systems are separated out:

(A) *A high speed general purpose CNC machining centre* with a minimum of 3 axes (XYZ), a tool magazine and an automatic tool changing device.

An unitary cost estimate of **USD 500,000** is used for this element. This estimate is based on the cost of similar machine elements used in 'agile' machining systems (Price 2003a).

(B) A working table device with several axes.

A unitary cost estimate of **20%** of the cost of unit (A) will be used for this element: which equates to **USD 100,000.** No such system element exists currently but the estimate is made based upon quoted costs of similar proprietary automation.

(C) Transport automation (e.g. a gantry robot and a roller conveyor).

Gantry robot - an unitary cost estimate of **USD 500,000** (Price 2003a) will be used for the robot. This equates to the cost of a similar type of robot used in the 'Agile' systems installed at the Ford Cleveland engine plant. The gantry robot will be used to serve several cells (therefore this investment cost should be split by a number of cells). Since Cross-Huller Agile systems can support up to 6 CNC machining centres per cell (each cell having it's own gantry robot) it is envisaged that a single robot will have the capability and capacity to serve at least 8 Q'@gile cells; since the cycle time of Q'@gile cells is expected to be superior to that of individual machines of Agile cells.

Roller conveyor - An unitary cost estimate of **10%** of the cost of unit (A) will be used; which equates to **USD 50,000**. Such a roller conveyor element is not yet commercially available but the cost estimate is made with reference to similar proprietary conveyor systems.

(D) Tools

A complete set of tools for each Q'@gile cell is estimated as having a cost around **30%** of the cost of unit (A). This equates to **USD 150,000** and is based upon the cost of tooling for similar automated systems.

The total investment needed for a single Q'@gile cell is therefore estimated as being: 500,000 + 100,000 + 50,000 + 150,000 = **USD 800,000**. In addition an investment of **USD 500,000** will be needed for access to a gantry robot shared by 8 other cells. At an exchange rate, dated 26th of July 2005, of 1 GBP to USD 1.7418, this equates to **£ 459,295** per cell plus **£ 287,059** per gantry robot.

The salvage value of each single cell system was also calculated by using the geometric depreciation method with a yearly depreciation rate of 13%. Since new Q'@gile cells may be installed regularly in the system (e.g. on a yearly basis) and can regularly be removed from installed systems, it was assumed that when a Q'@gile cell is sold the FIFO (First In First Out) method would be used, i.e. the oldest machines are sold first. Such an assumption is needed and is relevant for the calculation of the market value of the machines, since for instance a 3-year old machine has a completely different market value to that say of a 10-year old machine. This also influences the total value of the system at the end of the 15-year period.

The initial investment in DTL systems and the DTL-equivalent Q'@gile system for machining I4-Petrol engine blocks was calculated using the following algorithm:

1. For scenario 1, search for the maximum yearly demand over the 15-year period.

2. Multiply the maximum found by (100% + 11.3%) to calculate the DTL production capacity. This percentage (11.3%) was estimated in section 5.3

3. Multiply the maximum found by (100% + 1.2%) to calculate the Q'@gile production capacity equivalent to the DTL capacity. This percentage (1.2%) was also estimated in section 5.3

4. Divide the calculated Q'@gile capacity by that of the capacity of a single Q'@gile cell (i.e. 11,289 engines per year) to get the number of cells required for similar capacity. Round the number up.

5. Divide the number of cells required by 8 (each gantry robots serves up to 8 cells) to get the total number of gantry robots required. Round the number up.

6. Multiply the number of cells by the unitary cost of a cell. Multiply the number of gantry robots by the unitary cost of a gantry robot. Add the figures up. This yields the total cost of the Q'@gile system if all cells are installed before production starts at the beginning of year 2005.

7. Calculate the DTL initial investment (CASE 1) by using formula 7.3.

Q'@gile investment = DTL investment x (100% + 25%) ⇔

$$\Leftrightarrow \textbf{DTL Investment} = \textbf{Q'@gile investment x } (100\% + 25\%)^{-1} \quad (7.3)$$

8. Calculate the DTL initial investment (CASE 2) by using formula 7.4.

$$\textbf{DTL Investment} = \textbf{Q'@gile investment x } (100\% + 50\%)^{-1} \quad (7.4)$$

9. Calculate the DTL initial investment (CASE 3) by using formula 7.5.

$$\textbf{DTL Investment} = \textbf{Q'@gile investment x } (100\% + 75\%)^{-1} \quad (7.5)$$

10. Repeat point 1 above for scenarios 2 to 36.

Table 7.2 tabulates the results from the calculations performed over each one of the 36 scenarios using the above algorithm for I4-petrol engines. As an example, scenario 1 has a maximum yearly demand of 396,956 engines (required in year 2019) during the 15 year period. The DTL production capacity is 396,956 x (100% + 11.3%) = 441,812. This is the effective production capacity that must be installed to satisfy the anticipated engine demand volumes. The Q'@gile production capacity is 396,956 x (100% + 1.2%) = 401,719 engines per year. This is the DTL-equivalent production capacity. The number of cells required for a Q'@gile system to satisfy the demand is 401,719 / 11,289 = 36 cells. The number of required robots is 36 / 8 = 5 robots. The cost of 36 cells is 36 x USD 800,000 = USD 28,800,000. The cost of 5 gantry robots is 5 x USD 500,000 = USD 2,500,000. This adds up to USD 31,300,000. This is the investment in a Q'@gile system for DTL-equivalent capacity. CASE 1 defines that the **DTL Investment = Q'@gile investment x (100% + 25%)$^{-1}$**, therefore $DTL_{(Case\ 1)}$ = USD 31,300,000 x (125%)$^{-1}$ = USD 25,040,000. CASE 2 defines that the **DTL Investment = Q'@gile investment x (100% + 50%)$^{-1}$**, therefore $DTL_{(Case\ 2)}$ = USD 31,300,000 x (150%)$^{-1}$ = USD 20,866,667. CASE 3 defines that the **DTL Investment = Q'@gile investment x (100% + 75%)$^{-1}$**, therefore $DTL_{(Case\ 3)}$ = USD 31,300,000 x (175%)$^{-1}$ = USD 17,885,714.

Table 7.2 Estimated initial investment requirements for I4-Petrol DTL based systems and "equivalent" investments in Q'@gile based systems.

Scenario	Maximum Demand	Required DTL Capacity	Required Q'@gile Cells	Required Gantry Robots	Q'@gile Total Investment	DTL initial Investment (CASE 3)	DTL initial Investment (CASE 2)	DTL initial Investment (CASE 1)
1	396,956	441,812	36	5	31,300,000	17,885,714	20,866,667	25,040,000
2	342,348	381,033	31	4	26,800,000	15,314,286	17,866,667	21,440,000
3	585,983	652,199	53	7	45,900,000	26,228,571	30,600,000	36,720,000
4	359,151	399,735	33	5	28,900,000	16,514,286	19,266,667	23,120,000
5	359,705	400,352	33	5	28,900,000	16,514,286	19,266,667	23,120,000
6	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
7	491,469	547,005	45	6	39,000,000	22,285,714	26,000,000	31,200,000
8	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
9	377,690	420,369	34	5	29,700,000	16,971,429	19,800,000	23,760,000
10	342,348	381,033	31	4	26,800,000	15,314,286	17,866,667	21,440,000
11	491,469	547,005	45	6	39,000,000	22,285,714	26,000,000	31,200,000
12	342,348	381,033	31	4	26,800,000	15,314,286	17,866,667	21,440,000
13	359,705	400,352	33	5	28,900,000	16,514,286	19,266,667	23,120,000
14	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
15	434,761	483,889	39	5	33,700,000	19,257,143	22,466,667	26,960,000
16	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
17	359,705	400,352	33	5	28,900,000	16,514,286	19,266,667	23,120,000
18	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
19	453,664	504,928	41	6	35,800,000	20,457,143	23,866,667	28,640,000
20	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
21	359,705	400,352	33	5	28,900,000	16,514,286	19,266,667	23,120,000
22	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
23	472,567	525,967	43	6	37,400,000	21,371,429	24,933,333	29,920,000
24	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
25	377,690	420,369	34	5	29,700,000	16,971,429	19,800,000	23,760,000
26	342,348	381,033	31	4	26,800,000	15,314,286	17,866,667	21,440,000
27	472,567	525,967	43	6	37,400,000	21,371,429	24,933,333	29,920,000
28	342,348	381,033	31	4	26,800,000	15,314,286	17,866,667	21,440,000
29	359,705	400,352	33	5	28,900,000	16,514,286	19,266,667	23,120,000
30	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
31	415,859	462,851	38	5	32,900,000	18,800,000	21,933,333	26,320,000
32	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
33	359,705	400,352	33	5	28,900,000	16,514,286	19,266,667	23,120,000
34	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000
35	415,859	462,851	38	5	32,900,000	18,800,000	21,933,333	26,320,000
36	342,086	380,742	31	4	26,800,000	15,314,286	17,866,667	21,440,000

The remaining calculations for initial investment requirements for I4-Diesel DTL Based systems, V6-Petrol DTL Based systems, V6-Diesel DTL Based systems and respective "equivalent" investments in Q'@gile based systems are tabulated in Tables J.2, J.3 and J.4 of Appendix J.

7.2 PATTERNS OF INVESTMENT

7.2.1 DTL based system

Based on assumptions outlined in section 7.1.1, the time diagram related to investment in a DTL system with a production capacity of 441,812 engines per year is represented by Figures 7.3, 7.4 and 7.5. The time diagrams presented are typical in the cost engineering field. Above the time line are the positive cash flows. Below the time line are the negative cash flows. In the present study the negative cash flows will be the initial investment and needed reinvestments in minor and major retoolings. The positive cash flow will be the salvage value of the system at the end of the study period. The specific cash flows are sourced from the investment study undertaken over the I4-petrol engine blocks in Scenario 1:

Case 3: The Q'@gile system investment is 75% higher than an "equivalent" DTL system.

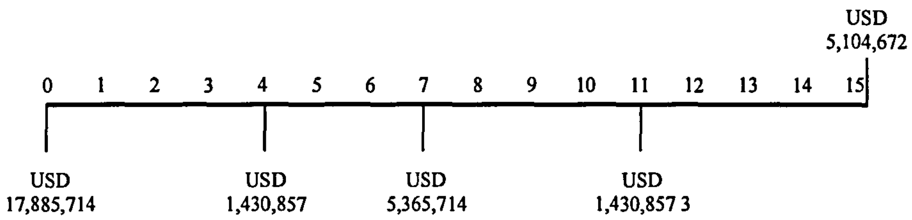


Figure 7.3 Case 3: DTL investment cash flows.

Case 3 includes an initial investment of USD 17,885,714, followed by a USD 1,430,857 investment in a minor retooling by year 4, plus a USD 5,365,714 investment in a major retooling by year 7 and another minor retooling by year 11 which amounts to another USD 1,430,857. The machinery is expected to have a salvage value (positive cash flow) of about USD 5,104,672 by the end of the study period.

On applying the NPV method (to bring all the cash flows to present time) gives a present value of **USD 21,211,350** as follows:

$$\mathbf{NPV}_{\mathbf{DTL\ (Scenario\ 1:\ I\text{-}4\ petrol)}} = (-17{,}885{,}714) + (-1{,}430{,}857) \times F_{SP,6\%,4} + (-5{,}365{,}714) \times F_{SP,6\%,7} + (-1{,}430{,}857) \times F_{SP,6\%,11} + 5{,}104{,}672 \times F_{SP,6\%,15}$$

Case 2: The Q'@gile system investment is 50% higher than an "equivalent" DTL system.

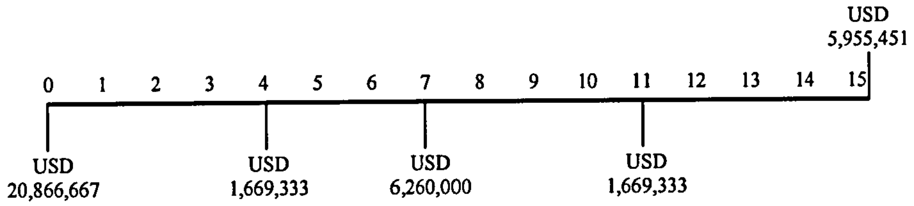


Figure 7.4 Case 2: DTL investment cash flows.

Case 2 includes an initial investment of USD 20,866,667, followed by a USD 1,669,333 investment in a minor retooling by year 4, plus a USD 6,260,000 investment in a major retooling by year 7 and another minor retooling by year 11 which amounts to another USD 1,669,333. The machinery is expected to have a salvage value (positive cash flow) of about USD 5,955,451 by the end of the study period.

On applying the NPV method (to bring all the cash flows to present time) gives a present value of **USD 24,746,575** as follows:

$$\mathbf{NPV}_{\mathbf{DTL\ (Scenario\ 1:\ I\text{-}4\ petrol)}} = (-20{,}866{,}667) + (-1{,}669{,}333) \times F_{SP,6\%,4} + (-6{,}260{,}000) \times F_{SP,6\%,7} + (-1{,}669{,}333) \times F_{SP,6\%,11} + 5{,}955{,}451 \times F_{SP,6\%,15}$$

Case 1: The Q'@gile system investment is 25% higher than an "equivalent" DTL system.

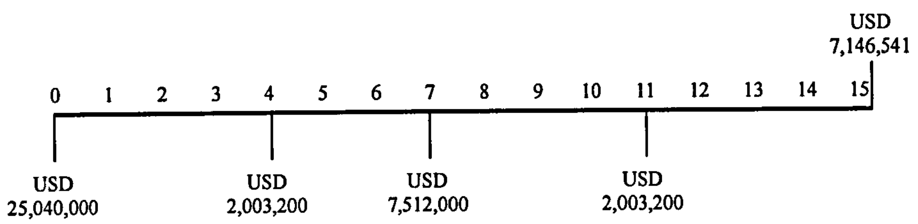


Figure 7.5 Case 1: DTL investment cash flows.

Case 1 includes an initial investment of USD 25,040,000, followed by a USD 2,003,200 investment in a minor retooling by year 4, plus a USD 7,512,000 investment in a major retooling by year 7 and another minor retooling by year 11 which amounts to another USD 2,003,200. The machinery is expected to have a salvage value (positive cash flow) of about USD 7,146,541 by the end of the study period.

On applying the NPV method (to bring all the cash flows to present time) gives a present value of **USD 29,695,890** as follows:

$$NPV_{DTL\ (Scenario\ 1:\ I\text{-}4\ petrol)} = (-25{,}040{,}000) + (-2{,}003{,}200) \times F_{SP,6\%,4} + (-7{,}512{,}000) \times F_{SP,6\%,7} + (-2{,}003{,}200) \times F_{SP,6\%,11} + 7{,}146{,}541 \times F_{SP,6\%,15}$$

This investment modelling methodology was applied for all 36 scenarios, which concerned relative engine demand shares for I4 petrol, I4 diesel, V6 petrol and V6 diesel engine types. The full set of results are tabulated in **Table J.5** of Appendix J.

7.2.2 Q'@gile based systems

Since each Q'@gile cell has an effective production capacity of 11,154 engines per year (I4-petrol engines) the required number of cells was calculated with respect to yearly-based engine demands from scenario 1, and the results tabulated in table 7.3. Therefore the initial investment in a Q'@gile system for machining I4-petrol engine blocks corresponds to the installation of 32 cells plus 4 gantry robots. Engine demand growths, by around 2007 (year 3), are likely to require the installation of an additional cell and another gantry robot. By the following year another cell has to be installed. By 2015 (year 11) it is forecasted that another cell will be required and one more by the year 2018 (year 14). By the end of the study period the total number of cells installed at the shop floor is likely to be 36 cells and 5 gantry robots.

Table 7.3 Required number of cells (Scenario 1: I4 petrol engines)

Year	Demand	Cells	Effective capacity	Install/Remove cells	Gantry robots
1	348,927	32	356,928	32	4
2	355,906	32	356,928		
3	363,024	33	368,082	+1	+1
4	370,284	34	379,236	+1	
5	377,690	34	379,236		
6	377,690	34	379,236		
7	377,690	34	379,236		
8	377,690	34	379,236		
9	377,690	34	379,236		
10	377,690	34	379,236		
11	381,467	35	390,390	+1	
12	385,282	35	390,390		
13	389,134	35	390,390		
14	393,026	36	401,544	+1	
15	396,956	36	401,544		

The time diagram for the required investments in a Q'@gile system is represented in the diagram of Figure 7.6. The specific cash flows are sourced from the investment study undertaken over the I4-petrol engine blocks in Scenario 1.

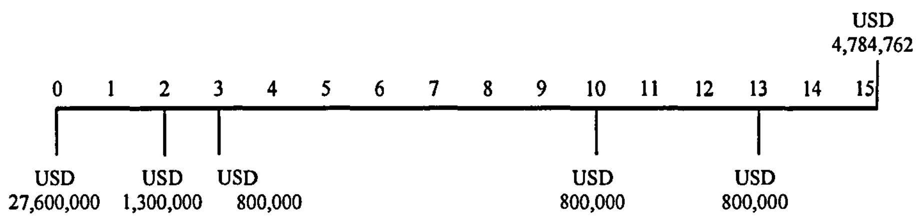


Figure 7.6 Q'@gile investment cash flows.

This includes an initial investment of USD 27,600,000 in 32 cells plus 4 gantry robots, followed by a USD 1,300,000 investment in one more cell and one more gantry robot by year end 2 (costing USD 800,000 and USD 500,000). The investment is realised in year 2 so that the respective production capacity is available at the beginning of year 3. By years 3, 10 and 13 new investments follow in single cell units amounting to USD 800,000 each. The machinery is expected to have a salvage value (positive cash flow) of about USD 4,784,762 by the end of the study period.

On applying the NPV method (to bring all the cash flows to present time) gives the present value of **USD 28,253,964** is obtained as follows:

$NPV_{Q'@gile\ (Scenario\ 1:\ I\text{-}4\ petrol)} = (-27{,}600{,}000) + (-1{,}300{,}000) \times F_{SP,6\%,2} + (-800{,}000) \times F_{SP,6\%,3} + (-800{,}000) \times F_{SP,6\%,10} + (-800{,}000) \times F_{SP,6\%,13} + 4{,}784{,}762 \times F_{SP,6\%,15}$

This investment modelling methodology was also applied with respect to all 36 scenarios covering possible future extremes of I4 petrol, I4 diesel, V6 petrol and V6 diesel engine type share. The results are tabulated in Table J.6 of Appendix J.

7.3 INVESTMENT COMPARISON

The investment model has been applied to each single scenario out of the 36 generated. For the machining of **I4-petrol engine blocks** it was found that (detailed results can be found in Table 7.4):

Case 3: For a full Q'@gile system investment of **75% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach to machine the engine blocks for 32 of the 36 scenarios. For the remaining 4 scenarios it would have been more sensible to adopt the Q'@gile approach.

Case 2: For a full Q'@gile system investment of **50% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach in 21 of the 36 scenarios. For the remaining 15 scenarios the Q'@gile approach is recommended.

Case 1: For a full Q'@gile system investment of **25% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a Q'@gile approach for all 36 scenarios.

Table 7.4 DTL *vs.* Q'@gile investments (over 36 Scenarios: I4 petrol engines).

Case 3

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	21,211,350	28,253,964	X	
2	18,161,795	21,655,009	X	
3	31,105,462	34,852,240	X	
4	19,584,920	24,211,880	X	
5	19,584,920	24,895,633	X	
6	18,161,795	18,502,660	X	
7	26,429,477	31,545,866	X	
8	18,161,795	20,968,718	X	
9	20,127,064	25,786,756	X	
10	18,161,795	19,099,464	X	
11	26,429,477	32,489,143	X	
12	18,161,795	21,591,738	X	
13	19,584,920	23,651,850	X	
14	18,161,795	17,028,927		X
15	22,837,779	30,126,271	X	
16	18,161,795	19,611,671	X	
17	19,584,920	23,866,475	X	
18	18,161,795	17,354,967		X
19	24,260,905	30,459,525	X	
20	18,161,795	19,903,001	X	
21	19,584,920	24,602,019	X	
22	18,161,795	18,202,492	X	
23	25,345,191	31,304,683	X	
24	18,161,795	20,688,381	X	
25	20,127,064	25,493,142	X	
26	18,161,795	18,858,281	X	
27	25,345,191	32,138,828	X	
28	18,161,795	21,302,563	X	
29	19,584,920	23,264,658	X	
30	18,161,795	16,737,597		X
31	22,295,636	29,948,511	X	
32	18,161,795	19,318,056	X	
33	19,584,920	23,264,658	X	
34	18,161,795	16,737,597		X
35	22,295,636	29,948,511	X	
36	18,161,795	19,318,056	X	
		Total:	32	4

Case 2

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	24,746,575	28,253,964	X	
2	21,188,761	21,655,009	X	
3	36,289,706	34,852,240		X
4	22,849,074	24,211,880	X	
5	22,849,074	24,895,633	X	
6	21,188,761	18,502,660		X
7	30,834,390	31,545,866	X	
8	21,188,761	20,968,718		X
9	23,481,574	25,786,756	X	
10	21,188,761	19,099,464		X
11	30,834,390	32,489,143	X	
12	21,188,761	21,591,738	X	
13	22,849,074	23,651,850	X	
14	21,188,761	17,028,927		X
15	26,644,076	30,126,271	X	
16	21,188,761	19,611,671		X
17	22,849,074	23,866,475	X	
18	21,188,761	17,354,967		X
19	28,304,389	30,459,525	X	
20	21,188,761	19,903,001		X
21	22,849,074	24,602,019	X	
22	21,188,761	18,202,492		X
23	29,569,390	31,304,683	X	
24	21,188,761	20,688,381		X
25	23,481,574	25,493,142	X	
26	21,188,761	18,858,281		X
27	29,569,390	32,138,828	X	
28	21,188,761	21,302,563	X	
29	22,849,074	23,264,658	X	
30	21,188,761	16,737,597		X
31	26,011,575	29,948,511	X	
32	21,188,761	19,318,056		X
33	22,849,074	23,264,658	X	
34	21,188,761	16,737,597		X
35	26,011,575	29,948,511	X	
36	21,188,761	19,318,056		X
		Total:	21	15

Case 1

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	29,695,890	28,253,964		X
2	25,426,513	21,655,009		X
3	43,547,647	34,852,240		X
4	27,418,889	24,211,880		X
5	27,418,889	24,895,633		X
6	25,426,513	18,502,660		X
7	37,001,268	31,545,866		X
8	25,426,513	20,968,718		X
9	28,177,889	25,786,756		X
10	25,426,513	19,099,464		X
11	37,001,268	32,489,143		X
12	25,426,513	21,591,738		X
13	27,418,889	23,651,850		X
14	25,426,513	17,028,927		X
15	31,972,891	30,126,271		X
16	25,426,513	19,611,671		X
17	27,418,889	23,866,475		X
18	25,426,513	17,354,967		X
19	33,965,267	30,459,525		X
20	25,426,513	19,903,001		X
21	27,418,889	24,602,019		X
22	25,426,513	18,202,492		X
23	35,483,268	31,304,683		X
24	25,426,513	20,688,381		X
25	28,177,889	25,493,142		X
26	25,426,513	18,858,281		X
27	35,483,268	32,138,828		X
28	25,426,513	21,302,563		X
29	27,418,889	23,264,658		X
30	25,426,513	16,737,597		X
31	31,213,891	29,948,511		X
32	25,426,513	19,318,056		X
33	27,418,889	23,264,658		X
34	25,426,513	16,737,597		X
35	31,213,891	29,948,511		X
36	25,426,513	19,318,056		X
		Total:	0	36

For the machining of I4-diesel engine blocks it was found that (detailed results can be found in Table 7.5):

Case 3: For a full Q'@gile system investment of **75% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach to machine the engine blocks in 29 of the 36 scenarios. For the remaining 7 scenarios it would have been more sensible to adopt the Q'@gile approach.

Case 2: For a full Q'@gile system investment of **50% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach in 26 of the 36 scenarios. For the remaining 10 scenarios the Q'@gile approach is recommended.

Case 1: For a full Q'@gile system investment of **25% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a Q'@gile approach for all of the 36 scenarios.

Table 7.5 DTL *vs.* Q'@gile investments (over 36 Scenarios: I4 diesel engines).

Case 3

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	18,703,938	24,651,894	X	
2	28,055,907	31,007,883	X	
3	15,993,222	18,379,971	X	
4	22,837,779	28,618,264	X	
5	16,535,365	21,562,202	X	
6	23,379,922	28,014,859	X	
7	15,993,222	15,323,893		X
8	20,669,207	25,542,247	X	
9	17,619,652	22,371,711	X	
10	23,379,922	28,692,484	X	
11	15,993,222	16,001,714	X	
12	21,211,350	26,366,975	X	
13	16,535,365	20,348,976	X	
14	20,669,207	26,654,568	X	
15	15,993,222	13,983,641		X
16	19,584,920	24,183,240	X	
17	16,535,365	20,590,160	X	
18	21,211,350	26,941,459	X	
19	15,993,222	14,224,824		X
20	19,584,920	24,397,865	X	
21	16,535,365	21,240,258	X	
22	22,295,636	27,612,113	X	
23	15,993,222	14,993,414		X
24	20,669,207	25,248,633	X	
25	17,619,652	22,106,927	X	
26	22,295,636	28,398,869	X	
27	15,993,222	15,673,518		X
28	21,211,350	25,981,608	X	
29	16,535,365	20,009,655	X	
30	19,584,920	26,360,954	X	
31	15,993,222	13,591,402		X
32	19,584,920	23,889,626	X	
33	16,535,365	20,009,655	X	
34	19,584,920	26,360,954	X	
35	15,993,222	13,591,402		X
36	19,584,920	23,889,626	X	
		Total:	29	7

Case 2

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	21,821,261	24,651,894	X	
2	32,731,891	31,007,883		X
3	18,658,759	18,379,971		X
4	26,644,076	28,618,264	X	
5	19,291,260	21,562,202	X	
6	27,276,576	28,014,859	X	
7	18,658,759	15,323,893		X
8	24,114,075	25,542,247	X	
9	20,556,260	22,371,711	X	
10	27,276,576	28,692,484	X	
11	18,658,759	16,001,714		X
12	24,746,575	26,366,975	X	
13	19,291,260	20,348,976	X	
14	24,114,075	26,654,568	X	
15	18,658,759	13,983,641		X
16	22,849,074	24,183,240	X	
17	19,291,260	20,590,160	X	
18	24,746,575	26,941,459	X	
19	18,658,759	14,224,824		X
20	22,849,074	24,397,865	X	
21	19,291,260	21,240,258	X	
22	26,011,575	27,612,113	X	
23	18,658,759	14,993,414		X
24	24,114,075	25,248,633	X	
25	20,556,260	22,106,927	X	
26	26,011,575	28,398,869	X	
27	18,658,759	15,673,518		X
28	24,746,575	25,981,608	X	
29	19,291,260	20,009,655	X	
30	22,849,074	26,360,954	X	
31	18,658,759	13,591,402		X
32	22,849,074	23,889,626	X	
33	19,291,260	20,009,655	X	
34	22,849,074	26,360,954	X	
35	18,658,759	13,591,402		X
36	22,849,074	23,889,626	X	
		Total:	26	10

Case 1

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	26,185,513	24,651,894		X
2	39,278,270	31,007,883		X
3	22,390,511	18,379,971		X
4	31,972,891	28,618,264		X
5	23,149,512	21,562,202		X
6	32,731,891	28,014,859		X
7	22,390,511	15,323,893		X
8	28,936,889	25,542,247		X
9	24,667,512	22,371,711		X
10	32,731,891	28,692,484		X
11	22,390,511	16,001,714		X
12	29,695,890	26,366,975		X
13	23,149,512	20,348,976		X
14	28,936,889	26,654,568		X
15	22,390,511	13,983,641		X
16	27,418,889	24,183,240		X
17	23,149,512	20,590,160		X
18	29,695,890	26,941,459		X
19	22,390,511	14,224,824		X
20	27,418,889	24,397,865		X
21	23,149,512	21,240,258		X
22	31,213,891	27,612,113		X
23	22,390,511	14,993,414		X
24	28,936,889	25,248,633		X
25	24,667,512	22,106,927		X
26	31,213,891	28,398,869		X
27	22,390,511	15,673,518		X
28	29,695,890	25,981,608		X
29	23,149,512	20,009,655		X
30	27,418,889	26,360,954		X
31	22,390,511	13,591,402		X
32	27,418,889	23,889,626		X
33	23,149,512	20,009,655		X
34	27,418,889	26,360,954		X
35	22,390,511	13,591,402		X
36	27,418,889	23,889,626		X
		Total:	26	36

For the machining of V6-petrol engine blocks it was found that (detailed results can be found in Table 7.6):

Case 3: For a full Q'@gile system investment of **75% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach to machine the engine blocks in 33 of the 36 scenarios. For the remaining 3 scenarios it would be more sensible to adopt the Q'@gile approach.

Case 2: For a full Q'@gile system investment of **50% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach in 23 of the 36 scenarios. For the remaining 13 scenarios the Q'@gile approach is recommended.

Case 1: For a full Q'@gile system investment of **25% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a Q'@gile approach in all of the 36 scenarios.

Table 7.6 DTL *vs.* Q'@gile investments (over 36 Scenarios: V6 petrol engines).

Case 3

Scenario	*DTL investment*	*Q'@gile investment*	*DTL*	*Q'@gile*
1	10,232,952	13,136,191	X	
2	8,267,683	10,203,512	X	
3	14,027,953	16,195,288	X	
4	8,809,826	11,196,406	X	
5	8,809,826	11,675,674	X	
6	8,267,683	8,721,248	X	
7	12,401,524	14,842,227	X	
8	8,267,683	9,861,645	X	
9	9,351,969	12,017,448	X	
10	8,267,683	8,955,791	X	
11	12,401,524	15,209,557	X	
12	8,267,683	10,203,969	X	
13	8,809,826	11,131,101	X	
14	8,267,683	8,129,232		X
15	10,775,095	14,178,559	X	
16	8,267,683	9,458,899	X	
17	8,809,826	11,190,086	X	
18	8,267,683	8,409,569	X	
19	11,317,238	14,300,968	X	
20	8,267,683	9,581,308	X	
21	8,809,826	11,503,118	X	
22	8,267,683	8,409,569	X	
23	11,859,381	14,614,321	X	
24	8,267,683	9,802,660	X	
25	9,351,969	11,898,673	X	
26	8,267,683	8,892,367	X	

Case 2

Scenario	*DTL investment*	*Q'@gile investment*	*DTL*	*Q'@gile*
1	11,938,443	13,136,191	X	
2	9,645,630	10,203,512	X	
3	16,365,946	16,195,288		X
4	10,278,130	11,196,406	X	
5	10,278,130	11,675,674	X	
6	9,645,630	8,721,248		X
7	14,468,445	14,842,227	X	
8	9,645,630	9,861,645	X	
9	10,910,630	12,017,448	X	
10	9,645,630	8,955,791		X
11	14,468,445	15,209,557	X	
12	9,645,630	10,203,969	X	
13	10,278,130	11,131,101	X	
14	9,645,630	8,129,232		X
15	12,570,944	14,178,559	X	
16	9,645,630	9,458,899		X
17	10,278,130	11,190,086	X	
18	9,645,630	8,409,569		X
19	13,203,444	14,300,968	X	
20	9,645,630	9,581,308		X
21	10,278,130	11,503,118	X	
22	9,645,630	8,409,569		X
23	13,835,944	14,614,321	X	
24	9,645,630	9,802,660	X	
25	10,910,630	11,898,673	X	
26	9,645,630	8,892,367		X

Case 1

Scenario	*DTL investment*	*Q'@gile investment*	*DTL*	*Q'@gile*
1	14,326,132	13,136,191		X
2	11,574,756	10,203,512		X
3	19,639,135	16,195,288		X
4	12,333,756	11,196,406		X
5	12,333,756	11,675,674		X
6	11,574,756	8,721,248		X
7	17,362,134	14,842,227		X
8	11,574,756	9,861,645		X
9	13,092,757	12,017,448		X
10	11,574,756	8,955,791		X
11	17,362,134	15,209,557		X
12	11,574,756	10,203,969		X
13	12,333,756	11,131,101		X
14	11,574,756	8,129,232		X
15	15,085,133	14,178,559		X
16	11,574,756	9,458,899		X
17	12,333,756	11,190,086		X
18	11,574,756	8,409,569		X
19	15,844,133	14,300,968		X
20	11,574,756	9,581,308		X
21	12,333,756	11,503,118		X
22	11,574,756	8,409,569		X
23	16,603,133	14,614,321		X
24	11,574,756	9,802,660		X
25	13,092,757	11,898,673		X
26	11,574,756	8,892,367		X

27	11,859,381	15,038,351	X	
28	8,267,683	10,037,203	X	
29	8,809,826	10,903,195	X	
30	8,267,683	8,006,823		X
31	10,232,952	13,898,222	X	
32	8,267,683	9,084,840	X	
33	8,809,826	10,903,195	X	
34	8,267,683	8,006,823		X
35	10,232,952	13,898,222	X	
36	8,267,683	9,084,840	X	
		Total:	33	3

27	13,835,944	15,038,351	X	
28	9,645,630	10,037,203	X	
29	10,278,130	10,903,195	X	
30	9,645,630	8,006,823		X
31	11,938,443	13,898,222	X	
32	9,645,630	9,084,840		X
33	10,278,130	10,903,195	X	
34	9,645,630	8,006,823		X
35	11,938,443	13,898,222	X	
36	9,645,630	9,084,840		X
		Total:	23	13

27	16,603,133	15,038,351		X
28	11,574,756	10,037,203		X
29	12,333,756	10,903,195		X
30	11,574,756	8,006,823		X
31	14,326,132	13,898,222		X
32	11,574,756	9,084,840		X
33	12,333,756	10,903,195		X
34	11,574,756	8,006,823		X
35	14,326,132	13,898,222		X
36	11,574,756	9,084,840		X
		Total:	0	36

For the machining of V6-diesel engine blocks it was found that (detailed results can be found in Table 7.7):

Case 3: For a full Q'@gile system investment of **75% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach to machine the engine blocks in 28 of the 36 scenarios. For the remaining 8 scenarios it would be better to adopt the Q'@gile approach.

Case 2: For a full Q'@gile system investment of **50% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a DTL approach in 26 scenarios. For the remaining 10 scenarios the Q'@gile approach is recommended.

Case 1: For a full Q'@gile system investment of **25% higher** than the cost of an equivalent initial DTL system investment, it would be economically advantageous to choose a Q'@gile approach for all of the 36 scenarios.

Table 7.7 DTL *vs.* Q'@gile investments (over 36 Scenarios: V6 diesel engines).

Case 3

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	8,809,826	11,483,366	X	
2	12,943,667	14,400,925	X	
3	7,725,540	8,818,865	X	
4	10,775,095	13,371,310	X	
5	7,725,540	10,158,338	X	
6	10,775,095	12,902,397	X	
7	7,725,540	7,212,674		X
8	9,351,969	11,762,000	X	
9	8,267,683	10,548,545	X	

Case 2

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	10,278,130	11,483,366	X	
2	15,100,945	14,400,925		X
3	9,013,129	8,818,865		X
4	12,570,944	13,371,310	X	
5	9,013,129	10,158,338	X	
6	12,570,944	12,902,397	X	
7	9,013,129	7,212,674		X
8	10,910,630	11,762,000	X	
9	9,645,630	10,548,545	X	

Case 1

Scenario	DTL investment	Q'@gile investment	DTL	Q'@gile
1	12,333,756	11,483,366		X
2	18,121,134	14,400,925		X
3	10,815,755	8,818,865		X
4	15,085,133	13,371,310		X
5	10,815,755	10,158,338		X
6	15,085,133	12,902,397		X
7	10,815,755	7,212,674		X
8	13,092,757	11,762,000		X
9	11,574,756	10,548,545		X

10	10,775,095	13,354,039	X	
11	7,725,540	7,620,631		X
12	10,232,952	12,126,950	X	
13	7,725,540	9,660,995	X	
14	9,351,969	12,260,121	X	
15	7,725,540	6,761,496		X
16	8,809,826	11,155,812	X	
17	7,725,540	9,719,979	X	
18	10,232,952	12,509,183	X	
19	7,725,540	6,883,905		X
20	8,809,826	11,386,002	X	
21	7,725,540	10,044,767	X	
22	10,775,095	12,843,412	X	
23	7,725,540	7,212,674		X
24	9,351,969	11,654,219	X	
25	8,267,683	10,429,770	X	
26	10,775,095	13,239,704	X	
27	7,725,540	7,620,631		X
28	10,232,952	12,126,950	X	
29	7,725,540	9,452,433	X	
30	8,809,826	12,029,931	X	
31	7,725,540	6,550,651		X
32	8,809,826	11,092,388	X	
33	7,725,540	9,452,433	X	
34	8,809,826	12,029,931	X	
35	7,725,540	6,550,651		X
36	8,809,826	11,092,388	X	
		Total:	28	8

10	12,570,944	13,354,039	X	
11	9,013,129	7,620,631		X
12	11,938,443	12,126,950	X	
13	9,013,129	9,660,995	X	
14	10,910,630	12,260,121	X	
15	9,013,129	6,761,496		X
16	10,278,130	11,155,812	X	
17	9,013,129	9,719,979	X	
18	11,938,443	12,509,183	X	
19	9,013,129	6,883,905		X
20	10,278,130	11,386,002	X	
21	9,013,129	10,044,767	X	
22	12,570,944	12,843,412	X	
23	9,013,129	7,212,674		X
24	10,910,630	11,654,219	X	
25	9,645,630	10,429,770	X	
26	12,570,944	13,239,704	X	
27	9,013,129	7,620,631		X
28	11,938,443	12,126,950	X	
29	9,013,129	9,452,433	X	
30	10,278,130	12,029,931	X	
31	9,013,129	6,550,651		X
32	10,278,130	11,092,388	X	
33	9,013,129	9,452,433	X	
34	10,278,130	12,029,931	X	
35	9,013,129	6,550,651		X
36	10,278,130	11,092,388	X	
		Total:	26	10

10	15,085,133	13,354,039		X
11	10,815,755	7,620,631		X
12	14,326,132	12,126,950		X
13	10,815,755	9,660,995		X
14	13,092,757	12,260,121		X
15	10,815,755	6,761,496		X
16	12,333,756	11,155,812		X
17	10,815,755	9,719,979		X
18	14,326,132	12,509,183		X
19	10,815,755	6,883,905		X
20	12,333,756	11,386,002		X
21	10,815,755	10,044,767		X
22	15,085,133	12,843,412		X
23	10,815,755	7,212,674		X
24	13,092,757	11,654,219		X
25	11,574,756	10,429,770		X
26	15,085,133	13,239,704		X
27	10,815,755	7,620,631		X
28	14,326,132	12,126,950		X
29	10,815,755	9,452,433		X
30	12,333,756	12,029,931		X
31	10,815,755	6,550,651		X
32	12,333,756	11,092,388		X
33	10,815,755	9,452,433		X
34	12,333,756	12,029,931		X
35	10,815,755	6,550,651		X
36	12,333,756	11,092,388		X
		Total:	0	36

Concluding remarks

Hence a developed investment model, based on the Net Present Value of successive investments required during the systems lifetime, was applied in respect of all future scenarios and engine configurations considered in this research study. Results from this investment model show that in general a 'DTL-equivalent' Q'@gile system requiring a total investment of 75% more than that of a comparable DTL system initial investment, is not economically sound. In such a case the DTL approach is probably economically preferable. Similar reasoning applies, but to a lesser extent, for the case of a 'DTL-equivalent' Q'@gile system requiring a total investment of 50% more than that of a comparable DTL system initial investment. If however the 'DTL-equivalent' Q'@gile system requires an investment of 25% greater than that of a comparable DTL system initial investment, then for all likely futures it is economically preferable to choose a Q'@gile system.

CHAPTER 8

RESULTS, ANALYSIS AND DISCUSSION

8.1 GENERAL ANALYSIS OF THE ECONOMY OF SCALE FACTOR

It is widely accepted within the automotive industry that economies of scale are attained when the production volume of a specific engine configuration surpasses a given yearly quantity (Daniels and Pemberton_Associates 1999; Shimokawa 1999). This has led to the widespread adoption of the traditional engine manufacturing approach based on the use of transfer line technology. Daniels and Pemberton Associates (1999) suggest that:

> "*...economy of scale curve for an engine manufacturing facility begins to flatten at about 300,000 units per year, and it may reach an optimum point at around 500,000 units per year. If the anticipated demand for a single engine family falls short of 300,000 the pressure to move to a modular approach, or to a joint venture with another manufacturer with a similar requirement is strong*".

Cross-Huller, a global provider in engine machining systems, recommends the use of transfer lines when demands exceeds 350,000 to 450,000 engines per year (Cross-Huller) as illustrated in figure 8.1.

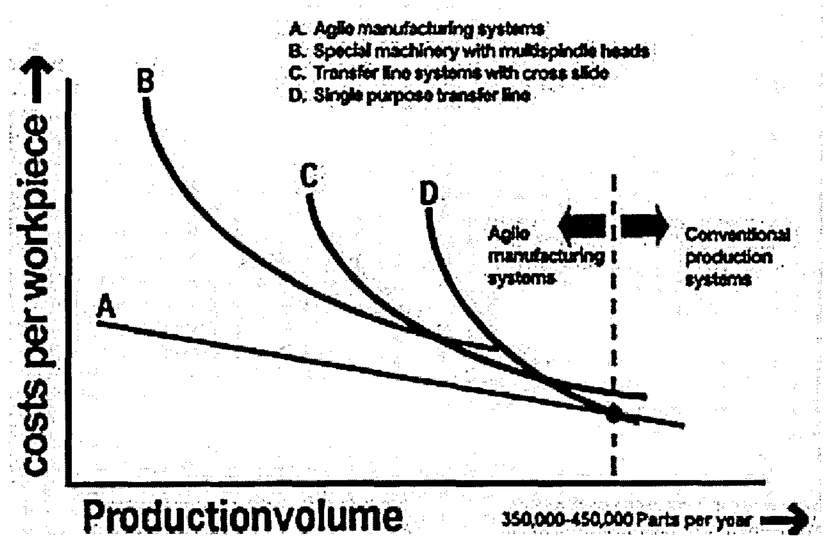


Figure 8.1 Economical justification of transfer lines. Source: Cross-Huller website (Cross-Huller).

However, such specific volume "thresholds", which theoretically justify the adoption of a specific engine manufacturing approach in detriment of another, might vary significantly according to specific strategies and goals from the individual vehicle manufacturers. These volume "thresholds" vary as well with the engine configuration type. For example a V6 diesel engine plant can be economically justified for lower production volumes than for a normal I4 petrol engine plant. This is because the value content of a V6 diesel engine is much higher than a normal I4 petrol engine. Very recently Ford Dagenham engine plant has made considerable investments in agile machining facilities to machine the prime parts of V6/V8 diesel engines with initial capacity at 150,000 engines per year (full capacity will be 250,000 engines per year, if required), thus supporting the foregoing. According to Verboden (2002) cited in (Sperling et al. 2004): *"...only 10-25% of the price premium for diesel vehicles can be attributed to their higher production costs (Verboden 2002). The remainder of the difference is due to firms discriminating between consumers travelling high and low-mileage, essentially charging more to consumers valuing fuel economy".*

Therefore, vehicle manufacturers decide such "threshold" levels for each specific engine configuration. If the real production volumes are significantly lower than the expected ones (particularly over several years) then traditional manufacturing approaches may not be the most economically sound decision, since the investment rationale for the given volume targets is not confirmed or a significant fraction of the installed capacity will be idle. In such cases it may prove significantly advantageous to use the Q'@gile system approach (proposed in this study) instead of DTLs, since then the production capacity can evolve synchronously with engine volume demand and investment risk should be significantly reduced.

For reference purposes only if hypothetical "thresholds" for the AUDI engine manufacturing business were set at 300,000 engines per year for I4 petrol engines and 250,000 for I4 diesel engines; and 150,000 engines per year for V6 petrol engines and 100,000 for V6 diesel engines, then:

1. Most scenarios presented in tables J.1 (Appendix J) for I4 petrol engine demands would satisfy such "thresholds". Therefore the investment results presented in section 7.3 for these types of engines would have been similar. The same applies to I4 diesel engine demands and respective investment results.

2. Most scenarios presented in table J.3 (from Appendix J) for V6 petrol engine demands would not satisfy such "thresholds". Most scenarios presented in table J.4 (from Appendix J) for V6 diesel engine demands would not satisfy such "thresholds" as well but to a lesser extent. Therefore the investment results presented in section 7.3 would have changed drastically.

The above considerations are based on scenarios studied which utilise data specific to the Audi Company. It shows that V6 engines could reach demand volumes lower than those required for economical production. It also shows that I4 engines are not likely to be subject to minimum production volume constraints. However, similar reasoning will apply automotive industry wide, bearing in mind that the I4 engine configuration is dominant in Europe and that the less significant V6 configuration in Europe could have a further reduced market share bearing in mind the trend towards fuel efficient engines.

The present study did not introduce minimum volume requirements for implementing DTL systems for the studied engine configurations. This is justified given the present lack of well grounded studies and very limited sources of information that could support such evidence. The author believes however that the few sources found which refer to specific minimum volume requirements are grounded in data from industry but do not represent the engine manufacturing industry as a whole and are partially complete since they omit the specific engine configuration.

One important aspect not taken into account while building the scenarios presented in chapter 6 was that of likely secondary effects of higher fuel costs or direct competition for ICE from other forms of vehicle propulsion. In fact, if the forecasted rise in crude oil price is confirmed over the next decade this will most likely increase further customer desires for fuel efficient vehicles. A direct implication could be a global shift from higher volume engines (more powerful but less fuel efficient) to lower volume engines, such as from V6 to I4 engines and from I4 to I3 engines. Following oil based fuel price increases other forms of propulsion, such as Fuel Cells, will become economically justified earlier than expected. It is expected that ICE business will then attempt to remain competitive by seeking more quickly to improve fuel efficiency. Here it is envisaged that following such events the pace of change in engine volumes and engine types would accelerate, therefore favouring the adoption of some form of agile manufacturing approach.

8.2 SYSTEM AGILITY

Use of the proposed Q'@gile system promises agility gains relative to the traditional approach to engine production for the following reasons:

1. In DTL systems the production capacity is constrained by system specifics. But in Q'@gile systems the capacity is limited only by plant space considerations and infrastructures limitations.

2. Q'@gile system components can be installed, dismantled or reallocated to other plants around the globe. While in DTL systems this is simply not possible.

3. The possibility to annually install, dismantle or reallocate Q'@gile cells allows the use of financial resources to be spread, since typically required investment patterns are progressive, and can be linked to more accurate annual demand forecasts.

4. It is possible to use different Q'@gile cells to machine engine parts for distinctive engine configurations, therefore enabling the simultaneous production of prime parts for different engines.

5. It is possible to allocate a number of cells to machine a single part belonging to a

specific engine while other cells are used to machine another part (for a different engine configuration). It is also possible to dynamically change the number of cells allocated to the machining of each engine part.

6. The production time lost when introducing new engines or upgrading old existing engines is much smaller than the downtime needed for DTLs.

The potential for Q'@gile systems to realise simultaneous production of a mix of parts belonging to different engines was not simulated and studied in the present study. In general DTL systems cannot allow the mixed production of parts from different engines (except when using strategy B which is presented in section 8.4). However Q'@gile system could easily accomplish this, but without comparative scenarios with DTL systems it was decided that any quantitative study of Q'@gile systems in this respect would have fairly meaningless results. However the ability to produce simultaneously a number of parts belonging to different engines, in various quantities which can be specifically defined and changed is expected to increasingly become a major advantage of Q'@gile systems relative to DTL systems.

The annual instalment or dismantlement of capacity has been a subject of quantitative analysis, with investment considerations discussed in sections 7.1.2 and 7.2.2 and considered with respect to possible future scenarios of engine demand. From an economic point of view an inherent capacity fluctuation enabled by Q'@gile systems allows for progressive investment flows which maps onto yearly engine demand patterns. This is completely distinct from DTL investment patterns. By applying the NPV method to patterns of investments required for DTL and Q'@gile systems the following results were tabulated (in Table 8.1) with respect to the 36 future scenarios of predicted engine share:

1. When the Q'@gile system investment overhead is 25% higher than the initial investment needed for a capacity equivalent DTL system, it was observed that NPV favours the adoption of a Q'@gile system for machining the following engine configurations: I4 petrol, I4 diesel, V6 petrol and V6 diesel engines. In short, from an economic viewpoint it would be preferable to adopt Q'@gile systems rather than DTL systems.

2. When the Q'@gile system investment overhead is 50% higher than the initial investment required for a capacity equivalent DTL system, NPV favours the

adoption of Q'@gile systems for 15 scenarios (of I4 petrol engines), 10 scenarios (of I4 diesel engines), 13 scenarios (of V6 petrol engines) and 10 scenarios (of V6 diesel engines). Therefore in most cases it would be economically preferable to adopt a DTL system.

3. When the Q'@gile system investment overhead is 75% higher than the initial investment required for a capacity equivalent DTL system, NPV favours the adoption of a Q'@gile system in 4 scenarios (of I4 petrol engines), 7 scenarios (of I4 diesel engines), 3 scenarios (of V6 petrol engines) and 8 scenarios (of V6 diesel engines). Therefore normally it would prove economic to adopt a DTL system, as expected.

Table 8.1 Results of applying the NPV investment method to the patterns of investments required for DTL and Q'@gile systems over the 36 scenarios.

	Percentage of scenarios where NPV investment model favours the adoption of a Q'@gile approach			
Q'@gile system investment overhead in percentage value (over a capacity equivalent initial DTL system investment)	**I-4 petrol engines**	**I-4 diesel engines**	**V6 petrol engines**	**V6 diesel engines**
25%	100%	100%	100%	100%
50%	42%	28%	36%	28%
75%	11%	19%	8%	22%

From an operational point of view production capacity fluctuation in Q'@gile systems may generate disorder and require increased activity on the shop floor, since possibly each year (but not necessarily) new systems could be installed or removed from the engine plant. This increase in plant activity is directly linked and is actually necessary because of increased levels of engine innovation and fluctuation in demand for specific engine configurations relative to equivalent observations at the present time. In Europe a trend towards higher share of diesel powered vehicles (fuelled by higher fuel efficiencies of diesel engines and lower average price of diesel fuel) has already led to a deficit in capacity available to produce diesel engines, while many petrol engine plants have overcapacity. It is therefore desired that future infrastructure systems and engineering activities are carefully planned in order to support the instalment or dismantlement of cells by minimizing disruptions to production activities realised by remaining system cells.

Three additional factors, that are likely to impact negatively on engine machining systems that deploy traditional methods are worthy of further consideration, namely:

a) During the forthcoming 15 year period it is most likely that existing and future engines will require significant design changes. The frequency of plant reconfigurations is most likely to increase as increased market competition and innovation leads to the design of faster and better engines. Consequently engine configurations are likely to have a relatively short lifetime (because engines may soon be viewed as being out of date).

b) Engine lifespan is already observed to be decreasing as the number of engine innovations increase (Harrison 1996; Landmann 2001). An outcome is a demand for more frequent changes to engine machining facilities. Engine lifespan issues are not explicitly accounted for in the 36 investment scenarios. Further consideration of these issues would likely have indicated that in some of the 36 scenarios more frequent retooling would be required. Also it is likely that reduced engine lifespan would increase the pressure to replace traditional engine machining systems because (as explained previously) DTLs have very limited capability to facilitate change.

c) When viewed as a whole, the 36 scenario forecasts indicate the possibility that there could be high levels of volatility in the automotive industry. This volatility is directly at odds with the inherent inflexibility of the industry's prime "mass production paradigm". Hence the present author's proposes that the automotive industry seek to offset risks associated with the potential volatility by investing significant strategic development effort into flexible machining technology akin to the Q'@gile engine machining approach.

8.3 OVERCAPACITY IMPROVEMENT

Production overcapacity will in general be a result of the following:

1. Dynamics of the market requirements and effects of competition;

2. Optimistic multiyear forecasts for specific vehicle manufacturer performances;

3. Use of production systems with a fixed production capacity;

4. Production capacity is decided around two years before production actually starts and many years before a production peak is expected.

In many cases long term forecasts may not be confirmed, because of a multitude of global and local factors impacting on the automotive business. The use of quanta of capacity within the Q'@gile system has potential to allow for the progressive instalment or dismantlement of production capacity allowing closer following of market dynamics and changing effects of competition for engine demand.

The theoretical installed capacity is also affected by major and minor retoolings during a DTL system lifespan. This requires full system halts for given periods of time, therefore necessitating utilisation rates of lower than 100% of the installed capacity. Furthermore other factors, such as individual machine breakdowns and part quality faults also impact negatively on the performance of DTL systems because system dependencies require full production halts for just a single station breakdown. Overall the impact of such factors may limit the rates of utilisation to as low as 80% of the installed capacity, the average being 88.7%.These figures were calculated without considering changing engine demands within the automotive industry. Because: (A) engine demand varies each year; and (B) production capacity is established many years prior to the expected production peak, it is likely that DTL utilisation rates will in future be much lower than the values presented above.

In the case of Q'@gile systems, inherent capabilities to cope with factors requiring a production halt are likely to enable average rates of 98.8% utilisation of installed capacity. On considering benefits of (A), since the production capacity varies yearly, and if the look ahead period need not be higher than 1 year before an initial capacity decision is made (although overall investment considerations may require a predicted look several years into the future), it is evident that the utilisation rate should not be significantly affected by yearly changes in demands. The author's study reported on in section 5.3 already considered impacts of annual changes in production capacity by installing (or dismantling) a number of Q'@gile cells.

8.4 Other Engine Manufacturing Strategies

The line of reasoning followed in this research study has been based on use of a specific strategy to machine prime parts of internal combustion engines. The new strategy investigated will necessitate a shift towards the use of more agile manufacturing facilities at the operational level, in order to cope with increasing changes in engine volumes, engine configurations and engine propulsion technology. However it is important to point out that other distinctive strategies could be adopted to face such challenges.

The following is a list of such engine manufacturing strategies currently being adopted by the industry.

A. Vehicle manufacturers' secure alliances to realise engine and engine production R&D and ICE production;

B. Rationalising the design of engine families to effectively increase opportunities for volume production;

C. Deploying more flexible manufacturing technology and agile manufacturing paradigms;

Strategy A – Powertrain alliances between competing vehicle manufacturers or between brands from different companies belonging to the same group are becoming more popular. These alliances seek to exploit economies of scale which lead to high volume production of one or more specific engine configurations used in a number of vehicle models from alliance members. Such an alliance allows for shared development costs and shared investments which reduce the risks associated with capital intensive engine plants. Some alliances also seek to exchange specific expertise from alliance members in order to research better engines and bring them to the marketplace in shorter timeframes. Examples of such strategies include the: Global Engine Alliance formed in 2002 (DaimlerCrysler, Mitsubishi and Hyundai) which recently developed and engineered a family of inline 4 cylinder engines (1.8L, 2.0L and 2.4 L), aimed at production volumes of the order of 1.5 million engines per year (in engine plants in Korea, Japan and USA); the Tritec joint-venture (DC/BMW) in Brazil which started production of 4 cylinders 1.4 and 1.6 litre petrol engines back in 2000; the PSA-BMW agreement for the production of small petrol engines by the end of 2005, focussed on Peugeot, Citroen and Mini vehicles which once at its maximum production capacity, the overall annual engine production is expected to reach 1 million units; the Fiat-GM Powertrain joint-venture aimed at volume production of diesel engines for Fiat and Opel vehicles in Europe,

Strategy B – An alternative approach to obtaining economies of scale during the production of engines is to produce several engine configurations using the same machining facilities. With current engine production technology this has required the design of engine families with similarities, and some form of engine type identification, which allows different engines to flow through the same transfer line and be machined specifically. This strategy is normally applied to a limited number of engine variants and has been successfully applied within the Ford I4/I5 programme which aimed to design and produce 1.8L, 2.0L, 2.3L and 2.4 L (4 cylinder engines) and 2.8L (5-cylinder engine) from similar engine components (Weston et al. 2003).

Strategy C – The use of more agile machining systems corresponds to a logical shift away from fixed production linked to stable demand to agile production linked to changing demand. Agile strategies seek to basically align the production approach with present trends towards unpredictability and higher rates of engine innovation. The strategy is directed at enabling machining systems that can economically produce engines in quantities smaller than usual. The production volumes may vary with time and the engine it self can be exchanged by modified versions or by completely new engine configurations without severe financial penalties. Toyota Shimoyama (Japan) engine plant and Ford Dagenham and Ford Bridgend new engine machining facilities have adopted such a strategy.

When low volume series are required for the production of a specific engine, but such volumes do not economically justify the costs involved in developing and running the engine production system, one obvious solution is to buy the engines from competitors. For example, BMW buys small quantities of diesel engines (about 30,000 engines per year) from Toyota for MINI vehicles. The vehicle manufacturer may not possess sufficient expertise about engine specifics (e.g. diesel engines) as well, in such cases buying the engines is highly recommended.

In certain circumstances it is possible and desirable to adopt a mix of strategies, such as those presented above. Strategies 'A' and 'B' use economies of scale as the main gear to obtain significant savings in engine plants (or machining facilities), and protect their respective investments which are highly intensive in this sector. Strategy 'A' would gain from rationalising the design of engine families (used in strategy 'B') to increase further demand for increased production volumes. The use of concepts such as engine family design (used in strategy 'B') could also favour strategy 'C' especially under a global engine strategy where capacity could be moved freely around the globe and relocated to engine plants where additional capacity is currently required. The present study investigated mainly Strategy 'C'. The remaining strategies (or a mix of those strategies) were not researched in depth during this study.

Specific vehicle manufacturers, as well as powertrain alliances, may choose to use distinctive strategies for different engine configurations. For example, currently 4-cylinder engine configuration (of both petrol and diesel engine types) is indisputably the prime engine configuration in Europe. This makes it more feasible in Europe to use mass production approaches to machine the main engine parts of I4 engines than it is for I3 and V6 engine configurations. This is likely to remain the case for the 15 year forecast period studied. Other engine configurations, with lower production volumes, are more likely to become good candidates for agile approaches, such as the one proposed on this study. Similar reasoning will apply in North America but primarily for V6 petrol engines. The V6 petrol engine configuration is the most popular configuration in the USA.

In the long term it is probable that customers will prefer cars with lower fuel consumption and cleaner engines. Along with foreseen improvements in the ICE performance and the successful introduction of hybrid vehicles (which require smaller engines), this may result in a significant increase in: I3 petrol and I3 diesel engines in Europe; and I4 petrol and I4 petrol hybrids in North America.

CHAPTER 9

CONCLUSIONS AND CONTRIBUTION TO KNOWLEDGE

9.1 RESEARCH REVIEW

The current research study has focused on the automotive engine manufacturing business. Specifically it has researched a new approach to machining the prime parts of internal combustion engines. The rationale behind such study lies partially in a series of previous research programmes at the MSI/RI which focused on developing component-based technology and its incorporation into machining systems used for the mass production of prime engine parts. The rationale for the research was completed after some initial data elicitation from several sources by using an inductive research approach. This essentially enabled initial understandings to be gained about present engine manufacturing limitations, future prominent problems and initial ideas that could be used to investigate possible improvements.

The strategy investigated was that of using agility at the operational level to economically cope with likely future patterns of change in engine volumes and engine configurations. The research path taken was grounded in industry-based evidence about lack of responsiveness with respect to engine changeovers, exacerbated financial penalties incurred because of frequent changeovers and a surprisingly major problem of excess of production capacity. The importance of this evidence was considered to be very relevant since predicted patterns of change were expected to impact heavily on the engine business by reinforcing problems arising from such limitations.

Other paths of strategic investigation could be followed, as explained in section 8.4. Such as with emphasis on relieving production volume constraints via: (1) several automotive companies sharing the same engine machining facility, therefore enabling lower production demands per company to be accommodated; (2) designing engines in a highly modular way to enable the machining of different engine parts via the same production lines. For the defined research project timeframe it was not considered feasible to study in-depth other manufacturing strategies of this ilk. Therefore these other strategies were only considered in outline.

It follows that this research has mainly focused on: (1) understanding factors that impact on the use of current engine machining approaches and their limitations; (2) gaining insights into promising automotive propulsion technologies and possible impacts on the future production of ICEs; (3) conceiving and developing the rationale behind a new engine machining approach with potential to overcome those limitations; (4) generating predictions about future scenarios for engine volumes and engine configurations over timeframes normally associated with the lifespan of one engine machining facility; (5) developing, testing and validating a simulation model which quantitatively contrasts new and traditional engine machining approaches; (6) using a cost engineering method to compare patterns of investment required for predicted future scenarios of engine demand in the new and traditional machining approaches; (7) analysing simulation results, future engine demand patterns and investment study results to report benefits and limitations of the new engine machining approach.

9.2 RESEARCH ACHIEVEMENTS

(1) The study has documented key historical decisions made in the automotive industry leading to the development of the mass production paradigm. The successful development of the automotive industry from the end of the 19th century onwards was essentially a result of causal effects arising from attractive prices of vehicles resulting from economies of scale and availability of a cheap fuel. Global and more aggressive competition along with general trends towards customised products,

increased fuel prices and more stringent emission legislation, have generally shifted the focus of production towards new Lean and responsive production systems. General production paradigms have been revised and their respective applications in the context of the engine manufacturing business have been considered. Advantages and limitations of such paradigms were also considered.

(2) A general literature search was also conducted relating to sustainable availability of fossil fuels to propel vehicles, vehicle emission standards, vehicle fuel efficiencies, and promising propulsion technologies. Their probable impacts on the ICE manufacturing business as a whole were discussed with emphasis on Europe and the USA. Generally it can be said that present and future propulsion systems must be optimised so as to reduce fuel consumption and emissions. Fuel cell technology, along with hydrogen fuel power sources, seems to be widely accepted as ultimate technologies and fuels to propel vehicles, but important challenges remain unsolved. The eventual acceptance of fuel cells to propel vehicles will probably impact drastically on production demands for ICEs.

(3) A novel Q'@gile manufacturing approach was researched and developed, aiming at advancing the machining of prime parts of internal combustion engines. The conceptual nature of the Q'@gile system was defined, the related specifics described and expected advantages and limitations listed. The new approach is grounded in independent Q'@gile cells which can readily be installed or removed from the production system. Each cell represents a given quantum of independent production capacity. This allows the production system to grow or diminish in quantum steps of capacity in alignment with market demand. A varying number of cells can be allocated to produce a specific engine configuration and responsively modified when such configurations become uncompetitive or obsolete, while other cells can produce alternative engines belonging to a different configuration. The number of cells allocated to each engine configuration may therefore vary over time without significant loss of production and unacceptable engineering costs. Therefore in principle Q'@gile systems can enable the simultaneous production of different engines. Given the independent nature of the cells the overall Q'@gile systems will demonstrate lower vulnerability to problems affecting systems uptime than that found in current engine production systems.

(4) Predictions about the nature and patterns of change likely for vehicle propulsion systems over a 15 year timeframe were made. A set of 36 alternative scenarios was developed for a specific vehicle manufacturer. Those scenarios are considered attempts to envelope effects of identified and likely trends currently impacting on the engine manufacturing industry. The study was made around four propulsion types: petrol engines, diesel engines, hybrid engines and fuel cell powered engines. The trends impacting this industry were identified as being: (a) the general introduction of progressively stricter emissions legislation in the most industrialised regions of the world; (b) reported growing acceptance of hybrid vehicles; (c) forecasted start of market introduction of fuel cell vehicles by around 2010; significant oil price increase by the end of the present decade. The 36 scenarios characterise key impacts of such trends. A simple scenario generator was built which uses change patterns (translated into specific figures) in a systemic way. The results are company specific, but the trends behind the predictions affect the whole automotive industry and the patterns of change are believed to envelope key aspects of industry dynamics over the studied timeframe. Projected rise in fuel prices and acceptance of fuel cells is expected to bring increased uncertainty to the engine manufacturing business in about a decade.

(5) A simulation model was developed to contrast the performance of Q'@gile systems against DTLs. The simulation model was tested and validated. Initial model runs were executed, with respect to specific engine configurations. This enabled use of representative industry data on the initial production capacity for both machining approaches and an initial quantum in capacity for Q'@gile systems. Factors impacting on the performance of each of the approaches were exercised in a systemic way. Eight combinations of such factors were studied in detail. The impact of such factors could impact by as much as 20% on the production capacity realised by DTL systems (11.3% on average for the 8 cases studied) while in Q'@gile systems the equivalent impact was predicted to be as little as 1.6% (1.2% on average for the 8 cases studied).

(6) The Net Present Value cost engineering method was used to compare different patterns of investment in DTL and Q'@gile approaches for each future scenario. After normalising all the cash flows to present time cost values, it was possible to effectively compare the approaches (when used to machine the same engine

configuration) from an economic standpoint. Each future scenario predicted demand for four engine configurations namely: I4-petrol engines; I4 diesel engines; V6 petrol engines and V6 diesel engines. Detailed study of the I3 diesel engine configuration was abandoned given the very low level of engine demand found in the predicted scenarios. A final NPV comparison was made in respect to Q'@gile system investment and investment in equivalent DTL production capacity. Provided that the cost of Q'@gile technology (for equivalent capacity) can be less than 125% of DTL technology initial investment it was found to be economically preferable to adopt a Q'@gile approach for all four types of engine configuration. But a DTL approach would be economically preferable in general if the cost of Q'@gile systems is greater than 150% of the initial cost of DTL systems.

(7) From an analysis of simulation results from a number of model runs; by analysing the predictions made by the modelled scenarios of engine demand for a specific vehicle manufacturer and by analysing results of the investment study, final conclusions were made about likely benefits and limitations of Q'@gile systems. Also considered was the validity of the input data used and of the methodology applied. Here it is recommended that the reuse of the main study findings by other vehicle manufacturers needs to be tempered by predicted demand specifics, as these can radically alter investment patterns and NPV findings. However many of the general trends identified are considered to apply industry wide, although their impacts will likely be different to particular companies. It is believed that the overall study methodology developed can be used generally in any automotive company and possibly even in other sectors of industry.

9.2.1 Contribution to knowledge

This research study has made the following contributions to knowledge:

1. It has identified and documented aspects of important trends and technologies that are currently impacting on the engine manufacturing business. It has also quantified some such impacts and has determined the extremities of likely change in patterns in demands for internal combustion engine configurations and their demand volumes;

2. It has conceived and developed a specification for novel Q'@gile manufacturing approach to machining the prime parts of internal combustion engines. The new approach was designed to outperform production systems commonly used by automotive companies today, by addressing flexibility limitations found in industrial practice and by seeking to address problems of excess of production capacity;

3. It has conceived, specified, developed and tested a simulation tool which can concurrently execute models of DTL and Q'@gile production lines, and thereby can compare their performances;

4. It has developed and used a methodology for assessing the use of flexible engine production technology which combines experiments and predicted patterns of change in ICEs in a systemic way. Use of the methodology has generated scenario-specific investment patterns for each engine configuration which can usefully inform strategy and investment decision making in the automotive industry;

5. It has generated an economic comparison of the novel Q'@gile approach relative to the DTL approach and in so doing has provided a basis for drawing similar comparisons between mass and agile production techniques in other industries;

9.3 CRITICAL REVIEW OF THE RESEARCH STUDY

9.3.1 Knowledge elicitation

The research study has adopted a mix of research strategies in order to bring forth relevant information from literature, and know-how from industry and academia. Grounded theory and initial exploratory studies were widely used to acquire relevant data and understandings about the existing approaches, the current approaches used in the automotive industry and the best practice in use. Exploratory studies have been useful as well to build a battery of understandings about the problems impacting on the engine manufacturing sector and helped to identify the relevant issues which will make important impacts in the future. Initial attempts to schematically represent and describe causal effects of key variables have resulted in additional doubts and an initial idea about a possible advance in best practice. Counselling interviews with academic experts, unstructured interviews with industrial experts and visits to industrial plants followed, this included engine plants, vehicle assembly plants and engine production machine builders. Such forms of eliciting information were considered essential to progress the study. A survey strategy was attempted which used a questionnaire for eliciting very specific data on engine production. This strategy was subsequently abandoned since companies classified such data as confidential. The best information baseline required to predict likely future patterns of propulsion systems was found available from a specific company but was incomplete. The author had to estimate some data and make some assumptions (as explained in sections 6.1.4 and 6.2) in order to use such data. These estimates do not question mark the validity of the prediction process.

9.3.2 Stakeholder involvement

The engine plants and engine production machinery builders in general are the real stakeholders of the present study. Their involvement in the present study was however quite limited. The author has attempted higher levels of involvement in two distinct stages, at an initial stage, while knowledge eliciting was fundamental, and at a near simulation model completion stage, where model feedback could be important. Such involvement has been realised but to a very limited extent and eventually during the thesis write up was discontinued. This limited involvement from industrial stakeholders results from the research study being largely initiated and conducted in a pure academic setting.

9.3.3 Research methodology

The use of research methodologies in the present study corresponds to that of eliciting field related knowledge, developing a new concept with potential to advance existing solutions and provide evidence of validity of the reasoning chain and findings. Future patterns of engine demands and scenario by scenario economic comparison were exercised since evidence about advancing best practice could be provided by using relevant variables identified for the specific engine sector, such as (1) economic issues; (2) future engine demands (volumes and configurations); and (3) assurance of quality standards. It was assumed that at least similar levels of quality standards could be met by the novel machining approach. The novel approach had previously been identified with potential to economically produce some patterns of engine demand. It is believed that the use of the proposed methodology, concepts, specific software tools and methods can be applied generally. In some respects though the particular findings of the present study are company specific and therefore are not directly generalisable.

9.3.4 Research weakness

The weaknesses of the research conducted and hereby documented may prove to be:

- The Q'@gile system approach is still only conceptual, and although care has been taken in the design of the system elements that make up a single cell, real life implementations may differ slightly from the descriptions made in section 4.5. This in turn may also have direct implications on the simulation model and its execution, and therefore on the simulation run results presented in sections 5.2 and 5.3;

- Access to specific industrial data on individual engine production data was restricted. The same applies to specific investments made in each line to machine each part of a single engine configuration. A wider base of this type of information would have been highly desirable;

- The future patterns of propulsion systems baseline presented in section 6.1 is based largely on AUDI AG company real data. This data was however partially complete and was subject to some extrapolations from the author, as explained in section 6.1.4. It would have been better if the raw data used for the scenarios baseline was complete and directly provided by the company;

- The quantitative effect of technological developments, such as in fuel cells and Hydrogen fuel, is impossible to accurately measure, especially over a long timeframe such as the one used in the development of the future scenarios. The author has tried to envelope the quantitative effects of a number of likely developments. However, it is possible (and maybe even likely) that the future will outpace the envelope defined by the 36 scenarios.

9.4 RECOMMENDED FURTHER RESEARCH

A real industrial case of using the concepts and methodology developed in this study would be highly desirable. Such a study should be conducted in collaboration with a given vehicle manufacturer, or a specific powertrain alliance or a machine builder. Free access to inner company data must be assured as well as to people in charge of defining powertrain strategies.

In the light of the latest developments in the crude oil price, it is suggested that a study could be undertaken to deeply understand the nature of the factors causing such phenomenon and the likelihood of reaching the world production peak before the end of the present decade (or to identify a possible date when this is likely to happen) and by way of wider study make grounded speculations about the implications on the automotive industry and on the transportation sector in general over defined timeframes.

The highly successful European pathway towards increased share of diesel cars *versus* the recent enthusiasm of the Japanese and North American marketplaces for hybrid petrol vehicles have been triggered by common interests, i.e. the adoption of more fuel efficient vehicles and more environmental friendly vehicles. This has triggered the idea: "why not combine the already higher efficiencies of diesel engines with the optimised driving cycle of hybrids?". The additional power from the electrical motor could help to reduce the capacity of the diesel engine, therefore giving rise to additional cuts in fuel consumption.

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APPENDICES

APPENDIX A

WORLDWIDE FUEL CELL VEHICLES

FUEL CELLS 2000
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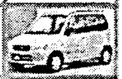
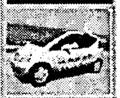
Fuel Cell Vehicles

(From Auto Manufacturers)

Automaker	Vehicle Type	Year Shown	Engine Type	Fuel Cell Size/type	Fuel Cell Mfr.	Range (mi/km)	MPG Equivalent*	Max. Speed	Fuel Type	Commercial Intro.	Picture
Audi	A2	2004	Fuel cell/battery hybrid	66KW/ PEM	Ballard	220km	N/a	175km/h	Gaseous hydrogen		
BMW	Series 7 (745 h) (Sedan)	2000	ICE (fuel cell APU)	5KW/ PEM	UTC	180mi 300km	N/a	140 mph	Gasoline/ Liquid hydrogen	Limited intro in 2000 (Munich Airport Hydrogen Vehicle Project)	
Daihatsu	MOVE EV - FC (micro van)	1999	Fuel cell/ battery hybrid	16KW/ PEM	Toyota	N/a	N/a	N/a	Methanol		
	MOVE FCV – K II (mini vehicle)	2001	Fuel cell/ battery hybrid	30 kW/ PEM	Toyota	75mi 120km	N/a	65mph 105km/h	Compress. hydrogen @ 3600 psi	Japan road testing started in early 2003.	
Daimler-Chrysler	NECAR 1 (180 van)	1994	12 fuel cell stacks	50KW/ PEM	Ballard	81mi 130km	N/a	56mph 90km/h	Compress. hydrogen @ 4300 psi		
	NECAR 2 (V-Class)	1996	Fuel cell	50KW/ PEM	Ballard	155mi 250km	N/a	68mph 110km/h	Compress. hydrogen @ 3600 psi		
	NECAR 3 (A-Class)	1997	2 fuel cell stacks	50KW/ PEM	Ballard Mark 700 Series	250mi 400km	N/a	75mph 120km/h	10.5 gal. of Liquid methanol	First methanol reforming FCV	
	NECAR 4 (A-Class)	1999	Fuel cell	70KW/ PEM	Ballard Mark 900 Series	280mi 450km	N/a	90mph 145km/h	Liquid hydrogen		
	Jeep Commander 2 (SUV)	2000	Fuel cell/ (90 kW) battery hybrid	50KW/ PEM	Ballard Mark 700 Series	118mi 190km	24 mpg (gasoline equiv.)	N/a	Methanol	Jeep Commander 1 came out in 1999.	
	NECAR 4 - Advanced (California NECAR)	2000	Fuel cell	85KW/ PEM	Ballard Mark 900 Series	124mi 200km	53.46 mpg equiv. (CaFCP est.)	90mph 145 km/h	4 lbs. (1.8kg) of Compress. hydrogen @ 5,000 psi		
	NECAR 5 (A-class)	2000	Fuel cell	85KW/ PEM	Ballard Mark 900 Series	280mi 450km	N/a	95mph 150km/h	Methanol		
	NECAR 5.2 (A-class)	2001	Fuel cell/ battery hybrid	85KW/ PEM	Ballard Mark 900 Series	300mi 482km	N/a	95mph 150km/h	Methanol	Awarded a road permit for Japanese roads. Completed CA – DC drive.	
	Sprinter (van)	2001	Fuel cell	85KW/ PEM	Ballard Mark 900 Series	93mi 150km	N/a	75mph 120km/h	Compress. Hydrogen @ 5,000 psi	Delivered to Hamburg parcel service, Hermes as part of the W.E.I.T. hydrogen project, also used by UPS	
	Natrium (Town & Country Mini Van)	2001	Fuel cell/ (40 kW) battery hybrid	54KW/ PEM	Ballard Mark 900 Series	300mi 483km	30 mpg equiv.	80mph 129km/h	Catalyzed chemical hydride - Sodium Borohydride	Uses Millennium Cell's 'Hydrogen on Demand' system with a 53 gallon fuel tank	
	F-Cell (A-class)	2002	Fuel cell/ battery hybrid	85KW/ PEM	Ballard Mark 900 Series	90mi 145km	56 mpg equiv.	87mph 140km/h	4 lbs. (1.8kg) of Compress. hydrogen @ 5,000 psi	60 fleet vehicles in US, Japan, Singapore, and Europe started in 2003 – small fleet in Michigan operated by UPS.	

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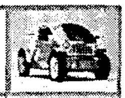
	Jeep Treo	2003	Fuel cell	N/a	N/a	N/a	N/a	N/a	N/a	Unveiled at Tokyo Motor Show – drive by wire technology	
ESORO	Hycar	2001	Fuel cell/ battery hybrid	6.4kW/ PEM	Nuvera	224mi 360km	N/a	75mph 120km/h	Compress. Hydrogen	Switzerland's first FCV	
Fiat	Seicento Elettra H2 Fuel Cell	2001	Fuel cell/ battery hybrid	7kW/ PEM	Nuvera	100mi 140km	N/a	60mph 100km/h	Compress. hydrogen		
	Seicento Elettra H2 Fuel Cell	2003	Fuel cell/ battery hybrid	N/a	Nuvera	N/a	N/a	N/a	Compress. hydrogen	Being investigated for use in Milan, Italy, where gasoline and diesel fueled vehicles are banned on smoggy days.	
Ford Motor Company	P2000 HFC (sedan)	1999	Fuel cell	75kW/ PEM	Ballard Mark 700 Series	100mi 160km	67.11 mpg equiv. (CaFCP est.)	N/a	Compress. hydrogen	First FCV by Ford	
	Focus FCV	2000	Fuel cell	85kW/ PEM	Ballard Mark 900 Series	100mi 160km	N/a	80mph 128km/h	Compress. hydrogen @ 3,600 psi		
	THINK FC5	2000	Fuel cell	85kW/ PEM	Ballard Mark 900 Series	N/a	N/a	80mph/ 128km/h	Methanol		
	Advanced Focus FCV	2002	Fuel cell/ battery hybrid	85kW/ PEM	Ballard Mark 900 Series	180mi 290km	~50 mpg equiv.	N/a	8.8 lb. (4kg) Compress. H2 @ 5,000 psi	3 year demonstration in Vancouver beginning late 2004. 30 fleet vehicles in Sacramento, Orlando and Detroit	
GM	Sintra (mini-van)	1997	Fuel cell	50kW/ PEM	N/a	N/a	N/a	N/a	N/a	Wants to be 1st automaker to sell 1 million FCVs profitably	
**Hydrogenics works with GM on FC development	Zafira (mini-van)	1998	Fuel cell	50kW/ PEM	Ballard	300mi 483km	80 mpg equiv.	75mph 120km/h	Methanol	GM has ceased efforts regarding methanol (2001)	
	Precept FCEV Concept only	2000	Fuel cell/ battery hybrid	100kW/ PEM	GM**	500mi 800km (est.)	108 mpg equiv. (est.)	120mph 193km/h	Hydrogen (stored in metal hydride)	These are concept projections	
	HydroGen 1 (Zafira van)	2000	Fuel cell/ battery hybrid	80kW/ PEM	GM**	250mi 400km	N/a	90mph 140km/h	16 gal. of Liquid hydrogen	GM plans to sell 75kW hydrogen stationary fuel cell generators in 2005	
	HydroGen 3 (Zafira van)	2001	Fuel cell	94kW/ PEM	GM**	250mi 400km	N/a	100mph 160km/h	Liquid hydrogen	Being used by FedEx Corp. in Tokyo, Japan from 6/2003 – 6/2004	
	Chevy S-10 (pickup truck)	2001	Fuel cell/ battery hybrid	25kW/ PEM	GM**	240mi 386km	40 mpg	70 mph	Low sulfur, clean gasoline (CHF)	GM has partnership with Toyota on reforming	
	AUTOnomy Concept only	2002	Fuel cell	N/a	N/a	N/a	Projected 100 mpg	N/a	N/a	GM's 2010 FCV concept Freedom of Design	
	Hy-Wire Proof of Concept	2002	Fuel cell	94kW/ PEM	GM**	80mi 129km	~41 mpg (gas equiv.)	97mph 160km/h	4.4 lbs.(2kg) Compress. h2 @ 5,000 psi	Uses HydroGen3's powertrain, so range & mpg theoretically could = HydroGen3	
	Advanced HydroGen 3 (Zafira van)	2002	Fuel cell	94kW/ PEM	GM**	170mi 270km	~55 mpg (gas equiv.)	~100mph 160km/h	6.8lbs. (3.1kg) Compress. h2 @ 10,000 psi	1st FCV to incorporate 10,000 psi tanks (by Quantum). 6 placed in Washington DC.	
	Diesel Hybrid Electric Military truck	2003	Fuel cell APU	5kW/ PEM	Hydrogenics	N/a	N/a	N/a	Low pressure metal hydrides	Turbo diesel ICE/battery hybrid with PEM FC APU. Under eval. for US Army's new fleet of 30,000 light tactical vehicles	

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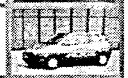
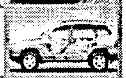
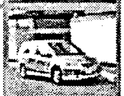
GM (Shanghai) PATAC	Phoenix (Mini van)	Oct 2001	Fuel cell/ battery hybrid	25kW / PEM	Shanghai GM**	120mi 200km	N/a	70mph 113km/h	Compress. hydrogen	Seventh FCV prototype out of China	
Honda	FCX-V1	1999	Fuel cell/ battery hybrid	60KW/ PEM	Ballard Mark 700 Series	110mi 177km	N/a	78mph 130km/h	Hydrogen (stored in metal hydride)		
	FCX-V2	1999	Fuel cell	60KW/ PEM	Honda	N/a	N/a	78mph 130km/h	Methanol	Honda has strict focus on pure hydrogen FCVs (2001)	
	FCX-V3	2000	Fuel cell/ Honda ultra capacitors	62KW/ PEM	Ballard Mark 700 Series	108mi 173km	N/a	78mph 130km/h	26 gal. of Compress. hydrogen at 3600 psi		
	FCX-V4	2001	Fuel cell/ Honda ultra capacitors	85KW/ PEM	Ballard Mark 900 series	185mi 300km	~50 mpg (gas equiv.)	84mph 140km/h	130 L (3.75kg) Compress. H2 @ 5,000 psi	Completed Japanese road testing - 1st FCV to receive CARB & EPA emission certs.	
	FCX	2002	Fuel cell/ Honda ultra capacitors	85KW/ PEM	Ballard Mark 900 series	220mi 355km	~50 mpg (gas equiv.)	93mph 150km/h	156.6 L Compress. hydrogen @ 5000 psi	Have 4 in Japan, 5 in L.A., 3 in San Francisco	
	Kiwami concept	2003	Fuel cell	N/a	N/a	N/a	N/a	N/a	Hydrogen	Unveiled at Tokyo Motor Show	
Hyundai	Santa Fe SUV	2000	Ambient-pressure Fuel cell	75KW/ PEM	UTC Fuel Cells	100mi 160km	N/a	77mph 124km/h	Compress. hydrogen		
	Santa Fe SUV	2001	Ambient-pressure Fuel cell	75KW/ PEM	UTC Fuel Cells	250mi 402km	N/a	N/a	Compress. hydrogen		
	Tucson	2004	Fuel cell	80kW PEM	UTC Fuel Cells	300km	N/a	150km/h	Compress. hydrogen	Will demonstrate 32 Tucson FCVs under DOE's Hydrogen Fleet and Infrastructure Demonstration and Validation Project by 2009	
Kia	Sportage	2004	Fuel cell	80kW PEM	UTC Fuel Cells	300km	N/a	150km/h	Compress. hydrogen		
Mazda	Demio (compact passenger car)	1997	Fuel cell/ ultra capacitor hybrid	20KW/ PEM	Mazda	106mi 170km	N/a	60mph 90km/h	Hydrogen (stored in metal hydride)		
	Premacy FC-EV	2001	Fuel cell	85kW/ PEM	Ballard Mark 900 Series	N/a	N/a	77mph 124km/h	Methanol	Awarded road permit for Japanese roads in 2001 – undergoing public road testing	
Mitsubishi	SpaceLiner Concept only	2001	Fuel cell/ battery hybrid	40KW/ PEM	N/a	N/a	N/a	N/a	Methanol		
	Grandis FCV (mini-van)	2003	Fuel cell/battery hybrid	68kW PEM	Daimler Chrysler/ Ballard	92mi 150km	N/a	87mph 140km/h	Compress. Hydrogen		
Nissan	R'nessa (SUV)	1999	Fuel cell/ battery hybrid	10KW/ PEM	Ballard Mark 700 Series	N/a	N/a	44mph 70km/h	Methanol	Partnership with Renault for gasoline fueled FCV until 2006	
**Made prototypes w/ each fuel cell stack	Xterra (SUV)	2000/2001	Fuel cell/ battery hybrid	85KW/ PEM	Ballard Mark 900 Series & UTC Fuel Cells**	100mi 161km	N/a	75mph 120km/h	Compress. hydrogen	Will begin driving trials in California and Arizona.	
	X-TRAIL (SUV)	2002	Fuel cell/ battery hybrid	75KW/ PEM	UTC Fuel Cells (Ambient-pressure)	N/a	N/a	78mph 125km/h	Compress. hydrogen @ 5,000 psi	Approved for Japanese Public road testing – 3 leased to Japanese gov.	
	Effis (commuter concept)	2003	Fuel cell/battery hybrid	N/a	N/a	N/a	N/a	N/a	N/a	Unveiled at Tokyo Motor Show	

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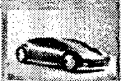
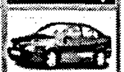
PSA Peugeot Citron	Peugeot Hydro-Gen	2001	Fuel cell/ battery hybrid	30kW/ PEM	Nuvera	186mi 300km	N/a	60mph 95km/h	Compress. hydrogen		
	Peugeot Fuel Cell Cab "Taxi PAC"	2001	Fuel cell/ battery hybrid	55kW/ PEM	H Power	188mi 300km	N/a	60mph 95km/h	80 Liters Compress. hydrogen @ 4300 psi		
	H2O fire-fighting Concept only	2002	Battery/ fuel cell APU	N/a	N/a	N/a	N/a	N/a	Catalyzed chemical hydride - Sodium Borohydride	Uses Millennium Cell's 'Hydrogen on Demand' system	
Renault	EU FEVER Project (Laguna wagon)	1997	Fuel cell/ battery hybrid	30kW/ PEM	Nuvera	250mi 400km	N/a	75mph 120km/h	Liquid hydrogen	Partnership with Nissan on gasoline fueled FCV	
Suzuki	Covie Concept only	2001	Fuel cell	N/a	GM	N/a	N/a	N/a	N/a		
	Mobile Terrace	2003	Fuel cell	N/a	GM	N/a	N/a	N/a	Hydrogen	Unveiled at Tokyo Motor Show	
Toyota	RAV 4 FCEV (SUV)	1996	Fuel cell/ battery hybrid	20kW/ PEM	Toyota	155mi 250km	N/a	62mph 100km/h	Hydrogen (stored in metal hydride)		
	RAV 4 FCEV (SUV)	1997	Fuel cell/ battery hybrid	25kW/ PEM	Toyota	310mi 500km	N/a	78mph 125km/h	Methanol		
	FCHV-3 (Kluger V/ Highlander SUV)	2001	Fuel cell/ battery hybrid	90kW/ PEM	Toyota	186mi 300km	N/a	93mph 150km/h	Hydrogen (stored in metal hydride)	Toyota is developing a Japanese residential 1kW stationary fuel cell system for 2005	
	FCHV-4 (Kluger V/ Highlander SUV)	2001	Fuel cell/ battery hybrid	90kW/ PEM	Toyota	155mi 250km	N/a	95mph 152km/h	Compress. Hydrogen @ 3,600 psi	Completed Japanese road testing	
	FCHV-5 (Kluger V/ Highlander SUV)	2001	Fuel cell/ battery hybrid	90kW/ PEM	Toyota	N/a	N/a	N/a	Low sulfur, clean gasoline (CHF)	Partnered with GM on gasoline CHP reforming technology	
	FCHV (Kluger V/ Highlander SUV)	2002	Fuel cell/ battery hybrid	90kW/ PEM [122 hp]	Toyota	180mi 200km	N/a	96mph 155km/h	Compress. hydrogen @ 5,000 psi	Total of 18 leased in California and Japan	
	FINE-S Concept only	2003	Fuel cell	N/a	N/a	N/a	N/a	N/a	N/a	Toyota's freedom of design concept	
VW	EU Capri Project (VW Estate)	1999	Fuel cell/ battery	15kW/ PEM	Ballard Mark 500 Series	N/a	N/a	N/a	Methanol	Involved Johnson-Matthey, ECN, VW, and Volvo	
	HyMotion	2000	Fuel cell	75kW/ PEM	N/a	220mi 350km	N/a	86mph 140km/h	13 gal. Of Liquid Hydrogen		
	HyPower	2002	Fuel cell/ super-capacitors hybrid	40kW/ PEM	Paul Scherrer Institute	94mi/ 150km	N/a	N/a	Compress. hydrogen		

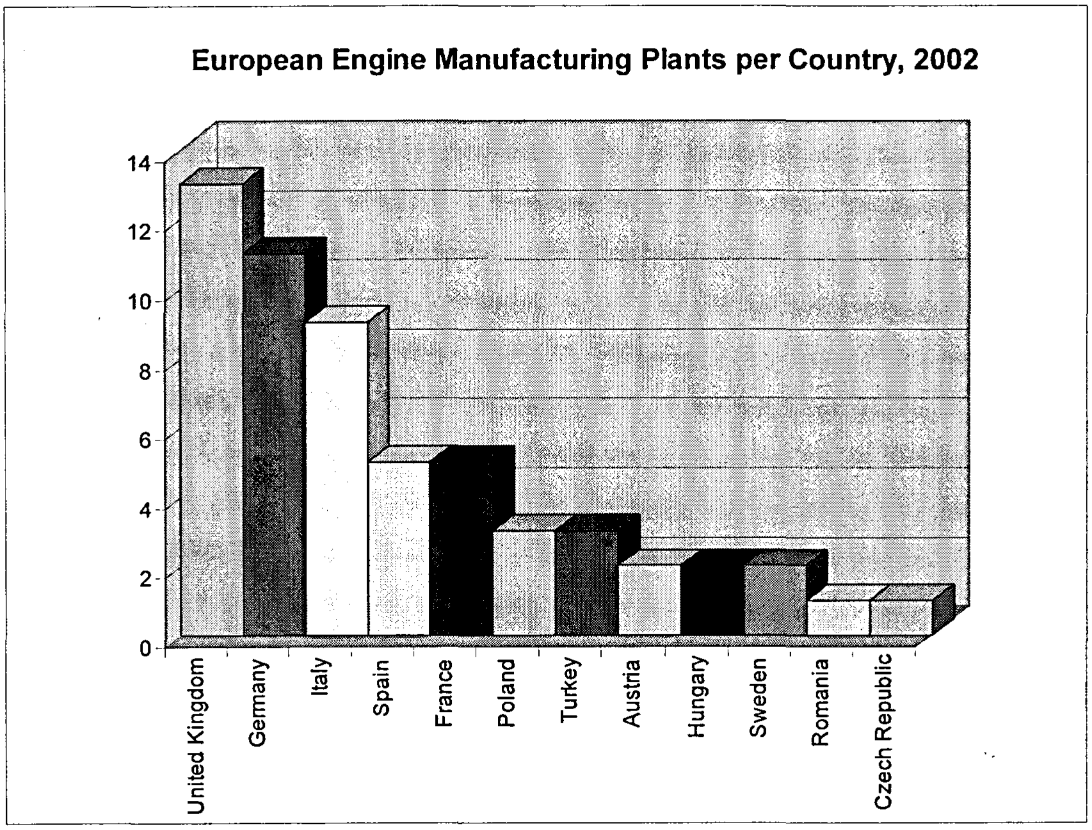
Note: mpg gas equivalent is based on conversion rate of 1 kg hydrogen = 1 gallon gasoline energy equivalent

Visit www.fuelcells.org for free downloadable charts, including Worldwide Installations, Worldwide Hydrogen Fueling Stations, Fuel Cell Buses, and Fuel Cell Specialty Vehicles.

APPENDIX B

ENGINE AND TRANSMISSION PLANTS IN EUROPE

Engine Manufacturing Plants in Europe, by country: 57 Engine Plants



United Kingdom 13 Plants	Engine Manufacturer
Hams Hall	BMW
Ellesmere Port	Fiat-GM Powertrain
Bridgend	Ford
Dagenham	Ford
Solihull	Ford
Swindon	Honda
Longbridge	MG Rover
Sunderland	Nissan
Deeside-North Wales	Toyota
Crewe	VW
Hethel	Lotus
Northampton headquarters	Cosworth Technology
Wellingborough Assembling	Cosworth Technology

Germany 11 Plants	Engine Manufacturer
Munich	BMW
Badcannstatt	DaimlerChrysler
Berlin-Marienfelde	DaimlerChrysler
Stutgard-Unterturkheim	DaimlerChrysler
Bochum	Fiat-GM Powertrain
Kaiserslautern #1	Fiat-GM Powertrain
Kaiserslautern #2	Fiat-GM Powertrain
Cologne	Ford
Zuffenhausen	Porsche
Chemnitz	VW
Salzgltler	VW

Italy 9 Plants	Engine Manufacturer
Foggia	Fiat Group
Maranello	Fiat Group
Arese	Fiat-GM Powertrain
Mirafiori	Fiat-GM Powertrain
Pratola Serra	Fiat-GM Powertrain
Termoli	Fiat-GM Powertrain
Sant'Agata Bolones	VW
Reggio Emilia	Lombardini SRL
Cento	Detroit Diesel/VW Motori

Spain 5 Plants	Engine Manufacturer
Valencia	Ford
Cuatro Vientos	Nissan
Valladolid	Renault
Martorell	VW
Pamplona	VW

France 5 Plants	Engine Manufacturer
Tremery	PSA
Douvrin	PSA
Cleon	Renault
Douvrin (Francaise de Mecanique)	Renault
Valenciennes	Toyota

Poland 3 Plants	Engine Manufacturer
Blelsko Biala	Fiat-GM Powertrain
Polkowice	VW
Tychy	Isuzu

Turkey 3 Plants	Engine Manufacturer
Bursa	Fiat-GM Powertrain
Ford Otosan	Ford
Bursa	Renault

Austria 2 Plants	Engine Manufacturer
Steyr	BMW
Aspern	Fiat-GM Powertrain

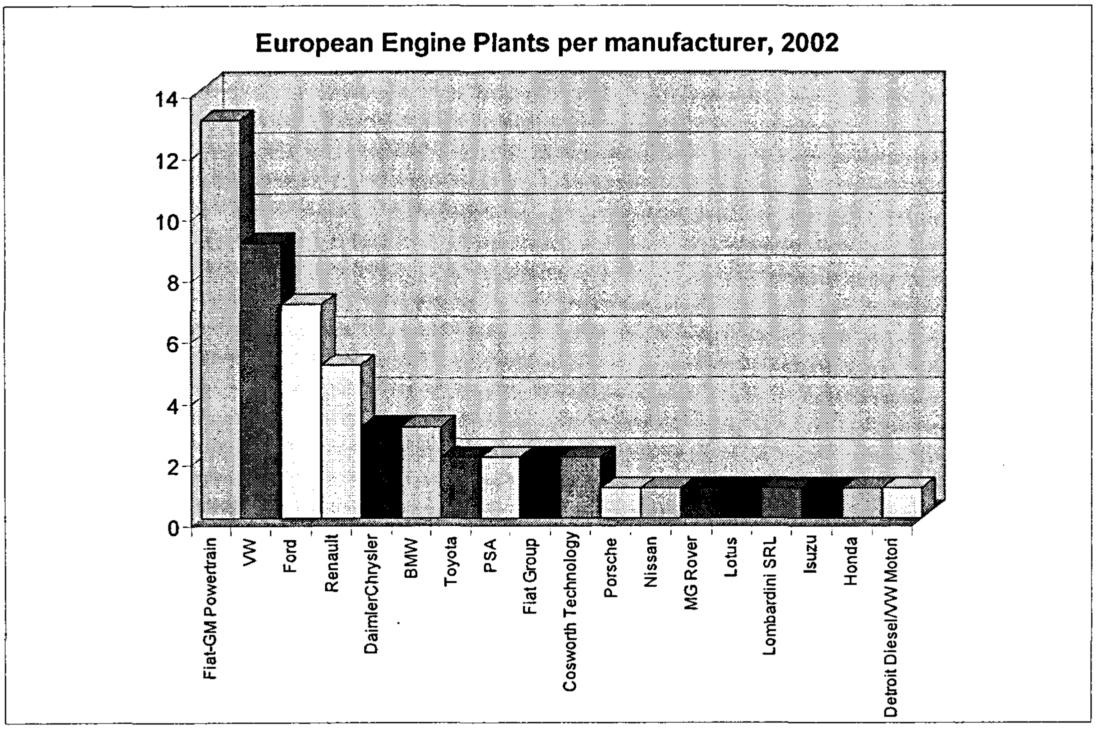
Hungary 2 Plants	Engine Manufacturer
Szentgotthard	Fiat-GM Powertrain
Gyor	VW

Sweden 2 Plants	Engine Manufacturer
Sodertalje	Fiat-GM Powertrain
Skovde	Ford

Romania 1 Plant	Engine Manufacturer
Dacia Pitesti	Renault

Czech Republic 1 Plant	Engine Manufacturer
Mlada Boleslav	VW

Engine Manufacturing Plants in Europe, by manufacturer: 57 Engine Plants



BMW	Country
Hams Hall	United Kingdom
Munich	Germany
Steyr	Austria

Cosworth Technology	Country
Northampton headquarters	United Kingdom
Wellingborough Assembling	United Kingdom

DaimlerChrysler	Country
Badcannstatt	Germany
Berlin-Marienfelde	Germany
Stutgard-Unterturkheim	Germany

Detroit Diesel/VW Motori	Country
Cento	Italy

Fiat Group	Country
Foggia	Italy
Maranello	Italy

Fiat-GM Powertrain	Country
Ellesmere Port	United Kingdom
Bochum	Germany
Kaiserslautern #1	Germany
Kaiserslautern #2	Germany
Arese	Italy
Mirafiori	Italy
Pratola Serra	Italy

Termoli	Italy
Blelsko Biala	Poland
Bursa	Turkey
Aspern	Austria
Szentgotthard	Hungary
Sodertalje	Sweden

Ford	**Country**
Bridgend	United Kingdom
Dagenham	United Kingdom
Solihull	United Kingdom
Cologne	Germany
Valencia	Spain
Ford Otosan	Turkey
Skovde	Sweden

Honda	**Country**
Swindon	United Kingdom

Isuzu	**Country**
Tychy	Poland

Lombardini SRL	**Country**
Reggio Emilia	Italy

Lotus	**Country**
Hethel	United Kingdom

MG Rover	**Country**
Longbridge	United Kingdom

Nissan	**Country**
Sunderland	United Kingdom
Cuatro Vientos	Spain

Porsche	**Country**
Zuffenhausen	Germany

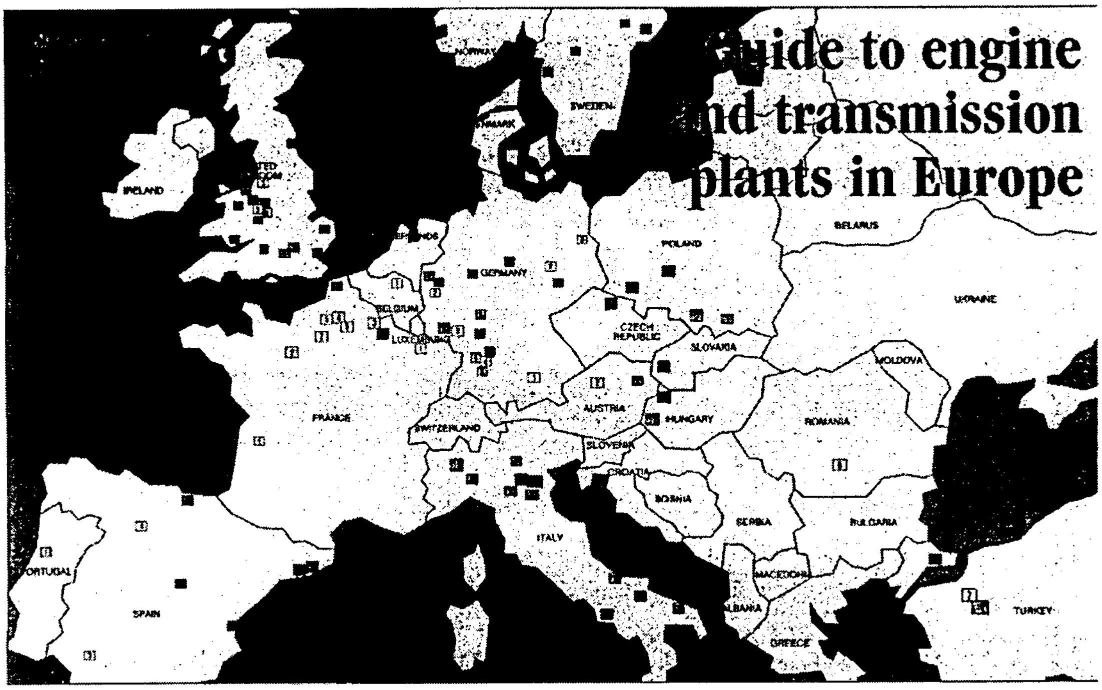
PSA	**Country**
Tremery	France
Douvrin	France

Renault	**Country**
Valladolid	Spain
Cleon	France
Douvrin (Francaise de Mecanique)	France
Bursa	Turkey
Dacia Pitesti	Romania

Toyota	**Country**
Deeside-North Wales	United Kingdom
Valenciennes	France

VW	**Country**
Crewe	United Kingdom
Chemnitz	Germany
Salzgltler – DE	Germany
Sant'Agata Bolonesa – IT	Italy
Martorell – ES	Spain
Pamplona - ES	Spain
Polkowice – PL	Poland
Gyor - HU	Hungary
Mlada Boleslav - CZ	Czech Republic

Guide to engine and transmission plants in Europe



Key to map

BMW GROUP

[1] **Munich, Germany (engine):** 8-cylinder gasoline (3 series, 5 series, 7 series, X5, Z3); V-8 gasoline (5 series, 7 series, X5); V-12 gasoline (7 series); V-8 diesel (7 series); M engines: 6-cylinder (M3, M coupe, M roadster), V-8 (M5, Z8)

[2] **Steyr, Austria (engine):** 4-cylinder gasoline (3 series, Z3); 4-cylinder diesel (3 series, 5 series); 6-cylinder diesel (3 series, 5 series, 7 series, X5); 6-cylinder gasoline (3 series, 5 series, 7 series, Z3, X5)

[3] **Hams Hall, England (engine):** 4-cylinder gasoline (3 series)

DAIMLERCHRYSLER

[1] **Hedelfingen, Germany (transmission):** Manual and automatic transmissions

[2] **Bad Cannstatt, Germany (engine):** V-6 and V-8 gasoline engine

[3] **Berlin-Marienfelde, Germany (engine):** 12-cylinder gasoline, 8-cylinder diesel, Smart engine (gasoline/diesel), components and parts for passenger-car engines (Mercedes-Benz and Smart); remanufactured engines and parts for passenger cars and commercial vehicles (Mercedes-Benz)

[4] **Stuttgart-Untertürkheim, Germany (engine):** Central site for engines, axles and transmissions for Mercedes-Benz passenger cars; foundry, forge
Stuttgart-Untertürkheim, Germany (transmission)

FIAT GROUP

Foggia, Italy (engine): Sofim turbodiesel engines for light commercial vehicles

Maranello, Italy (engine): 3.6-liter V-8 and 5.5-5.7-liter V-12 (all Ferraris), 4.2-liter V-8 (all Maseratis)
Maranello, Italy (transmission)

FIAT-GM POWERTRAIN

Arese, Italy (engine): 2.5-liter, 3.0-liter, 3.2-liter V-6 (Alfa Romeo, Lancia)

Aspern, Austria (engine): Ecotec 3-cylinder 1.0-liter 12-valve; Ecotec 4-cylinder 1.2-liter 16-valve (Opel, Vauxhall)
Aspern, Austria (transmission)

Bochum, Germany (engine): 1.4-liter 8-valve, 1.4-liter 16-valve, 1.6-liter (Chevrolet, Holden, Opel, Vauxhall)
Bochum, Germany (transmission)

Ellesmere Port, England (engine): 2.6-liter, 3.0-liter, 3.2-liter V-6 (Cadillac, Opel, Saab, Saturn, Vauxhall)

Kaiserslautern #1 and #2, Germany (engine): DI - diesel engine, 2.2-liter gasoline (Chevrolet, Holden, Opel, Saab, Vauxhall)

Mirafiori, Italy (engine): 1.6-liter Torque gasoline (Lancia, Alfa Romeo)
Mirafiori, Italy (transmission)

Pratola Serra, Italy (engine): 1.6-liter, 1.8-liter, 2.0-liter, 2.4-liter gasoline; 1.9-liter, 2.4-liter turbodiesel (Fiat, Lancia, Alfa Romeo)

Rüsselsheim, Germany (transmission)

Termoli, Italy (engine): 1.1-liter, 1.2-liter gasoline (Fiat, Lancia)
Termoli, Italy (transmission)

Verrone, Italy (transmission)

Szentgotthard, Hungary (engine): 1.4-liter, 1.6-liter, 1.8-liter (Opel, Vauxhall)

Bielsko Biala, Poland (engine): 100 GL (Fiat)
Bielsko Biala, Poland (transmission)

Gothenburg, Sweden (transmission)

Sodertalje, Sweden (engine): 2.0-liter, 2.3-liter (Saab)

Bursa, Turkey (engine): 1.4-liter 4-V, 8-V, 1.6-liter 8-V, 131, 138 (Fiat)
Bursa, Turkey (transmission)

FORD MOTOR COMPANY

Bridgend, England (engine): 4-cylinder 1.4-liter, 1.6-liter, 1.8-liter, 2.0-liter Zetec; 3.2-liter, 4.0-liter V-8 (Jaguar)

Cologne, Germany (engine): 4.0-liter V-6 single overhead camshaft

Dagenham, England (engine): 1.8DI, 2.0-liter, 2.4-liter Duratorq diesel engines; 2.0-liter OOHC gasoline

Koping, Sweden (transmission)

Skovde, Sweden (engine): 4-cylinder, 5-cylinder and 6-cylinder inline engines

Solihull, England (engine): L Series 2.0-liter diesel (Rover 25, 45); Storm 5-cylinder 2.5-liter diesel (Defender, Defender Military, Discovery); 4.0-liter V-8 gasoline and 4.6-liter gasoline (Discovery 4.0, Range Rover 4.0 and 4.6)
Solihull, England (transmission)

Valencia, Spain (engine): 1.3-liter Endura E

Ford Otosan, Turkey (engine): 6-cylinder 6.0-liter, 6-cylinder 6.2-liter, 4-cylinder 2.5-liter, 4-cylinder 2.0-liter
Ford Otosan, Turkey (transmission)

GETRAG

Neuenstein, Germany (transmission)

Bari, Italy (transmission)

Ludwigsburg, Germany (transmission)

GETRAG FORD

[1] **Bordeaux, France (transmission)**

[2] **Cologne, Germany (transmission)**

[3] **Halewood, England (transmission)**

HONDA

Swindon, England (engine): 4-cylinder 1.6-liter, 2.0-liter, 2.3-liter gasoline (Accord range); 1.4-liter, 1.6-liter, 2.0-liter gasoline (Civic range); 2.0-liter, 2.4-liter gasoline (CR-V range)

MG ROVER

Longbridge, England (engine): K series 4-cylinder and V-6 engines for MG Rover and Land Rover
Longbridge, England (transmission)

NISSAN MOTOR

Cuatro Vientos, Spain (engine): 4-cylinder 2.66-liter (Terrano II); 4-cylinder 2.18-liter (Almera Tino)

Sunderland, England (engine): 1.0-liter, 1.4-liter gasoline (Micra); 1.5-liter gasoline (Almera); 1.6-liter gasoline (Primera); 1.8-liter gasoline (Primera, Almera); 2.0-liter gasoline and diesel (Primera; cylinder head for diesel bought in from Japan); 2.2-liter diesel (Almera, Primera; engine block imported from Spain)

PORSCHE

Zuffenhausen, Germany (engine): 6-cylinder engines for all Porsche models

PSA

[1] **Metz-Borny, France (transmission)**

[2] **Tremery, France (engine):** EW gasoline (Citroen Xsara, Picasso, C5, C8, Jumpy; Peugeot 206, 307, 406, 607, 807, Expert); DW diesel (Citroen Xsara, Picasso, C5, C8, Jumpy, Jumper, Berlingo, C15; Peugeot 206, 307, 406, 607, 807, Expert, Partner, Boxer)

[3] **Valenciennes, France (transmission)**

[4] **Douvrin, France (engine):** TU gasoline (Citroen C3, Saxo, Xsara, Picasso, Berlingo; Peugeot 106, 206, 306, 307, Partner); ES/L gasoline (Citroen C5, Peugeot 406, 607), TU diesel (Citroen Saxo, Peugeot 106); DV diesel (Peugeot 206, 307)

RENAULT

[1] **Cacia, Portugal (transmission)**

[2] **Cleon, France (engine):** 4-cylinder gasoline/diesel (Clio, Kangoo, Megane, Laguna II, Espace, New Trafic, Master); 4-cylinder diesel (Espace, Master)
Cleon, France (transmission)

[3] **Seville, Spain (transmission)**

[4] **Valladolid, Spain (engine):** 4-cylinder gasoline/diesel (Clio, Kangoo, Megane, Laguna II)

[5] **Douvrin (Francaise de Mecanique), France (engine):** 4-cylinder gasoline (Twingo, Clio, Kangoo); 24-valve V-6 (Clio, Laguna II, Espace, Avantime)

[6] **Dacia (Pitesti), Romania (engine):** 4-cylinder gasoline (Dacia SuperNova, Berline, Break, Pickup)

[7] **Bursa, Turkey (engine):** 4-cylinder gasoline (Clio, Kangoo, Megane)

TOYOTA

Deeside, North Wales (engine): 1.0-liter (Yaris), 1.4-liter (Corolla), 1.6-liter (Corolla, Avensis), 1.8-liter gasoline (Avensis)

Walbrzych, Poland (transmission)

Valenciennes, France (engine): 1.0-liter, 1.3-liter gasoline (Yaris), 1.4-liter diesel (from 2003)

VOLKSWAGEN

Chemnitz #1, Germany (engine): 1.0-liter, 1.4-liter, 1.6-liter 4-cylinder gasoline (various group models)

El Prat, Spain (transmission)

Crewe, England (engine): 6.75-liter (V-8 Bentley)

Kassel, Germany (transmission)

Martorell, Spain (engine assembly)

Pamplona, Spain (engine assembly)

Salzgitter, Germany (engine): VR5 (VW Golf, Bora, Passat and Beetle; Seat Toledo, Cordoba and Leon; Skoda Octavia); VR6 (VW Golf, Bora and Sharan; Seat Leon and Alhambra; Mercedes-Benz Vito); W8 (VW Passat); W12 (Audi A8); 1.2-liter gasoline, 3-cylinder 1.4-liter diesel (VW Lupo, Audi A2); 1.0/1.4/1.6 4-cylinder gasoline (Seat Arosa, Ibiza, Cordoba, Leon/Toledo; Skoda Fabia; VW Lupo, Polo, Golf; Audi A2 & A3) 1.6/2.0 liter, 4-cylinder gasoline (VW Golf, Bora, Passat; Audi A4; Skoda Octavia; Seat Ibiza, Cordoba, Leon, Toledo plus all engines for light commercial vehicles)

Gyor, Hungary (engine): 4-cylinder 1.6-liter, 1.8-liter, 2.0-liter gasoline and diesel (Audi A4, TT plus other VW group models); 2.8-liter, 3.0-liter V-6 gasoline and diesel (Audi A4, A6, A8 plus diesel engines for VW Passat); 3.2-liter, 4.0-liter V-8 gasoline and diesel (Audi A6, A8)

Polkowice, Poland (engine): 4-cylinder 1.9-liter pump-injection diesel (all 1.9-liter VW, Audi, Seat and Skoda models)

Bratislava/Marfa, Slovak Republic (transmission)

Mlada Boleslav, Czech Republic (engine): 4-cylinder 1.0-liter (Skoda Fabia; Seat Arosa; VW Lupo); 4-cylinder 1.3-liter (Skoda Felicia);

Sant'Agata Bolognese, Italy (engine): 6.2-liter V-12 gasoline (Lamborghini Murcielago)
Sant'Agata Bolognese, Italy (transmission)

ZF FRIEDRICHSHAFEN

[1] **Sint Truiden, Belgium (transmission)**

[2] **Brandenburg, Germany (transmission)**

[3] **Saarbrucken, Germany (transmission)**

OTHERS

ISUZU

Tychy, Poland (engine)

LOMBARDINI SRL

Reggio Emilia, Italy (engine): Diesel engines up to 70hp for automotive, power-station and agricultural applications; engine families; LGV series (microcars and city cars such as Ligier, TownLife, Grecav, Tasso and Piaggio)

LOTUS

Hethel, England (engine)

SOCIETE DE TRANSMISSIONS AUTOMATIQUES (RENAULT 80%, PSA 20%)

Ruitz, France (transmission)

DETROIT DIESEL/VM MOTORI

Cento, Italy (engine)

COSWORTH TECHNOLOGY

Northampton headquarters, England: Ford STV Focus 4-cylinder engine

Wellingborough Machining and Assembly, England: Audi RS4; Aston Martin DB7, Vantage and Vanquish

Source: Automotive News Europe

APPENDIX C

LABVIEW

***Lab**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench*

LabVIEW is a software development application from National Instruments company. The first commercial version of this development tool, was launch in October 1986. Labview is a general purpose development tool and has been used widely in instrumentation, data acquisition, control and analysis software applications.

Labview uses a graphical programming language, named G language, to create programs in block diagram form. Labview programming uses graphical symbols and links, which makes programming tasks rather different from text based languages. Labview has a compiler and a debugger and an independent application generator which enables the execution of stand-alone computer programs.

The modules developed under Labview are named Virtual Instruments (VIs). Labview has libraries of VIs which can be reused or changed freely in order to fit end user computer applications. The programmer can also build new VIs and add them up to the VI library. A Virtual Instrument is logically divided into two components:

1. Front Panel

The front panel is a component, which incorporates the interactive Human-Machine Interface (HMI). The front panel includes knobs, push buttons, graphs, LEDs and other controls and indicators. Figure C.1 shows an example of a *front panel* for a computer application.

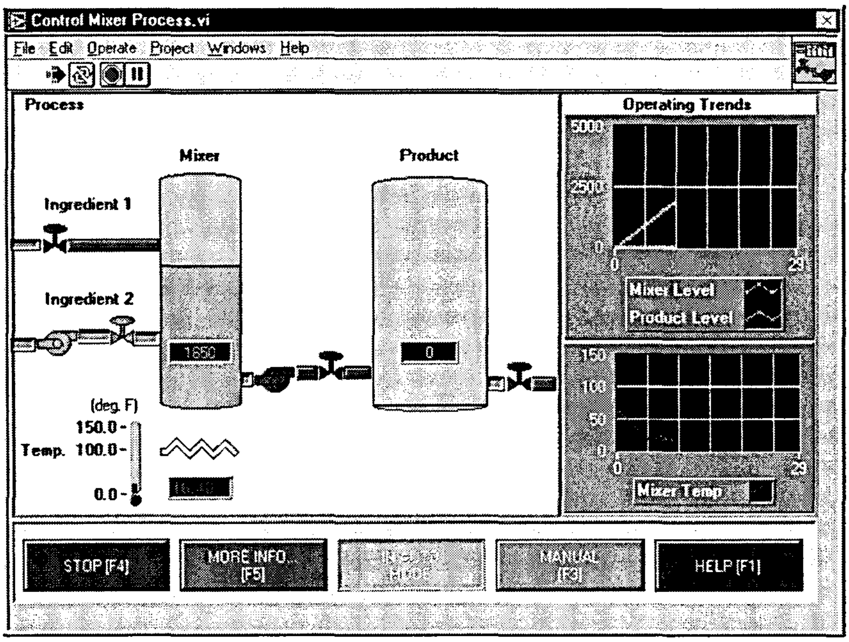


Figure C.1 Example of a Front Panel of a Virtual Instrument: *Control Mixer Process.vi*

2. Block Diagram

Virtual Instruments receive instructions from a block diagram, which is built using the G language. The block diagram has the original code of the VI. This code is based in links, which represent data flows, between VIs. VIs are represented by icons. Different types of data flows are represented by different types of links between the VIs, therefore it is easy to interpret the flow of information among VIs which make up a block diagram. Figure C.2 presents a block diagram of the ***Control Mixer Process. VI*** virtual instrument.

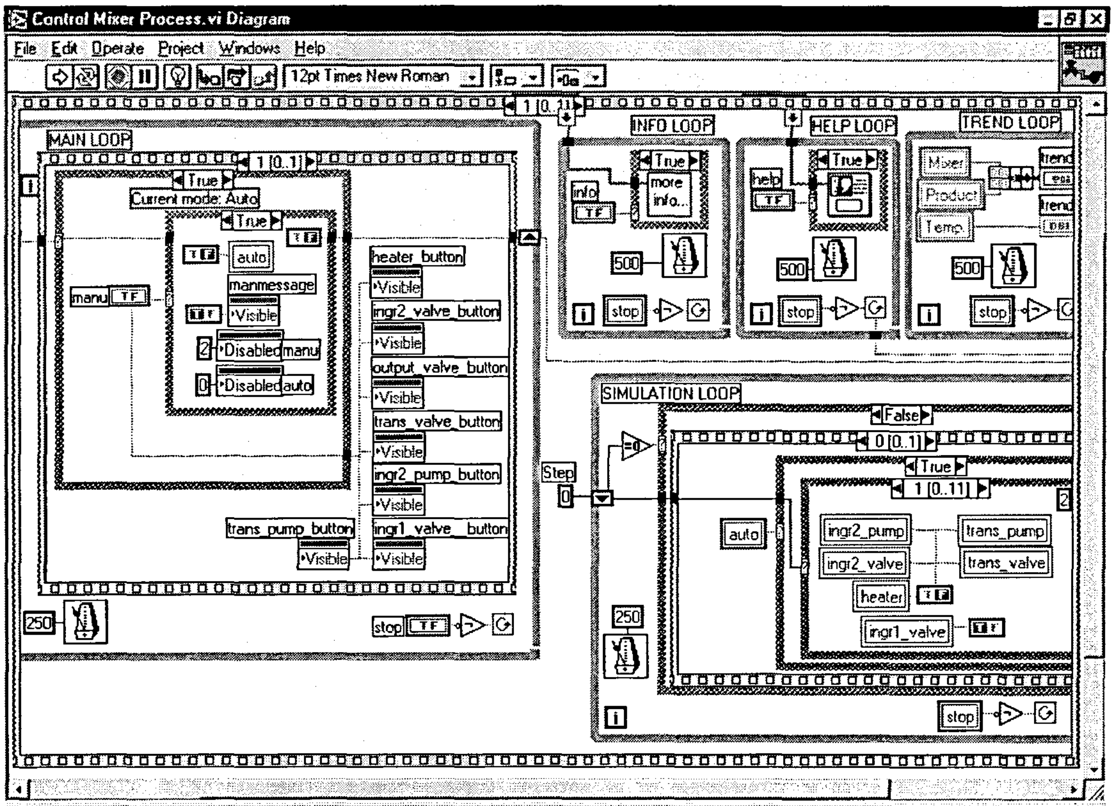


Figure C.2 Example of a Block Diagram of a Virtual Instrument.

Each VI is hierarchically organized into a series of sub-VIs, which correspond to a division of a full problem into a series of tasks, which in turn are decomposed into sub-tasks, so that in the end a complicated problem becomes a series of simple subtasks. Although this assumes that those systems and tasks modelled can be decomposed into essentially decoupled models of subsystems and sub-tasks. Figure C.3 presents the hierarchy of VIs for a given application.

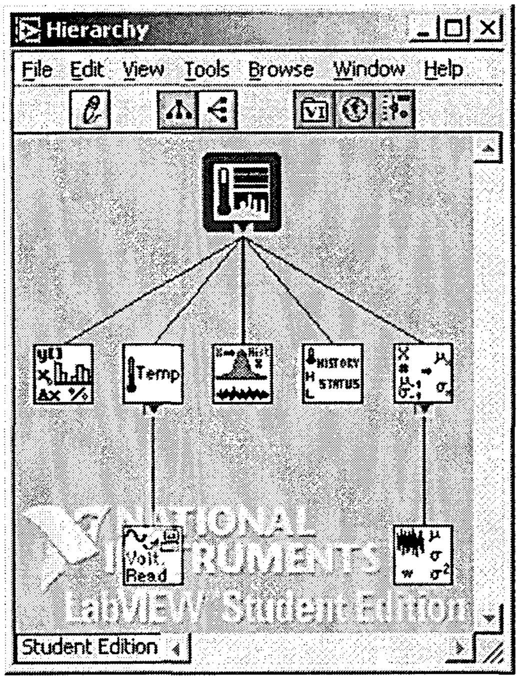


Figure C.3 Representation of a Virtual Instrument hierarchy.

Each VI has its own icon, which visually represents its function, and a conector pane which gives a set of points for external connection with other VIs. It is through these connection points that data will flow to and from other VIs. Figure C.4 shows the connection points for a specific VI and the respective meaning of data that flows through respective links.

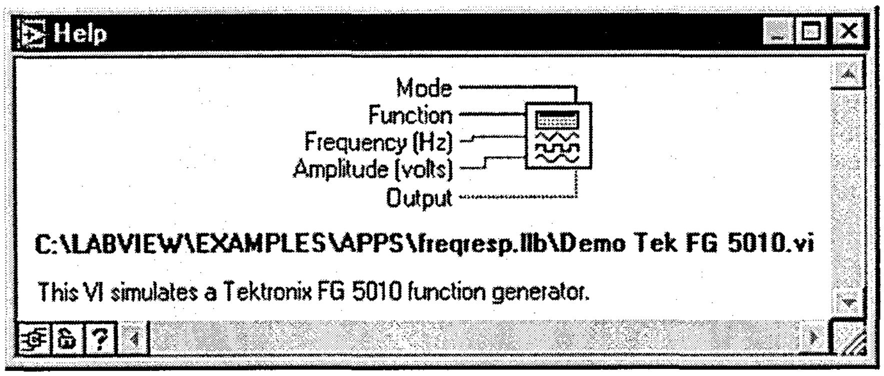


Figure C.4 Example of a VI icon and connector pane.

The construction of a program under Labview consists essentially of two tasks, namely:

A) the construction of the HMI in the VI front panel, by using the control palette. The control toolbar is presented in figure C.5.

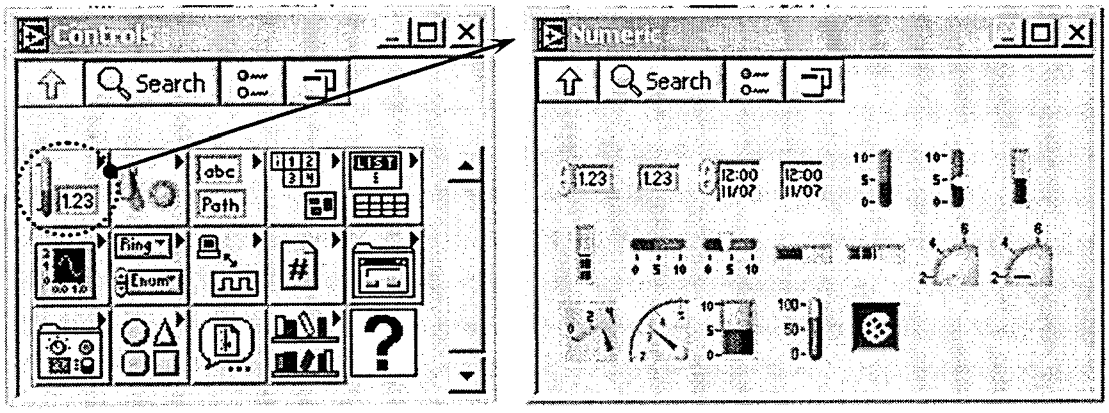


Figure C.5 Controls palette, e.g. numeric controls.

B) The development of the VI structure and functions of a block diagram, by using the functions toolbar. The function toolbar is presented in figure C.6.

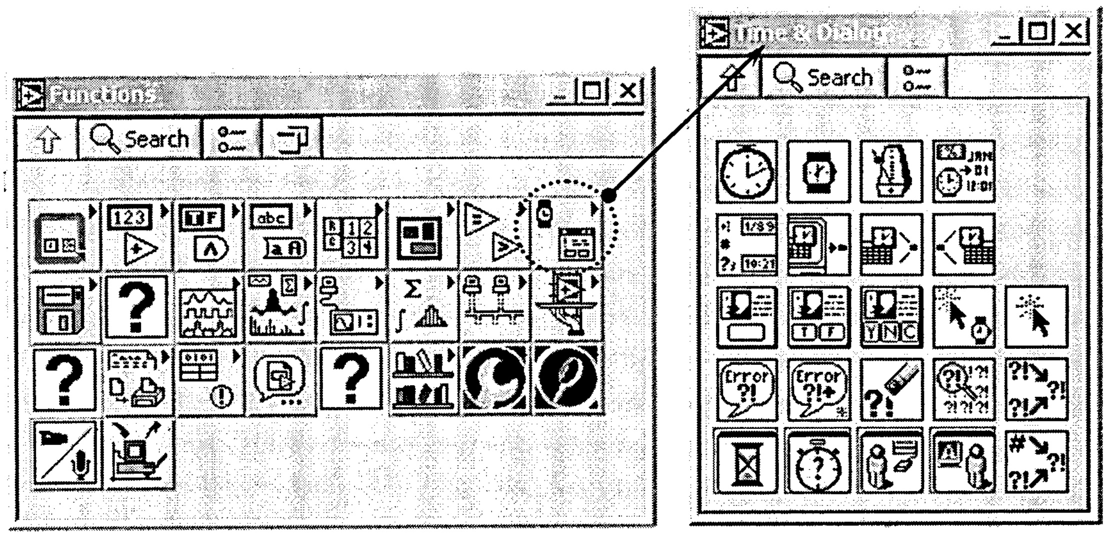


Figure C.6 Library of functions, e.g. time & dialog functions.

APPENDIX D

SIMULATION MODEL

(SOURCE CODE EXTRACTS)

The programming language used in LabVIEW is the G language. This language is a graphical language which uses icons and connectors to implement programming functionalities.

The program which simulates Q'@gile and DTL systems takes the form of a sequence of steps:

1. The user specifies the simulation parameters, these define the:
   - configuration of engine to be manufactured;
   - type of engine and respective timings for machining (if different from the timings already associate with particular engines);
   - simulation speed (timer);
   - simulation goal, i.e. produce a fixed number of engine parts or simulate a fixed timeframe;
   - whether or not the Q'@gile and DTL models run simultaneously or only one of them at a time;
   - working regime;
   - initial number of Q'@gile cells in the system.
2. The model gets executed
   - processes are run;
   - user events are enabled and take place, which impact on the simulation processes;
   - relevant information is displayed for the user, which enables the simulation processes to be monitored.
3. Relevant simulation data is displayed in appropriate format, and data is saved or export to an Excel spreadsheet.

The first step was implemented via a while loop. This enables the user to configure simulation parameters. The system runs the simulation only when the user triggers the RUN button, which in terms of code execution means the end of the while loop. Figure D.1 presents the G language code for this stage.

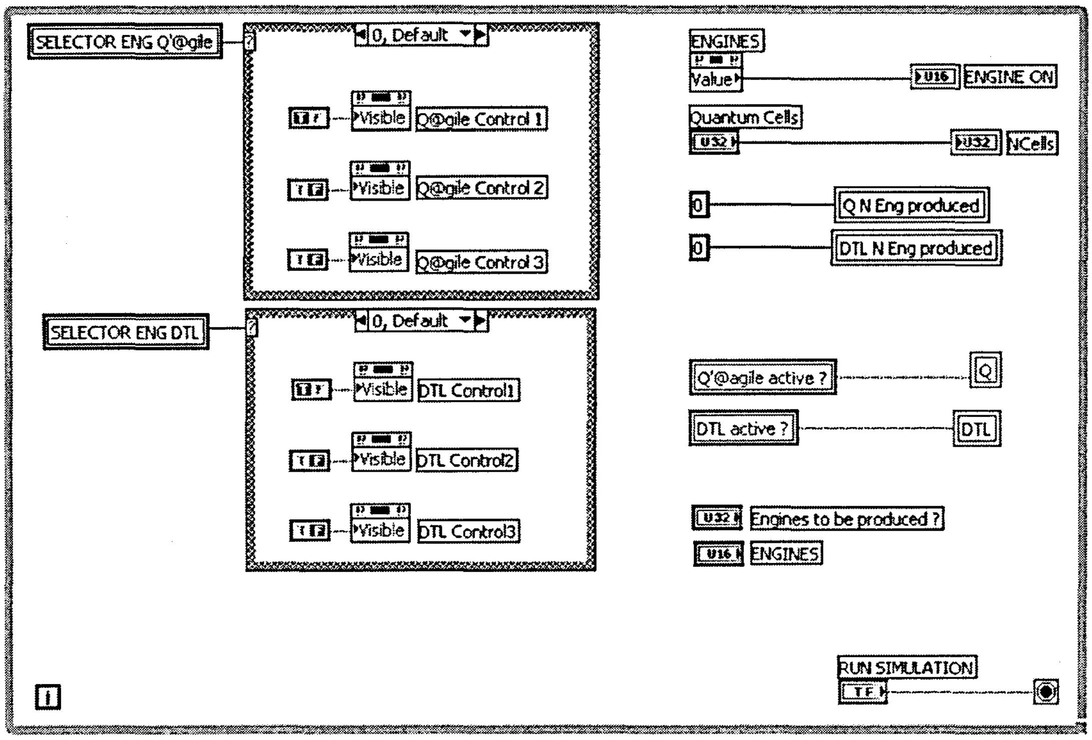


Figure D.1 G language code of the setup of the simulation parameters.

The second step was implemented by two processes which run in parallel, one for the Q'@gile system and the other for the DTL system.

The Q'@gile system is presented in figure D.2 along with its respective operations i.e.: machining operations, tool & face changes, breakdowns and quality faults. These system elements are presented graphically in figure D.3 a), D.3 b), D.3 c) and D.3 d) respectively.

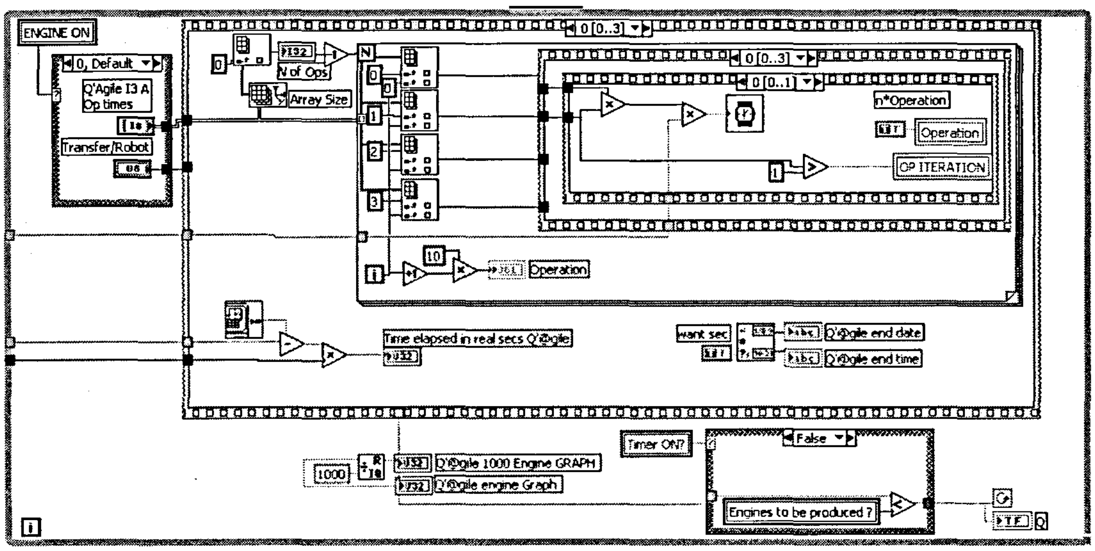


Figure D.2 G language code of the Q'@gile model.

a)

b)

c)

d)

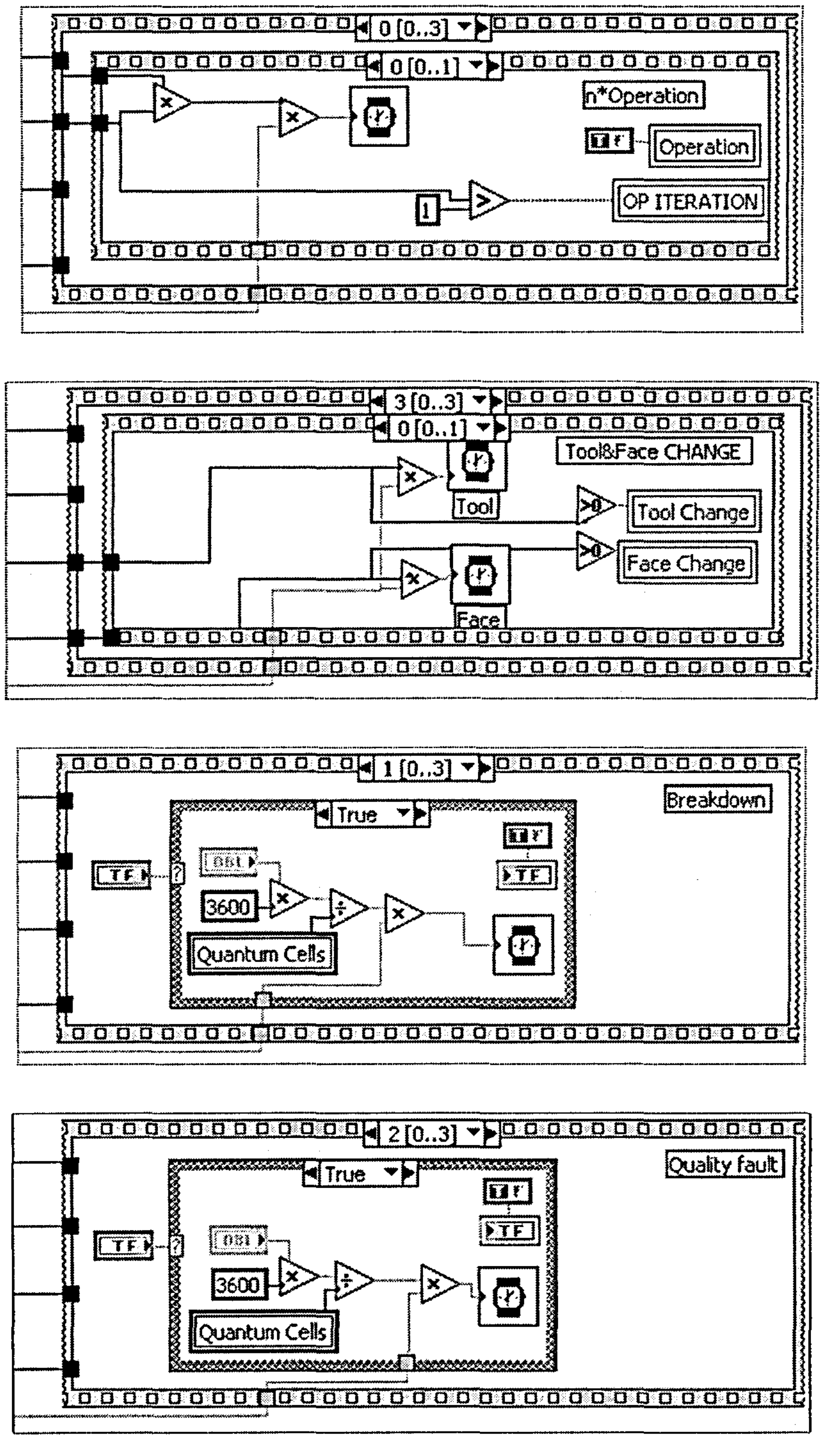


Figure D.3 G language code of the Q'@gile model: a) Machining Op.; b).tool and face change; c) breakdown; and d) quality fault

For DTL system machines elements work in parallel. This principle was applied also at the programming level, i.e. each station was coded into a process which runs concurrently with other processes. Since machines have to wait for each others completion before they can proceed with the transfer of parts to the next station, the same happens with the processes coded by the simulation program. An extract of the DTL system source code of machining operations is presented in figure D.4. Unclamp, transfer and clamp operations are presented respectively in figures D.5 a), D.5 b), and D.5 c).

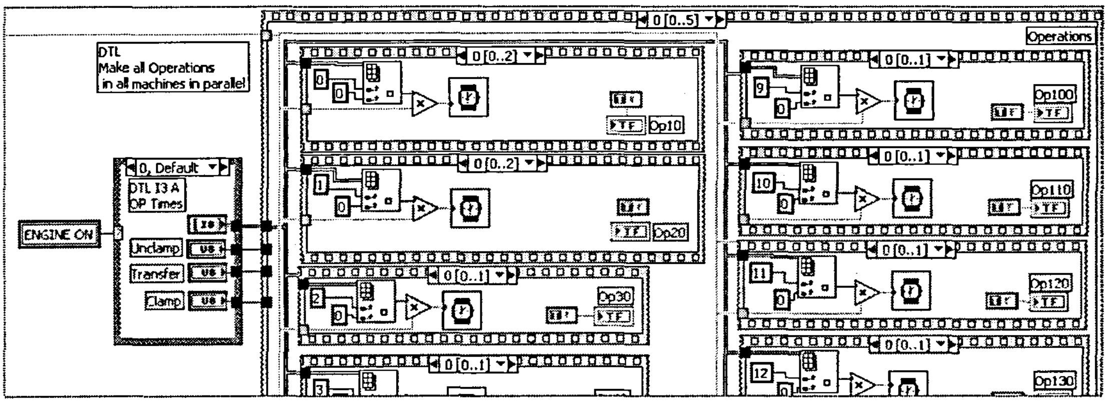


Figure D.4 G language code extract of the DTL model.

a)

b)

c)

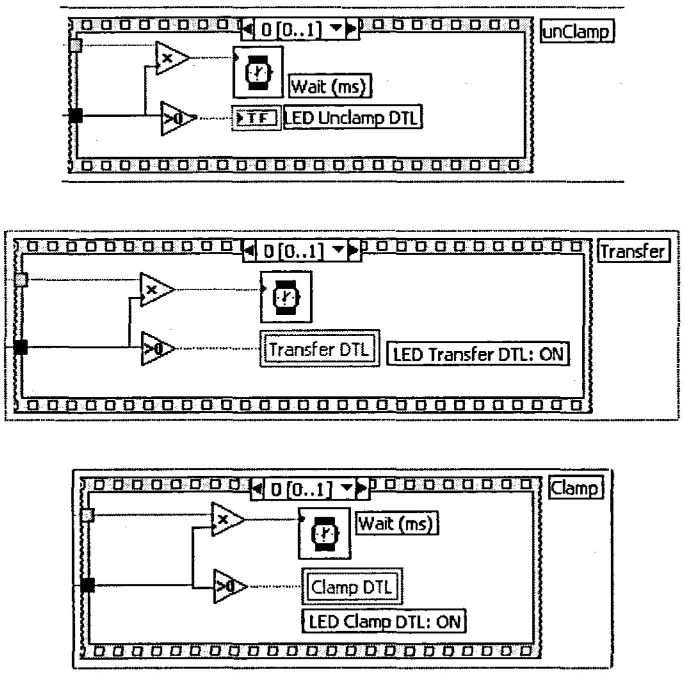


Figure D.5 G language code extract of the DTL model: a) unclamp; b) transfer; c) clamp.

APPENDIX E

SIMULATION TOOL

RESULTS OF THE TYPE 2 TESTS

Type 2 tests include the execution of the model for a particular engine type under a different timer setup. Each timer setup was chosen for tests purposes only, i.e. 1/1000 ratio; 1/100 ratio; 1/10 ratio and 1/1 ratio. Each test was conducted twice using the same timer setup to confirm its validity. A timer setup, such as 1/1000 ratio, means that the model will be executed in a fraction of the real time consumed by the real processes. For the given timer setup ratio of 1/1000 this means that the processes in the model will execute 1000 times faster than real live processes. The tests included a number of simulation runs for the DTL only model (results presented in Table E.1); the Q'@gile only model (results presented in Table E.2); and combined operation of the DTL and Q'@gile models (results are presented in Table E.3)

Table E.1 Results for Type 2 tests using DTL only simulation runs.

Simulation Runs 25.11.2004 (DTL system only)					Cycle time (seconds)	39
					Engine Type	I4-A

Simulation A.1	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	TimeOverhead (%)
	1/1000	100	3,900	3,953.0	3.95	1.36%
	1/1000	1,000	39,000	39,516.0	39.52	1.32%
	1/1000	10,000	390,000	395,531.0	395.53	1.42%
	1/1000	100,000	3,900,000	3,955,969.0	3,955.97	1.44%

Simulation A.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)
	1/1000	100	3,900	3,953.0	3.95	1.36%
	1/1000	1,000	39,000	39,516.0	39.52	1.32%
	1/1000	10,000	390,000	395,532.0	395.53	1.42%
	1/1000	100,000	3,900,000	3,957,922.0	3,957.92	1.49%

Simulation B.1	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)
	1/100	10	390	392.2	3.92	0.56%
	1/100	100	3,900	3,916.0	39.16	0.41%
	1/100	1,000	39,000	39,159.0	391.59	0.41%
	1/100	10,000	390,000	391,544.0	3,915.44	0.40%

Simulation B.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)
	1/100	10	390	392.2	3.92	0.56%
	1/100	100	3,900	3,916.0	39.16	0.41%
	1/100	1,000	39,000	39,180.0	391.80	0.46%
	1/100	10,000	390,000	391,554.7	3,915.55	0.40%

Simulation C.1	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)
	1/10	1	39	39.032	3.90	0.08%
	1/10	10	390	390.320	39.03	0.08%
	1/10	100	3,900	3,902.030	390.20	0.05%
	1/10	1,000	39,000	39,022.340	3,902.23	0.06%

Simulation C.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)
	1/10	1	39	39.016	3.90	0.04%
	1/10	10	390	390.160	39.02	0.04%
	1/10	100	3,900	3,902.190	390.22	0.06%
	1/10	1,000	39,000	39,021.560	3,902.16	0.06%

Simulation D.1	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)
	1	1	39	39.000	39.00	0.00%
	1	10	390	390.094	390.09	0.02%
	1	100	3,900	3,900.016	3,900.02	0.00%

Simulation D.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)
	1	1	39	39.000	39.00	0.00%
	1	10	390	390.016	390.02	0.00%
	1	100	3,900	3,900.000	3,900.00	0.00%

Table E.2 Results for Type 2 tests using Q'@gile only simulation runs.

Simulation Run (Q'@gile system only)	Cycle time (seconds)	334
	Engine Type	I4-A

Simulation A.1

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/1000	100	33,400	33,859.0	33.86	1.37%	a)
1/1000	1,000	334,000	338,562.0	338.56	1.37%	a)
1/1000	10,000	334,000	338,547.0	338.55	1.36%	b)
1/1000	100,000	3,340,000	3,385,422.0	3,385.42	1.36%	b)

Simulation A.2

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/1000	100	33,400	33,860.0	33.86	1.38%	a)
1/1000	1,000	334,000	338,547.0	338.55	1.36%	a)
1/1000	10,000	334,000	338,547.0	338.55	1.36%	b)
1/1000	100,000	3,340,000	3,385,125.0	3,385.13	1.35%	b)

Simulation B.1

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/100	10	3,340	3,356.3	33.56	0.49%	a)
1/100	100	33,400	33,542.2	335.42	0.43%	a)
1/100	1,000	33,400	33,542.2	335.42	0.43%	b)
1/100	10,000	334,000	335,418.7	3,354.19	0.42%	b)

Simulation B.2

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/100	10	3,340	3,354.7	33.55	0.44%	a)
1/100	100	33,400	33,540.6	335.41	0.42%	a)
1/100	1,000	33,400	33,542.2	335.42	0.43%	b)
1/100	10,000	334,000	335,417.2	3,354.17	0.42%	b)

Simulation C.1

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/10	1	334	334.060	33.41	0.02%	a)
1/10	10	3,340	3,341.250	334.13	0.04%	a)
1/10	100	3,340	3,341.250	334.13	0.04%	b)
1/10	1,000	33,400	33,412.500	3,341.25	0.04%	b)

Simulation C.2

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/10	1	334	334.060	33.41	0.02%	a)
1/10	10	3,340	3,341.250	334.13	0.04%	a)
1/10	100	3,340	3,341.250	334.13	0.04%	b)
1/10	1,000	33,400	33,410.000	3,341.00	0.03%	b)

Simulation D.1

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/1	1	334	334.020	334.02	0.01%	a)
1/1	10	334	334.010	334.01	0.00%	b)
1/1	100	3,340	3,340.010	3,340.01	0.00%	b)

Simulation D.2

Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	
1/1	1	334	334.000	334.00	0.00%	a)
1/1	10	334	334.020	334.02	0.01%	b)
1/1	100	3,340	3,340.000	3,340.00	0.00%	b)

a) simulation run with 1 Q'@gile cell
b) simulation run with 10 Q'@gile cells

Table E.3 Results for Type 2 tests using combined DTL and Q'@gile simulation runs.

Simulation Run (DTL + Q'@gile)								Cycle time (seconds)	39	Cycle time (seconds)	334	
								Engine Type	I4-A	Engine Type	I4-A	
			DTL				Q'@gile					
	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
Simulation A.1	1/1000	100	3,900	3,968.0	3.97	1.74%	33,400	33,890.0	33.89	1.47%	a)	
	1/1000	1,000	39,000	39,640.0	39.64	1.64%	334,000	338,937.0	338.94	1.48%	a)	
	1/1000	10,000	390,000	396,297.0	396.30	1.61%	334,000	341,687.0	341.69	2.30%	b)	
	1/1000	100,000	3,900,000	3,962,750.0	3,962.75	1.61%	3,340,000	3,417,141.0	3,417.14	2.31%	b)	
Simulation A.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
	1/1000	100	3,900	3,953.0	3.95	1.36%	33,400	33,875.0	33.88	1.42%	a)	
	1/1000	1,000	39,000	39,625.0	39.63	1.60%	334,000	338,937.0	338.94	1.48%	a)	
	1/1000	10,000	390,000	396,172.0	396.17	1.58%	334,000	341,750.0	341.75	2.32%	b)	
	1/1000	100,000	3,900,000	3,962,407.0	3,962.41	1.60%	3,340,000	3,417,344.0	3,417.34	2.32%	b)	
Simulation B.1	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
	1/100	10	390	392.2	3.92	0.56%	3,340	3,353.1	33.53	0.39%	a)	
	1/100	100	3,900	3,914.0	39.14	0.36%	33,400	33,534.4	335.34	0.40%	a)	
	1/100	1,000	39,000	39,148.5	391.49	0.38%	33,400	33,465.6	334.66	0.20%	b)	
	1/100	10,000	390,000	391,486.0	3,914.86	0.38%	334,000	334,664.1	3,346.64	0.20%	b)	
Simulation B.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
	1/100	10	390	392.2	3.92	0.56%	3,340	3,354.7	33.55	0.44%	a)	
	1/100	100	3,900	3,914.0	39.14	0.36%	33,400	33,534.3	335.34	0.40%	a)	
	1/100	1,000	39,000	39,150.0	391.50	0.38%	33,400	33,465.6	334.66	0.20%	b)	
	1/100	10,000	390,000	391,485.9	3,914.86	0.38%	334,000	334,676.5	3,346.77	0.20%	b)	
Simulation C.1	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
	1/10	1	39	39.060	3.91	0.15%	334	334.060	33.41	0.02%	a)	
	1/10	10	390	390.310	39.03	0.08%	3,340	3,341.250	334.13	0.04%	a)	
	1/10	100	3,900	3,902.500	390.25	0.06%	3,340	3,341.100	334.11	0.03%	b)	
	1/10	1,000	39,000	39,026.710	3,902.67	0.07%	33,400	33,409.680	3,340.97	0.03%	b)	
Simulation C.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
	1/10	1	39	39.060	3.91	0.15%	334	334.220	33.42	0.07%	a)	
	1/10	10	390	390.150	39.02	0.04%	3,340	3,341.250	334.13	0.04%	a)	
	1/10	100	3,900	3,902.650	390.27	0.07%	3,340	3,341.090	334.11	0.03%	b)	
	1/10	1,000	39,000	39,025.780	3,902.58	0.07%	33,400	33,409.840	3,340.98	0.03%	b)	
Simulation D.1	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
	1/1	1	39	39.000	39.00	0.00%	334	334.000	334.00	0.00%	a)	
	1/1	10	390	390.000	390.00	0.00%	334	334.000	334.00	0.00%	b)	
	1/1	100	3,900	3,900.020	3,900.02	0.00%	3,340	3,340.000	3,340.00	0.00%	b)	
Simulation D.2	Timer (fraction of a sec.)	Engine parts	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)	Theoretical time (seconds)	Simulation result (seconds)	Real time used in the Simulation (seconds)	Time Overhead (%)		
	1/1	1	39	39.000	39.00	0.00%	334	334.000	334.00	0.00%	a)	
	1/1	10	390	390.000	390.00	0.00%	334	334.000	334.00	0.00%	b)	
	1/1	100	3,900	3,900.050	3,900.05	0.00%	3,340	3,340.030	3,340.03	0.00%	b)	

a) simulation run with 1 Q'@gile cell
b) simulation run with 10 Q'@gile cells

APPENDIX F

SIMULATION RUNS RESULTS

Table F.1 DTL production system type ‘E’ 4-cylinders engine block operation times.

DTL	Type 'E' I-4 engine block		
Station	**Operation ID**	**Time (seconds)**	**Max**
Station 1 Left (1L)	Op. 10	21	**27**
Station 2 Left (2L)	Op. 20	15	**Unclamp**
Station 2 Right (2R)	Op. 30	13	**2**
Station 3 Left (3L)	Op. 40	12	**Transfer**
Station 3 Right (3R)	Op. 50	21	**8**
Station 4 Left (4L)	Op. 60	25	**Clamp**
Station 4 Right (4R)	Op. 70	27	**2**
Station 5 Left (5L)	Op. 80	15	**Total**
Station 6 Left (6L)	Op. 90	14	**39**
Station 6 Right (6R)	Op. 100	19	
Station 7 Right (7L)	Op. 110	25	
Station 8 Left (8L)	Op. 120	23	
Station 8 Right (8R)	Op. 130	20	
Station 9 Left (9L)	Op. 140	14	
Station 9 Right (9R)	Op. 150	9	
Station 10 Left (10L)	Op. 160	16	
Station 11 Left (11L)	Op. 170	13	
Station 11 Right (11R)	Op. 180	19	

Table F.2 Q’@gile production system type ‘E’ 4-cylinders engine block operation times.

Q'@gile	Type 'E' I-4 engine block					
Operation ID	**Time (seconds)**	**Number of times to repeat**	**Tool exchange**	**Block face change**	**MAX**	**Total (seconds)**
Op. 10	21	1	2	0	2	23
Op. 20	15	4	2	0	2	62
Op. 30	13	8	2	0	2	106
Op. 40	12	10	2	2	2	122
Op. 50	21	1	2	0	2	23
Op. 60	25	4	2	0	2	102
Op. 70	27	8	2	0	2	218
Op. 80	15	4	2	0	2	62
Op. 90	14	1	2	2	2	16
Op. 100	19	1	2	0	2	21
Op. 110	25	4	2	0	2	102
Op. 120	23	1	2	2	2	25
Op. 130	20	4	2	0	2	82
Op. 140	14	6	2	0	2	86
Op. 150	9	4	2	0	2	38
Op. 160	16	1	2	2	2	18
Op. 170	13	1	2	0	2	15
Op. 180	19	4	2	0	2	78
		1,163 Sec			**Total:**	**1,199**

Table F.3 Production halts affecting the manufacture of prime engine parts using DTLs.

Production Halts (DTL)	Occurrences	In 1 year	In 15 years	Average duration of production halt time			
1. Major retooling	1 in 15 years		1	A	B	C	D
				9 months	6 months	3 months	1 month
2. Minor retooling	2 in 15 years		2	E	F	G	H
				2 months	1 month	2 weeks	1 week
3. Engine part Quality Fault	5 per year	5	75	I	J	K	L
				3 days	2 days	2 shifts	1 shift
4. Breakdown of a single machine	1 per year	18	270	M	N	O	P
(assuming a 18 M/Cs based DTL)	(per machine)			2 shifts	1 shift	4h	2h

Table F.4 Simulation results for 8 combinations of production halts using DTLs.

Number	Combination	Simulation Result DTL Capacity (engines)	Percentage of the theoretical Capacity of DTL	Average Yearly Capacity (engines)
1	A-E-I-M	4,164,930	80.0%	277,662
2	C-F-I-M	4,310,410	82.8%	287,361
3	D-F-J-M	4,457,330	85.6%	297,155
4	B-F-J-N	4,580,270	88.0%	305,351
5	A-F-K-P	4,766,100	91.5%	317,740
6	B-G-K-P	4,837,570	92.9%	322,505
7	C-G-K-O	4,842,440	93.0%	322,829
8	D-H-L-P	4,992,000	95.9%	332,800
	Average:	4,618,881	88.7%	307,925
	Theoretical:	5,206,154		347,077

Table F.5 Production halts affecting the manufacture of prime engine parts using Q'@gile systems.

Production Halts (Q'@gile)	Occurrences	In 1 year	In 15 years	Average duration of Production halt time			
1. New engine introduction	1 in 15 years		1	A	B	C	D
(disruption of the machining in all cells)				2 weeks	1 week	3 days	1 day
2. Introduction of new cells to the system	1 per year	1	15	E	F	G	H
(disruption of the machining in all cells)				1 week	3 days	1 day	1 shift
3. Engine part Quality Fault	5 per year	5	75	I	J	K	L
(disruption of the machining in a single cell)				3 days	2 days	2 shifts	1 shift
4. Breakdown of a single Cell	1 per year	20	300	M	N	O	P
(assuming a fixed 20 Cells based Q'@gile)	(per cell)			2 shifts	1 shift	4h	2h

Table F.6 Simulation results for 8 combinations of production halts using Q'@gile systems.

Number	Combination	Simulation Result Q'@gile capacity: 20 cells (engines)	Percentage of the theoretical capacity of Q'@gile	Average Yearly Capacity (engines)
1	A-E-I-M	3,332,980	98.4%	222,199
2	C-F-I-M	3,334,760	98.5%	222,317
3	D-F-J-M	3,336,180	98.5%	222,412
4	B-F-J-N	3,344,100	98.7%	222,940
5	A-F-K-P	3,352,020	99.0%	223,468
6	B-G-K-P	3,356,060	99.1%	223,737
7	C-G-K-O	3,354,800	99.1%	223,653
8	D-H-L-P	3,358,860	99.2%	223,924
	Average:	3,346,220	98.8%	223,081
	Theoretical:	3,386,822		225,788

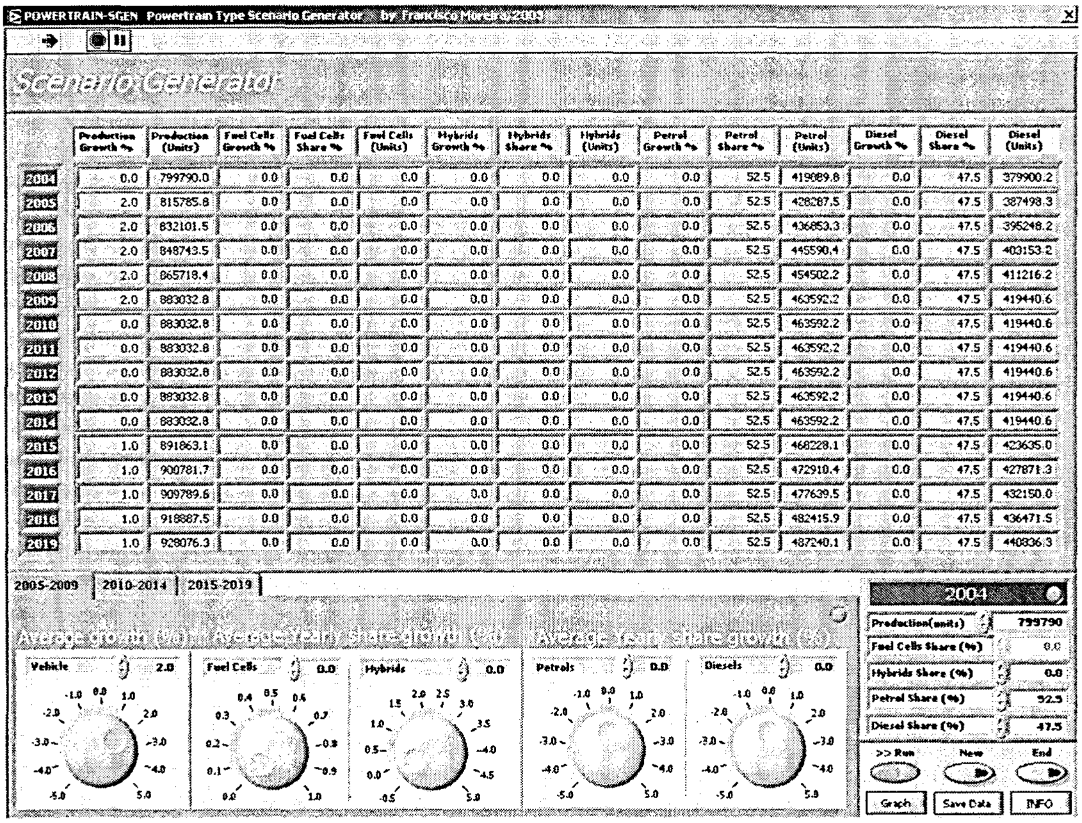
APPENDIX G

36 POWERTRAIN SHARES FUTURE SCENARIOS

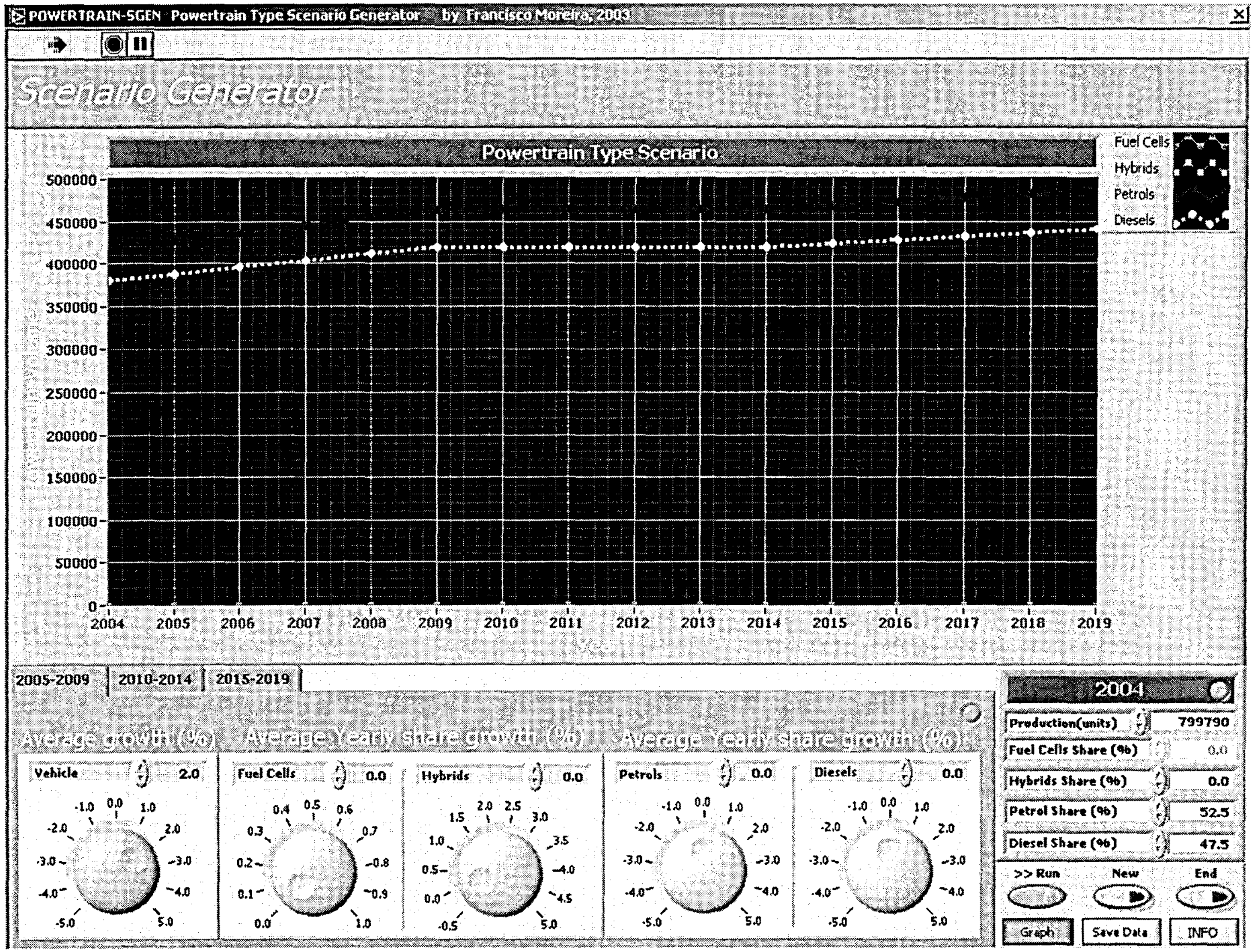
SCENARIO 1

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**
3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.
4. Hybrid vehicles fail to gain market share following market introduction around 2005.
5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0.0**	**0.0**	**0.0**	**0.0**	**Not relevant**
2010-2014	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**	**Smooth**



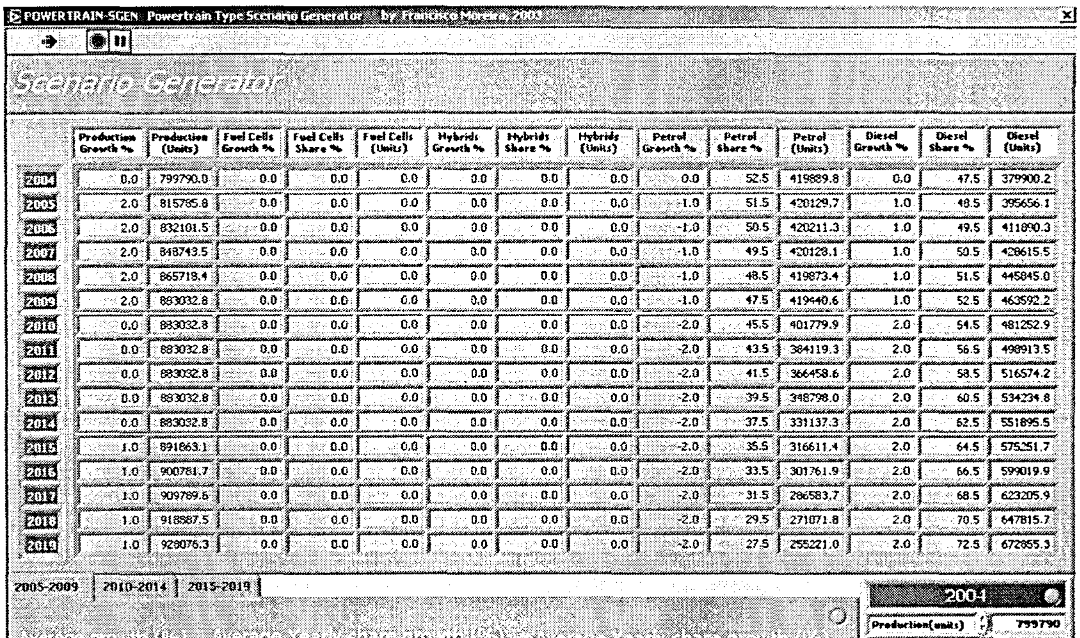
	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	428287.5	0.0	47.5	387498.3
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	436853.3	0.0	47.5	395248.2
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	445590.4	0.0	47.5	403153.2
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	454502.2	0.0	47.5	411216.2
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2010	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2011	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2012	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2013	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2014	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2015	1.0	891863.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	468228.1	0.0	47.5	423635.0
2016	1.0	900781.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	472910.4	0.0	47.5	427871.3
2017	1.0	909789.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	477639.5	0.0	47.5	432150.0
2018	1.0	918887.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	482415.9	0.0	47.5	436471.5
2019	1.0	928076.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	487240.1	0.0	47.5	440836.3


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols 0.0
Diesels 0.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

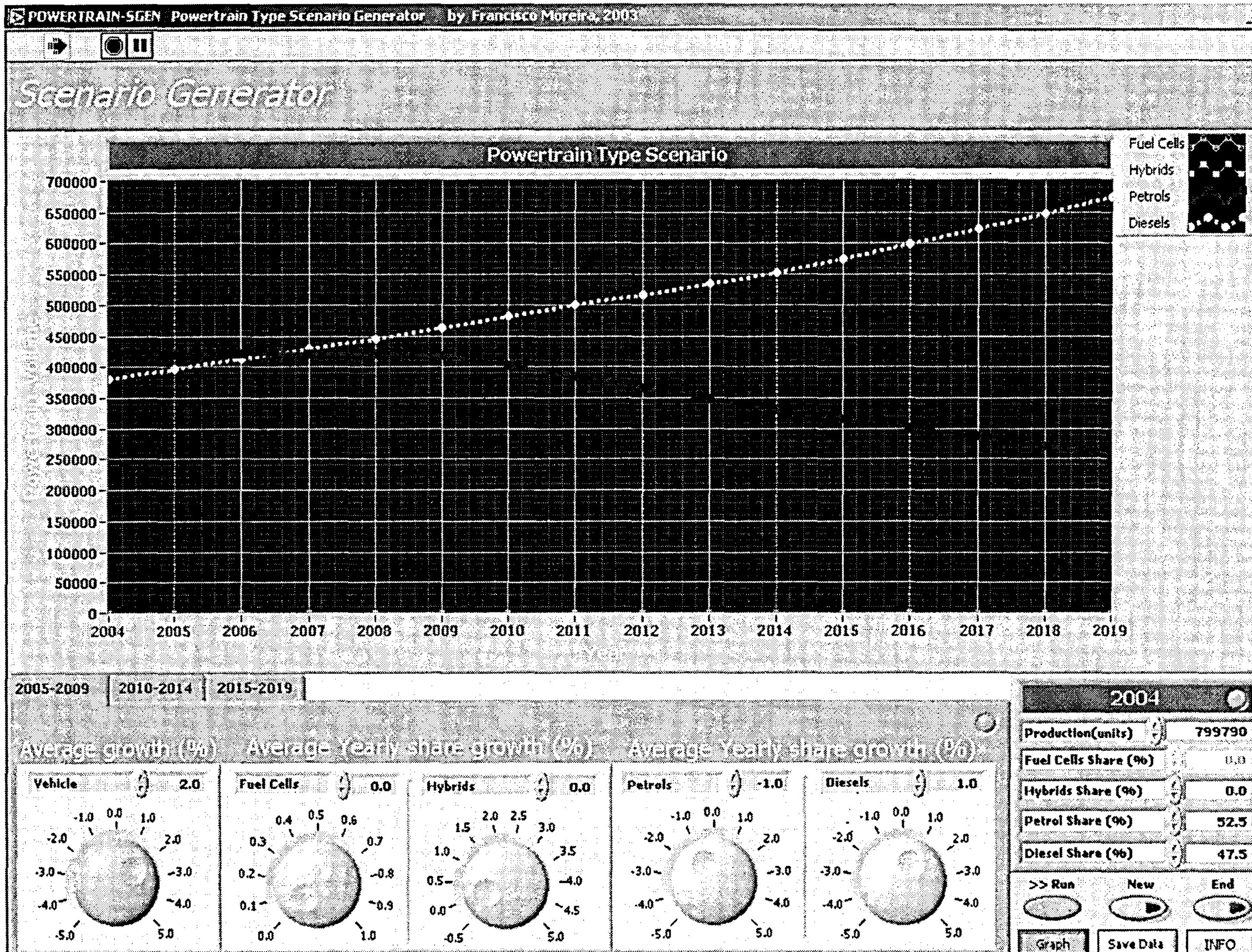
SCENARIO 2

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.
2. **Diesels progressively gain market share against Petrol based vehicles (current trend).**
3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.
4. Hybrid vehicles fail to gain market share following market introduction around 2005.
5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**Not relevant**
2010-2014	**0.0**	**-2.0**	**2.0**	**0.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**-2.0**	**2.0**	**0.0**	**0.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	51.5	420129.7	1.0	48.5	395656.1
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	50.5	420211.3	1.0	49.5	411890.3
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	49.5	420128.1	1.0	50.5	428615.5
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	48.5	419873.4	1.0	51.5	445845.0
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	47.5	419440.6	1.0	52.5	463592.2
2010	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	45.5	401779.9	2.0	54.5	481252.9
2011	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	43.5	384119.3	2.0	56.5	498913.5
2012	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	41.5	366458.6	2.0	58.5	516574.2
2013	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	39.5	348798.0	2.0	60.5	534234.8
2014	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	37.5	331137.3	2.0	62.5	551895.5
2015	1.0	891863.1	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	35.5	316611.4	2.0	64.5	575251.7
2016	1.0	900781.7	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	33.5	301761.9	2.0	66.5	599019.9
2017	1.0	909789.6	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	31.5	286583.7	2.0	68.5	623205.9
2018	1.0	918887.5	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	29.5	271071.8	2.0	70.5	647815.7
2019	1.0	928076.3	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	27.5	255221.0	2.0	72.5	672855.3


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
700000
650000
600000
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols -1.0
Diesels 1.0
2004
Production(units) 799790
Fuel Cells Share (%)
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 3

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

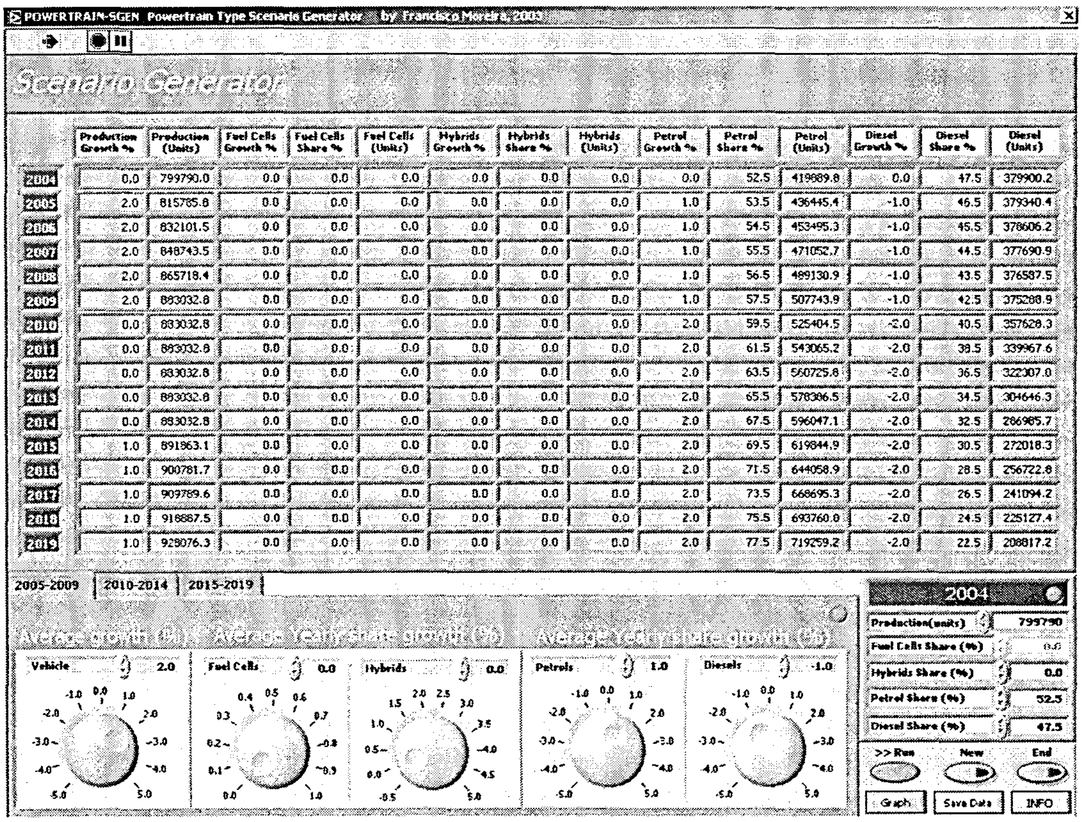
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

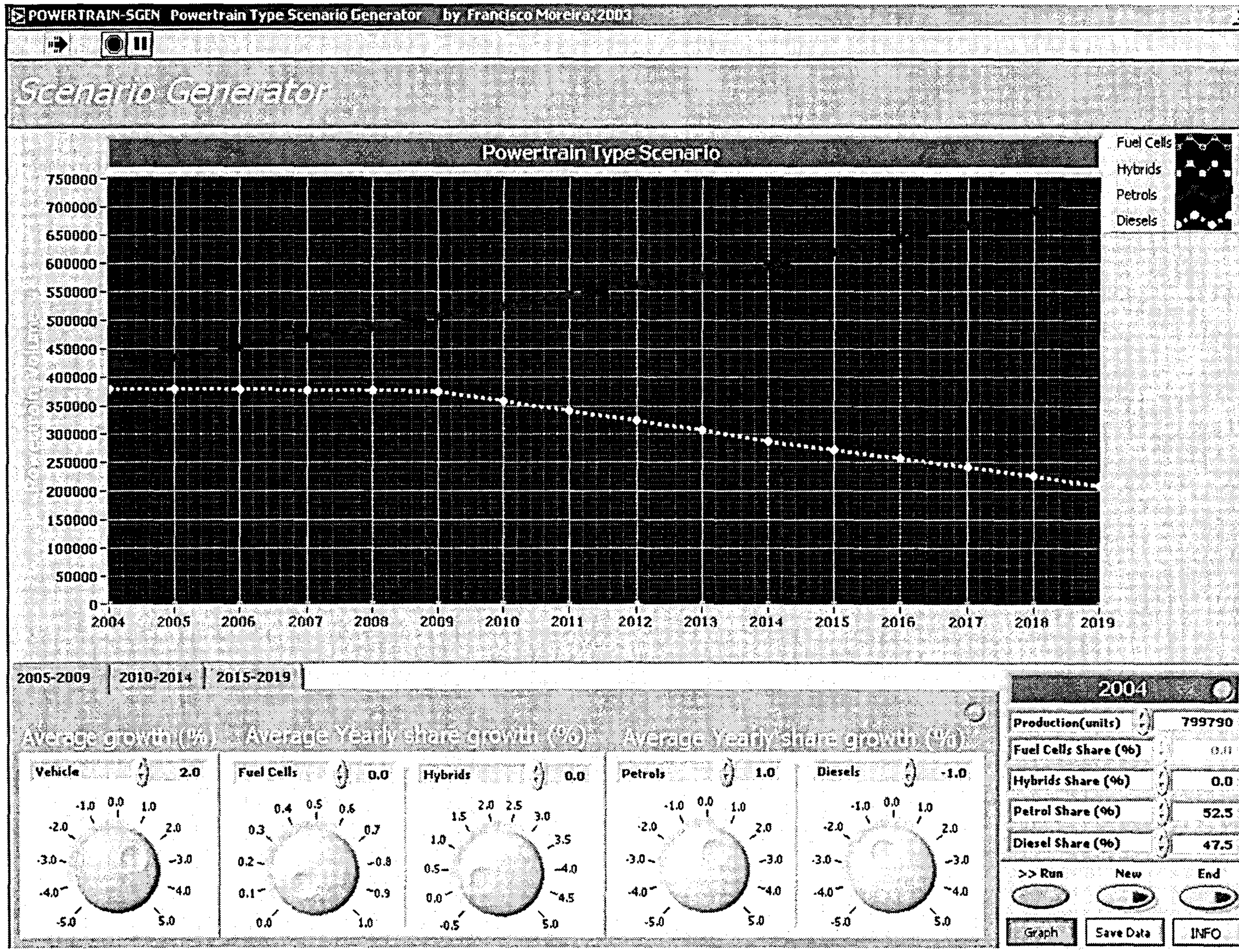
4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**1.0**	**-1.0**	**0.0**	**0.0**	**Not relevant**
2010-2014	**0.0**	**2.0**	**-2.0**	**0.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**2.0**	**-2.0**	**0.0**	**0.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	1.0	53.5	436445.4	-1.0	46.5	379340.4
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	54.5	453495.3	-1.0	45.5	378606.2
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	55.5	471052.7	-1.0	44.5	377690.9
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	1.0	56.5	489130.9	-1.0	43.5	376587.5
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	1.0	57.5	507743.9	-1.0	42.5	375288.9
2010	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0	59.5	525404.5	-2.0	40.5	357628.3
2011	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0	61.5	543065.2	-2.0	38.5	339967.6
2012	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0	63.5	560725.8	-2.0	36.5	322307.0
2013	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0	65.5	578386.5	-2.0	34.5	304646.3
2014	0.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0	67.5	596047.1	-2.0	32.5	286985.7
2015	1.0	891863.1	0.0	0.0	0.0	0.0	0.0	0.0	2.0	69.5	619844.9	-2.0	30.5	272018.3
2016	1.0	900781.7	0.0	0.0	0.0	0.0	0.0	0.0	2.0	71.5	644058.9	-2.0	28.5	256722.8
2017	1.0	909789.6	0.0	0.0	0.0	0.0	0.0	0.0	2.0	73.5	668695.3	-2.0	26.5	241094.2
2018	1.0	918887.5	0.0	0.0	0.0	0.0	0.0	0.0	2.0	75.5	693760.0	-2.0	24.5	225127.4
2019	1.0	928076.3	0.0	0.0	0.0	0.0	0.0	0.0	2.0	77.5	719259.2	-2.0	22.5	208817.2


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
750000
700000
650000
600000
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols 1.0
Diesels -1.0
2004
Production(units) 799790
Fuel Cells Share (%)
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 4

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

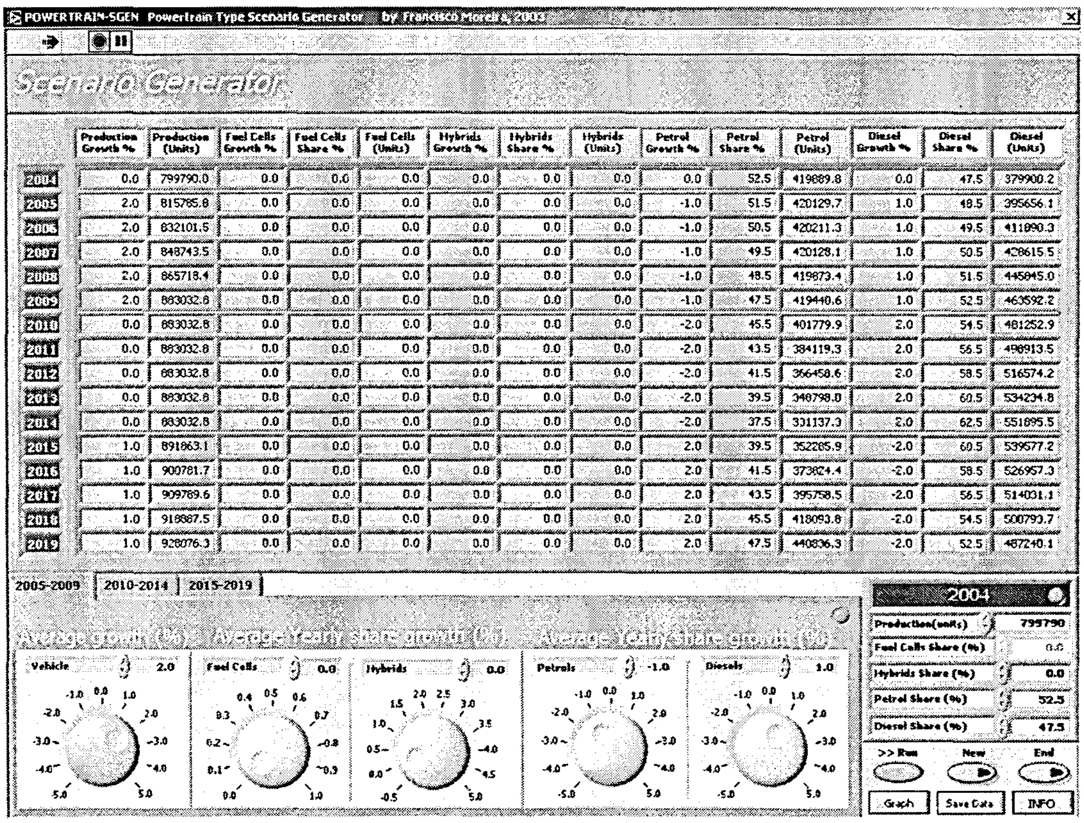
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

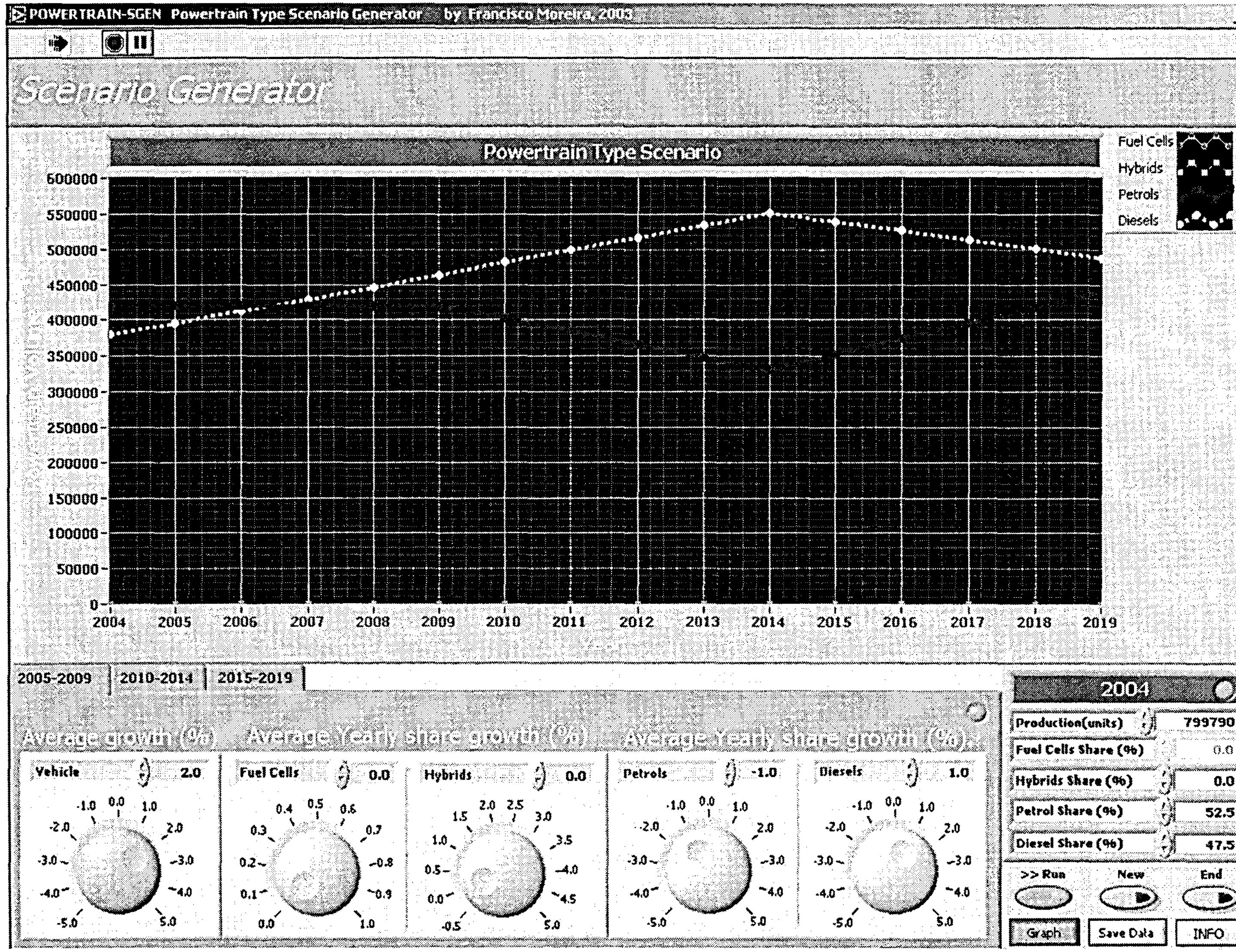
3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-2.0**	**2.0**	**0.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**2.0**	**-2.0**	**0.0**	**0.0**	**Smooth**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
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550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols -1.0
Diesels 1.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 5

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

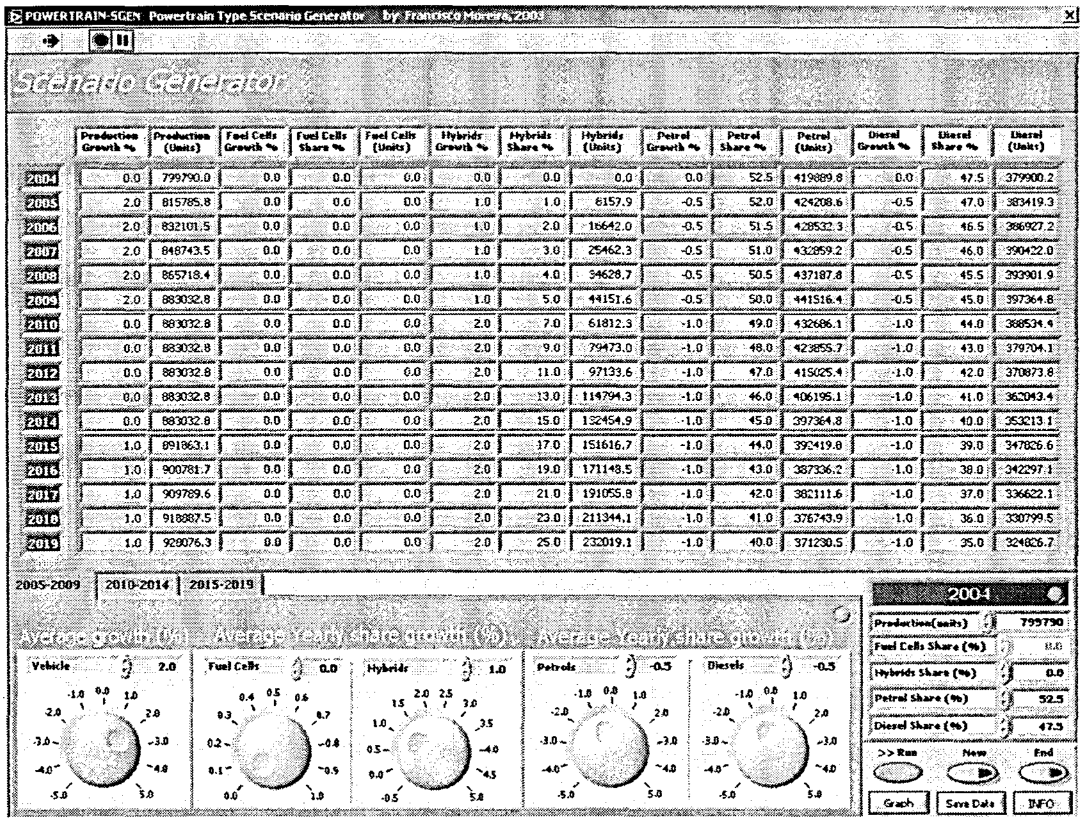
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**

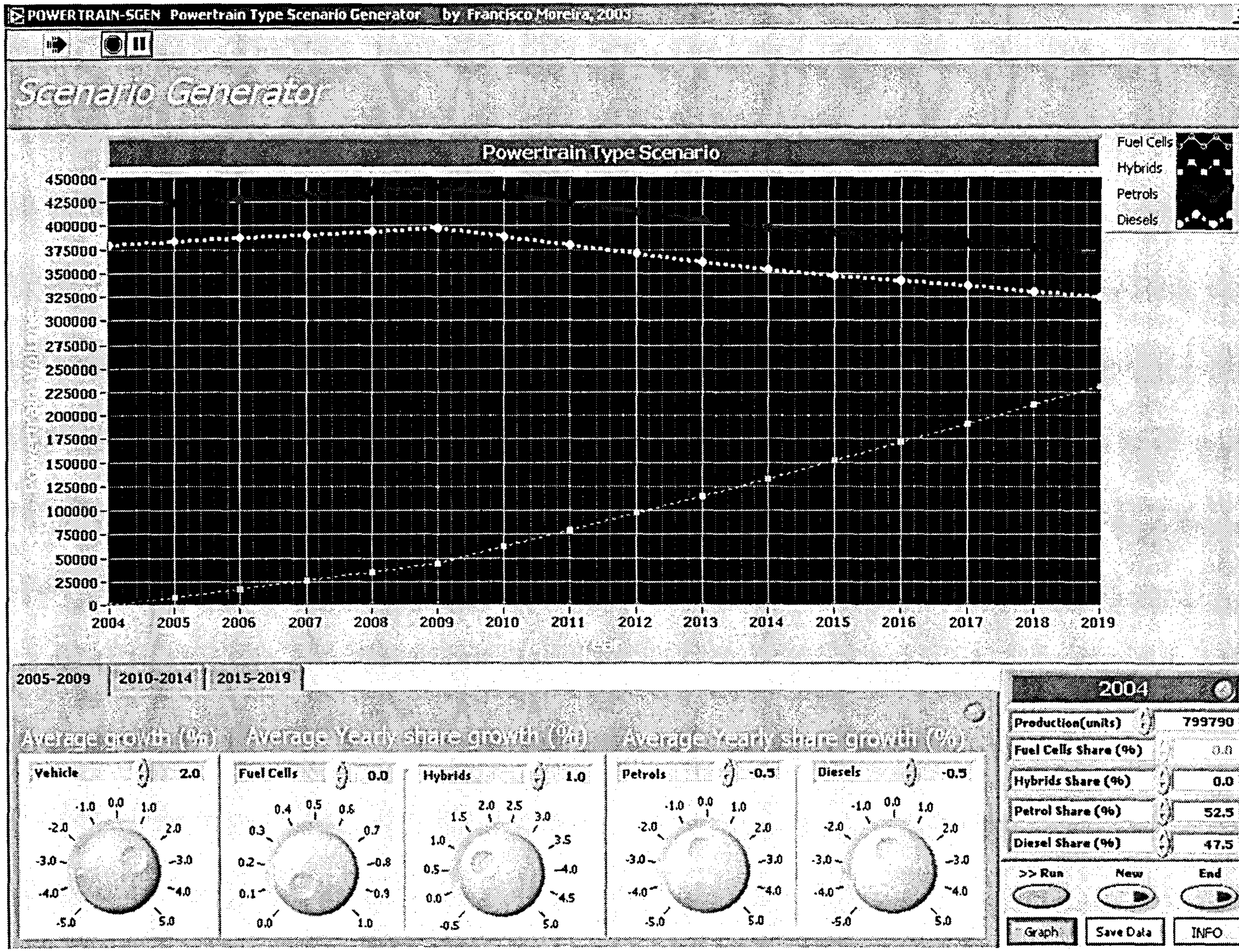
3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-0.5**	**-0.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**-1.0**	**-1.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**-1.0**	**-1.0**	**0.0**	**2.0**	**Smooth**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
450000
425000
400000
375000
350000
325000
300000
275000
250000
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
Year
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -0.5
Diesels -0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 6

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

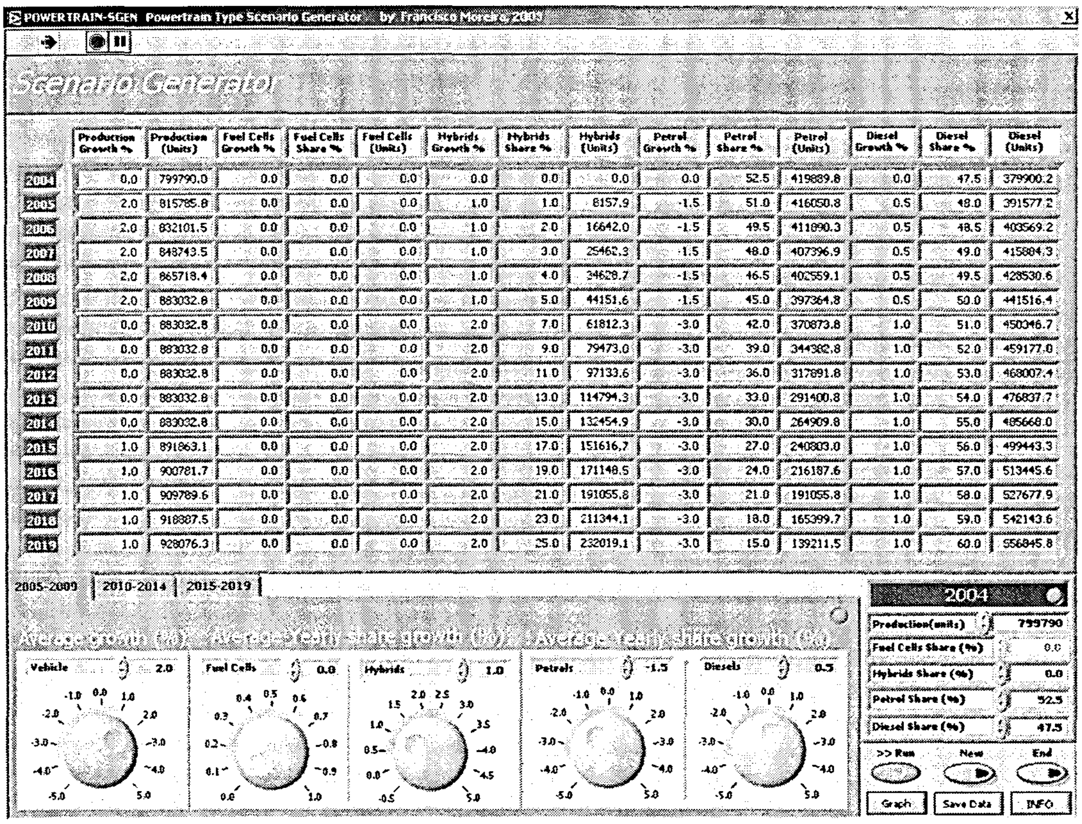
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

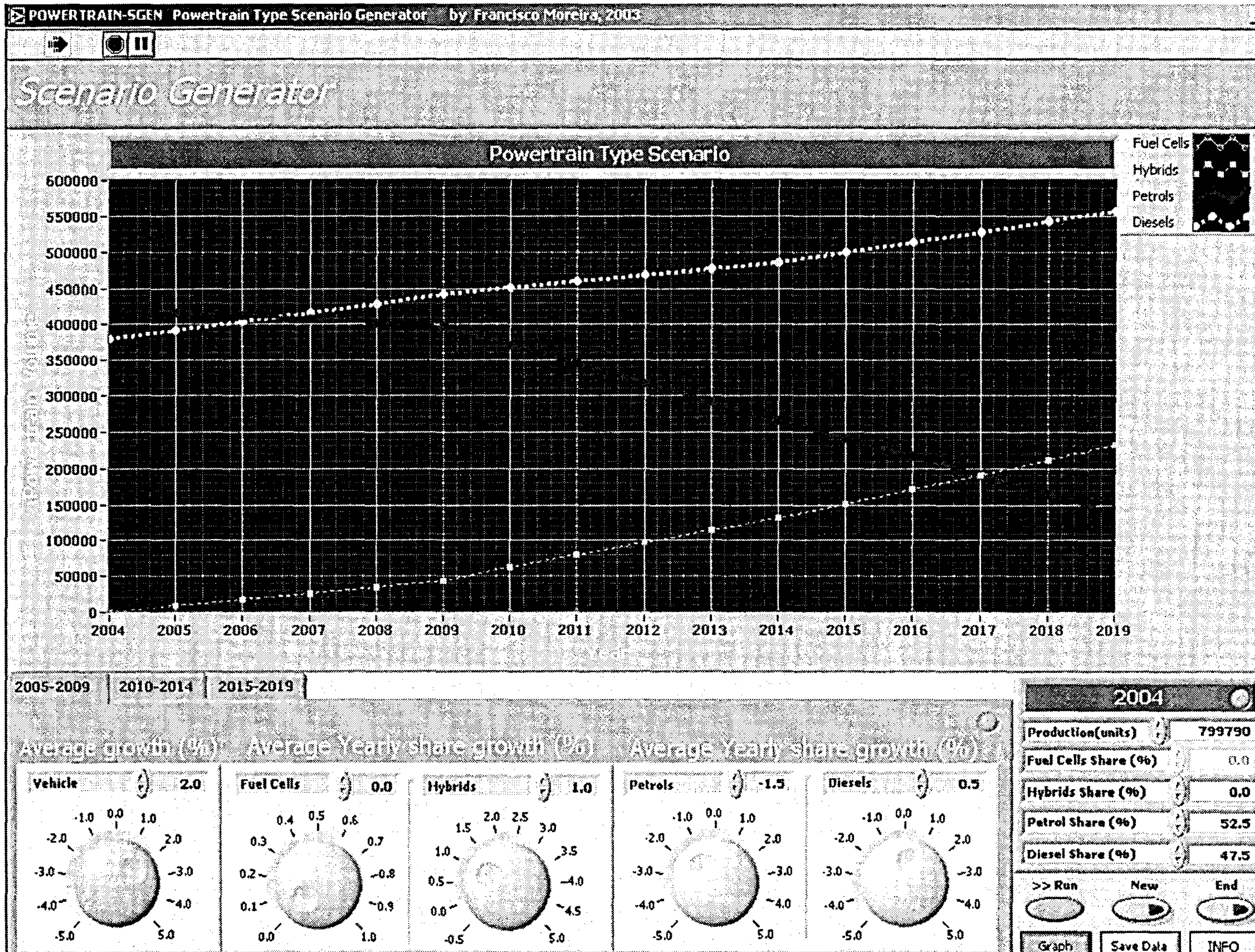
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**-3.0**	**1.0**	**0.0**	**2.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	0.0	0.0	0.0	2.0	7.0	61812.3	-3.0	42.0	370873.8	1.0	51.0	450346.7
2011	0.0	883032.8	0.0	0.0	0.0	2.0	9.0	79473.0	-3.0	39.0	344382.8	1.0	52.0	459177.0
2012	0.0	883032.8	0.0	0.0	0.0	2.0	11.0	97133.6	-3.0	36.0	317891.8	1.0	53.0	468007.4
2013	0.0	883032.8	0.0	0.0	0.0	2.0	13.0	114794.3	-3.0	33.0	291400.8	1.0	54.0	476837.7
2014	0.0	883032.8	0.0	0.0	0.0	2.0	15.0	132454.9	-3.0	30.0	264909.8	1.0	55.0	485668.0
2015	1.0	891863.1	0.0	0.0	0.0	2.0	17.0	151616.7	-3.0	27.0	240803.0	1.0	56.0	499443.3
2016	1.0	900781.7	0.0	0.0	0.0	2.0	19.0	171148.5	-3.0	24.0	216187.6	1.0	57.0	513445.6
2017	1.0	909789.6	0.0	0.0	0.0	2.0	21.0	191055.8	-3.0	21.0	191055.8	1.0	58.0	527677.9
2018	1.0	918887.5	0.0	0.0	0.0	2.0	23.0	211344.1	-3.0	18.0	165399.7	1.0	59.0	542143.6
2019	1.0	928076.3	0.0	0.0	0.0	2.0	25.0	232019.1	-3.0	15.0	139211.5	1.0	60.0	556845.8


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
600000
550000
500000
450000
400000
350000
300000
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200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 7

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

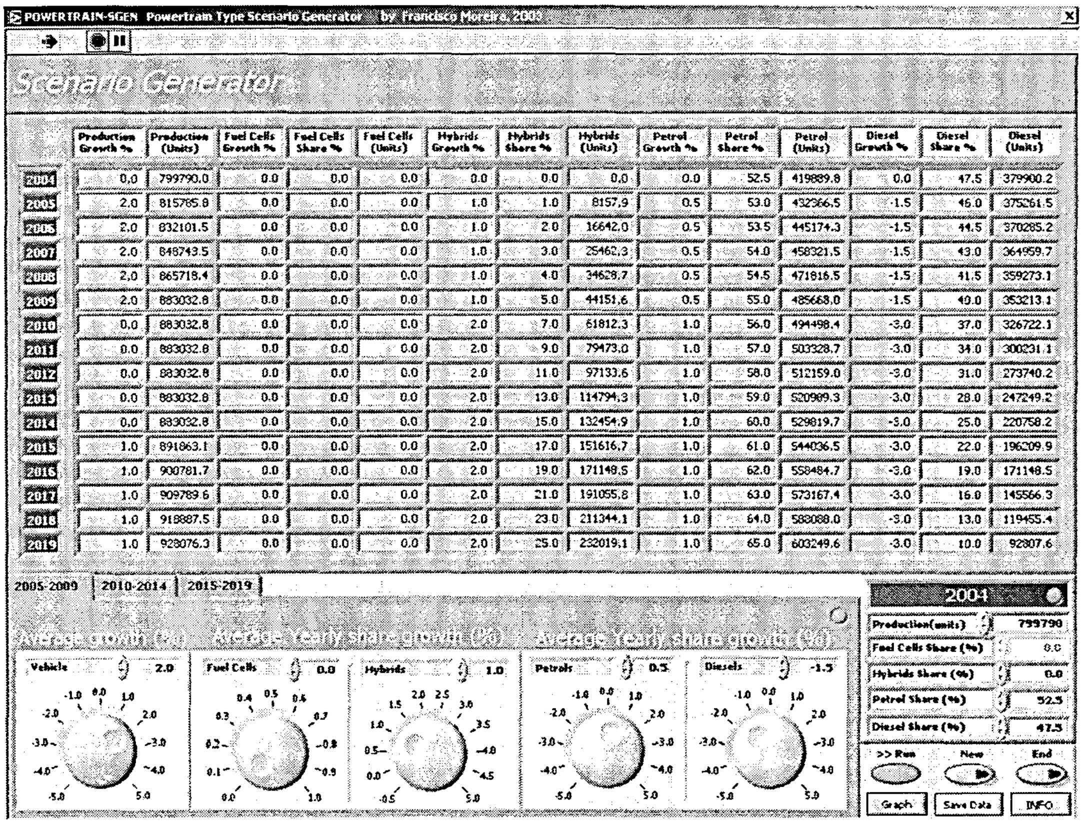
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

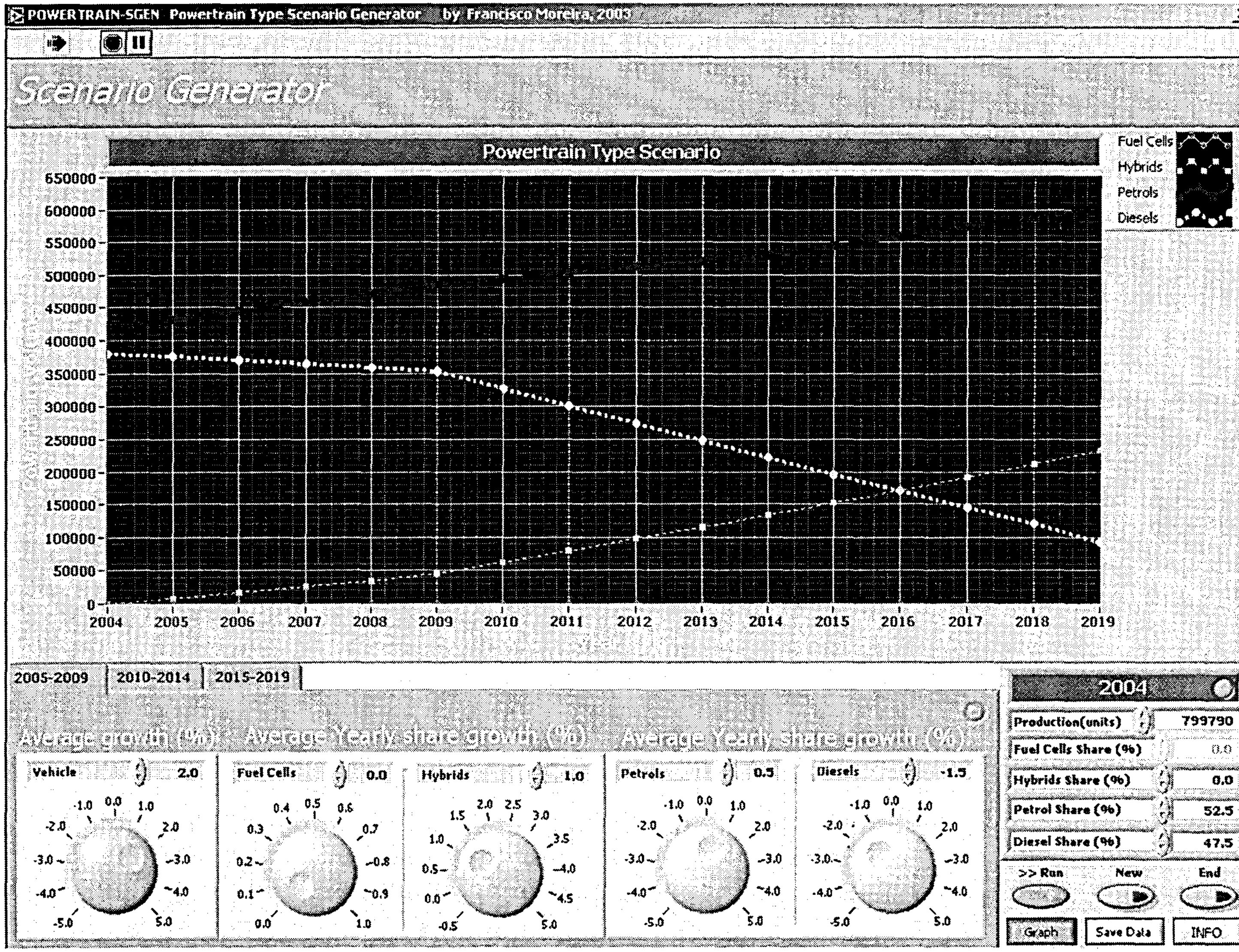
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0.5**	**-1.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**1.0**	**-3.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**1.0**	**-3.0**	**0.0**	**2.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	0.5	53.0	432366.5	-1.5	46.0	375261.5
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	0.5	53.5	445174.3	-1.5	44.5	370285.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	0.5	54.0	458321.5	-1.5	43.0	364959.7
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	0.5	54.5	471816.5	-1.5	41.5	359273.1
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	0.5	55.0	485668.0	-1.5	40.0	353213.1
2010	0.0	883032.8	0.0	0.0	0.0	2.0	7.0	61812.3	1.0	56.0	494498.4	-3.0	37.0	326722.1
2011	0.0	883032.8	0.0	0.0	0.0	2.0	9.0	79473.0	1.0	57.0	503328.7	-3.0	34.0	300231.1
2012	0.0	883032.8	0.0	0.0	0.0	2.0	11.0	97133.6	1.0	58.0	512159.0	-3.0	31.0	273740.2
2013	0.0	883032.8	0.0	0.0	0.0	2.0	13.0	114794.3	1.0	59.0	520989.3	-3.0	28.0	247249.2
2014	0.0	883032.8	0.0	0.0	0.0	2.0	15.0	132454.9	1.0	60.0	529819.7	-3.0	25.0	220758.2
2015	1.0	891863.1	0.0	0.0	0.0	2.0	17.0	151616.7	1.0	61.0	544036.5	-3.0	22.0	196209.9
2016	1.0	900781.7	0.0	0.0	0.0	2.0	19.0	171148.5	1.0	62.0	558484.7	-3.0	19.0	171148.5
2017	1.0	909789.6	0.0	0.0	0.0	2.0	21.0	191055.8	1.0	63.0	573167.4	-3.0	16.0	145566.3
2018	1.0	918887.5	0.0	0.0	0.0	2.0	23.0	211344.1	1.0	64.0	588088.0	-3.0	13.0	119455.4
2019	1.0	928076.3	0.0	0.0	0.0	2.0	25.0	232019.1	1.0	65.0	603249.6	-3.0	10.0	92807.6


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
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100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols 0.5
Diesels -1.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 8

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

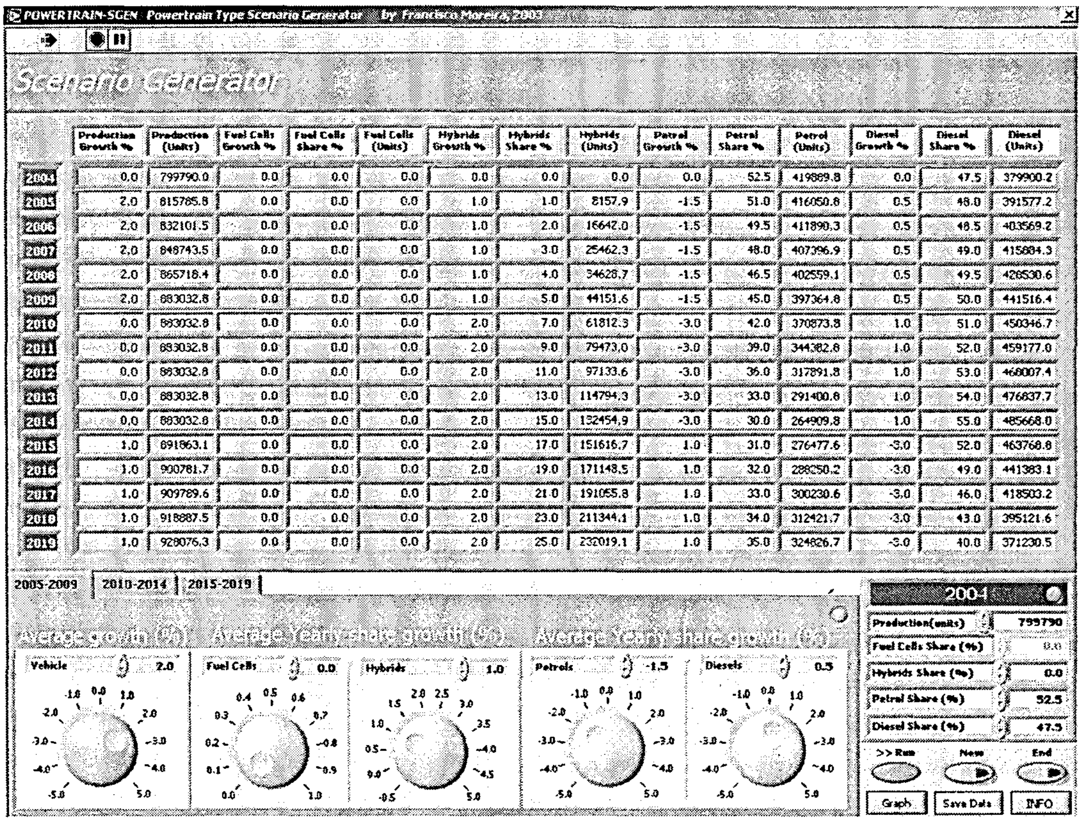
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

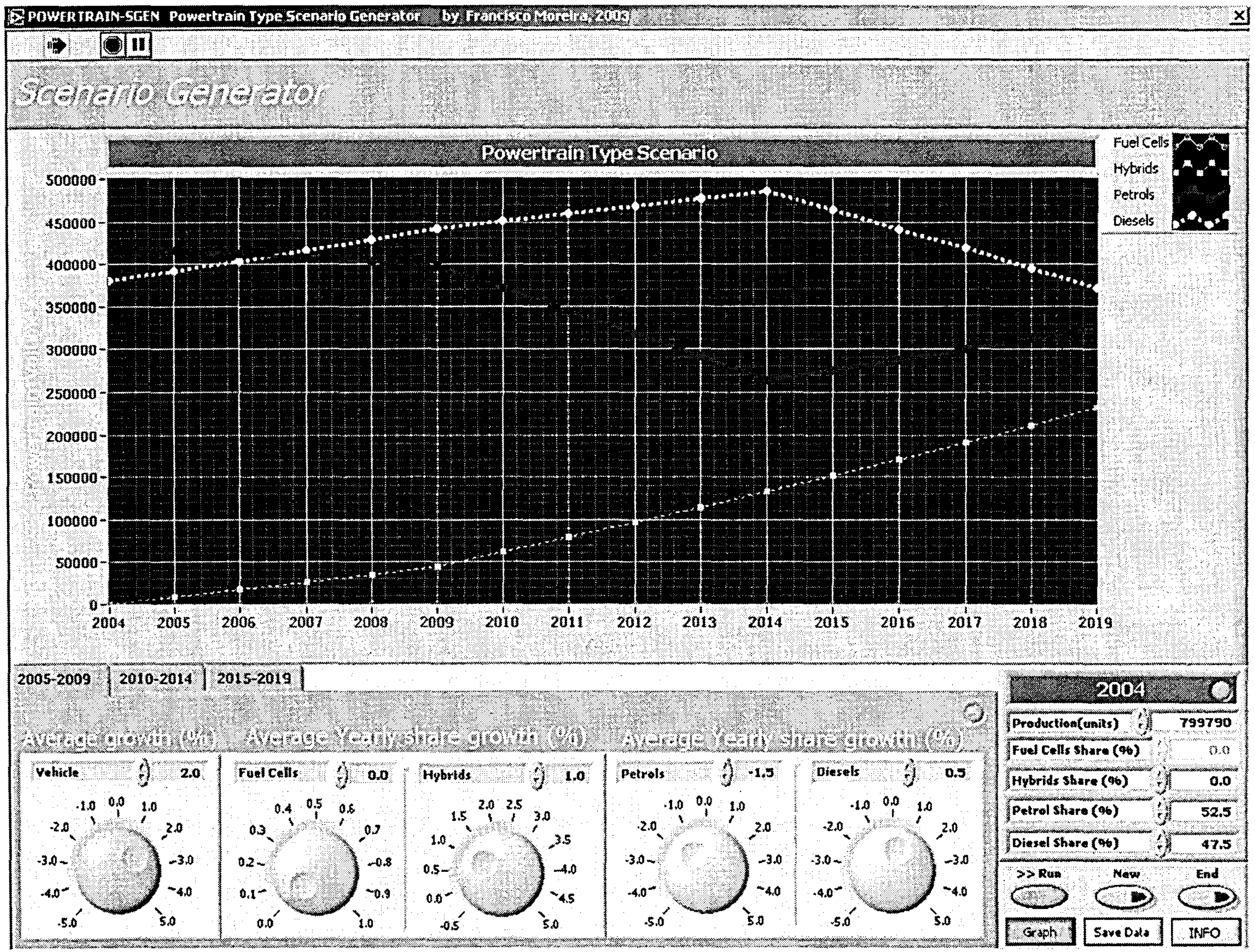
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**1.0**	**-3.0**	**0.0**	**2.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	0.0	0.0	0.0	2.0	7.0	61812.3	-3.0	42.0	370873.8	1.0	51.0	450346.7
2011	0.0	883032.8	0.0	0.0	0.0	2.0	9.0	79473.0	-3.0	39.0	344382.8	1.0	52.0	459177.0
2012	0.0	883032.8	0.0	0.0	0.0	2.0	11.0	97133.6	-3.0	36.0	317891.8	1.0	53.0	468007.4
2013	0.0	883032.8	0.0	0.0	0.0	2.0	13.0	114794.3	-3.0	33.0	291400.8	1.0	54.0	476837.7
2014	0.0	883032.8	0.0	0.0	0.0	2.0	15.0	132454.9	-3.0	30.0	264909.8	1.0	55.0	485668.0
2015	1.0	891863.1	0.0	0.0	0.0	2.0	17.0	151616.7	1.0	31.0	276477.6	-3.0	52.0	463768.8
2016	1.0	900781.7	0.0	0.0	0.0	2.0	19.0	171148.5	1.0	32.0	288250.2	-3.0	49.0	441383.1
2017	1.0	909789.6	0.0	0.0	0.0	2.0	21.0	191055.8	1.0	33.0	300230.6	-3.0	46.0	418503.2
2018	1.0	918887.5	0.0	0.0	0.0	2.0	23.0	211344.1	1.0	34.0	312421.7	-3.0	43.0	395121.6
2019	1.0	928076.3	0.0	0.0	0.0	2.0	25.0	232019.1	1.0	35.0	324826.7	-3.0	40.0	371230.5


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
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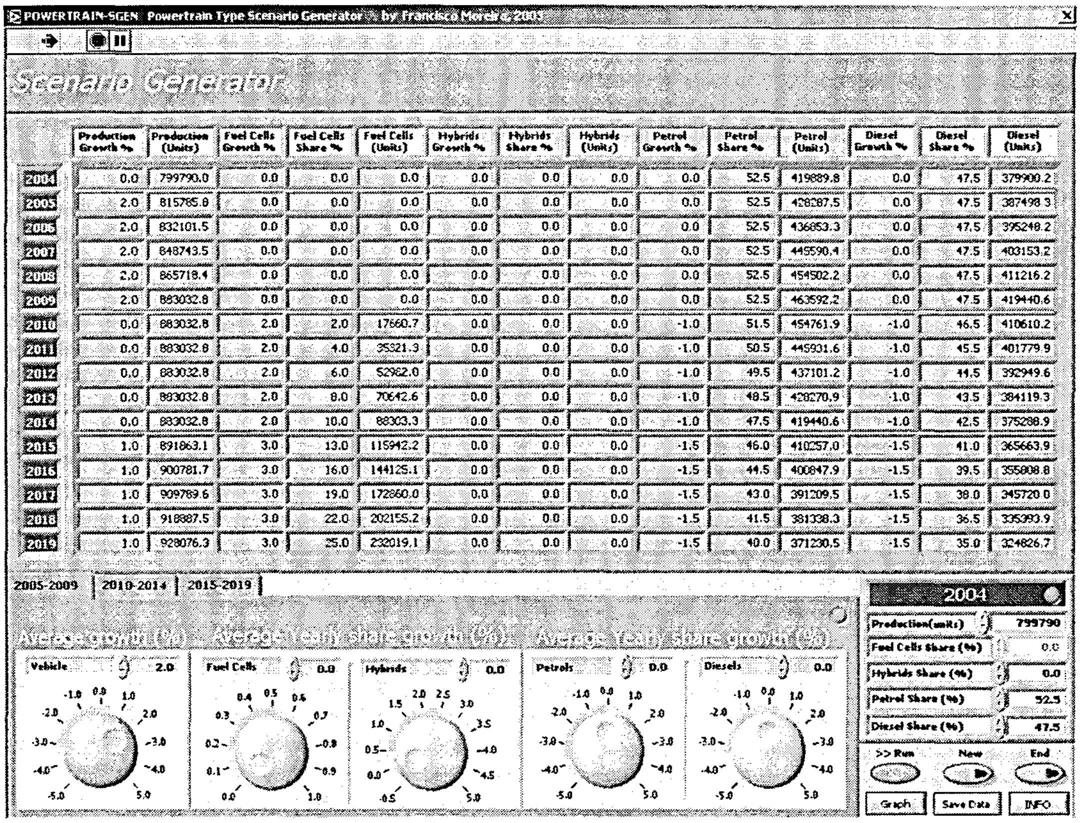
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

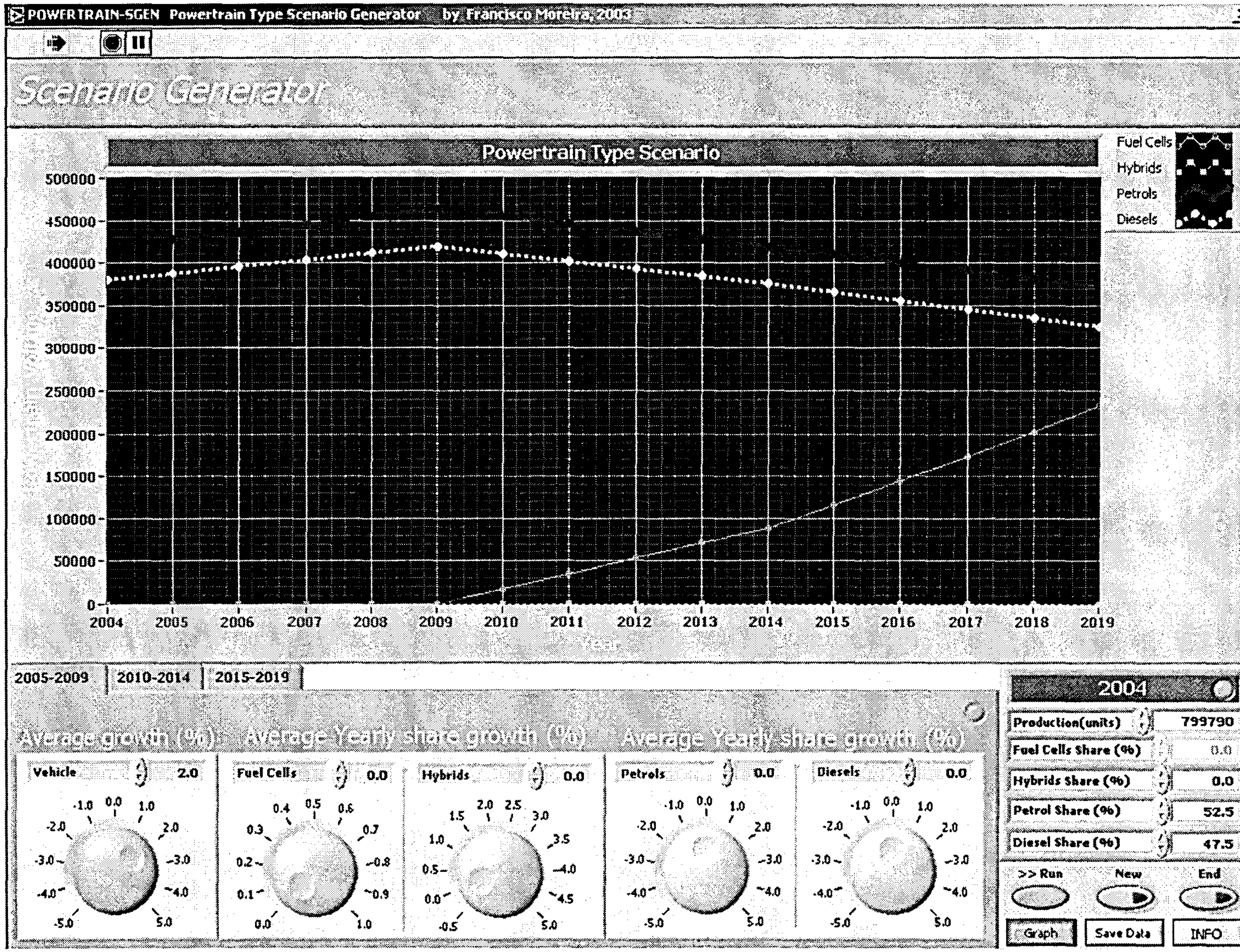
SCENARIO 9

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**
3. **Fuel Cell vehicles gain market share following market introduction around 2010.**
4. Hybrid vehicles fail to gain market share following market introduction around 2005.
5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0**	**0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-1.0**	**-1.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**-1.5**	**-1.5**	**3.0**	**0.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	428287.5	0.0	47.5	387498.3
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	436853.3	0.0	47.5	395248.2
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	445590.4	0.0	47.5	403153.2
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	454502.2	0.0	47.5	411216.2
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2010	0.0	883032.8	2.0	2.0	17660.7	0.0	0.0	0.0	-1.0	51.5	454761.9	-1.0	46.5	410610.2
2011	0.0	883032.8	2.0	4.0	35321.3	0.0	0.0	0.0	-1.0	50.5	445931.6	-1.0	45.5	401779.9
2012	0.0	883032.8	2.0	6.0	52982.0	0.0	0.0	0.0	-1.0	49.5	437101.2	-1.0	44.5	392949.6
2013	0.0	883032.8	2.0	8.0	70642.6	0.0	0.0	0.0	-1.0	48.5	428270.9	-1.0	43.5	384119.3
2014	0.0	883032.8	2.0	10.0	88303.3	0.0	0.0	0.0	-1.0	47.5	419440.6	-1.0	42.5	375288.9
2015	1.0	891863.1	3.0	13.0	115942.2	0.0	0.0	0.0	-1.5	46.0	410257.0	-1.5	41.0	365663.9
2016	1.0	900781.7	3.0	16.0	144125.1	0.0	0.0	0.0	-1.5	44.5	400847.9	-1.5	39.5	355808.8
2017	1.0	909789.6	3.0	19.0	172860.0	0.0	0.0	0.0	-1.5	43.0	391209.5	-1.5	38.0	345720.0
2018	1.0	918887.5	3.0	22.0	202155.2	0.0	0.0	0.0	-1.5	41.5	381338.3	-1.5	36.5	335393.9
2019	1.0	928076.3	3.0	25.0	232019.1	0.0	0.0	0.0	-1.5	40.0	371230.5	-1.5	35.0	324826.7


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
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250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
Year
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols 0.0
Diesels 0.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 10

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

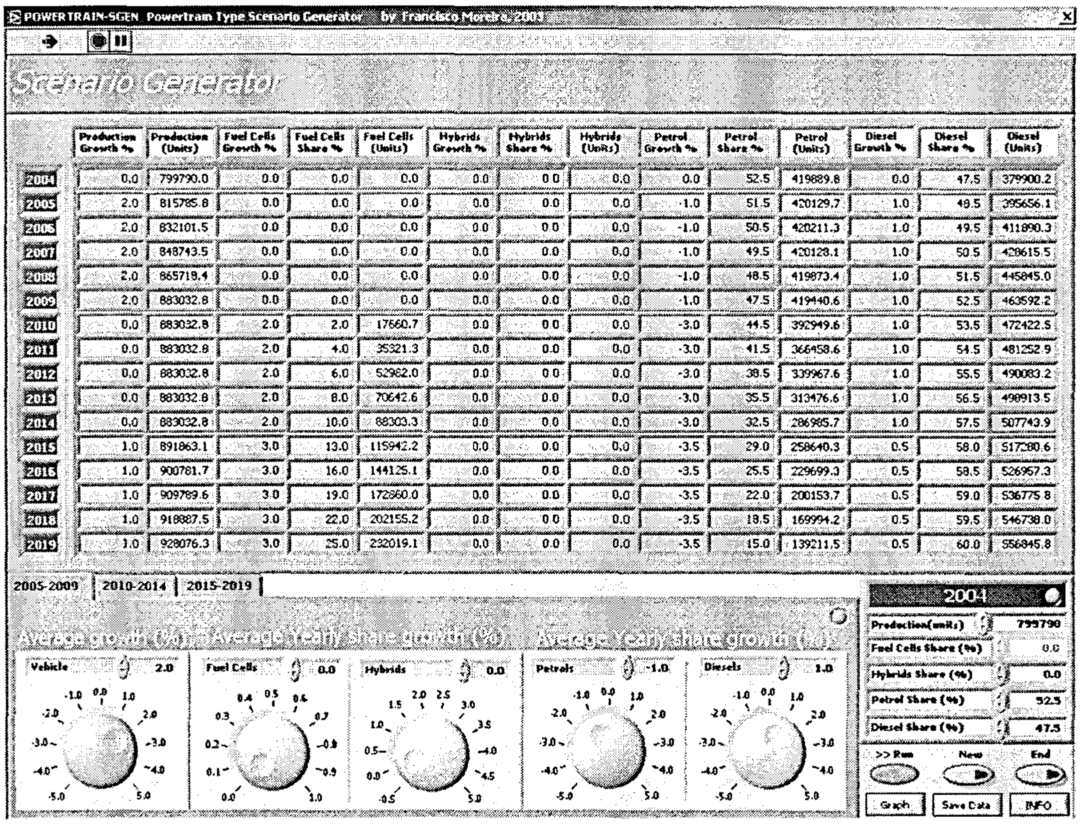
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

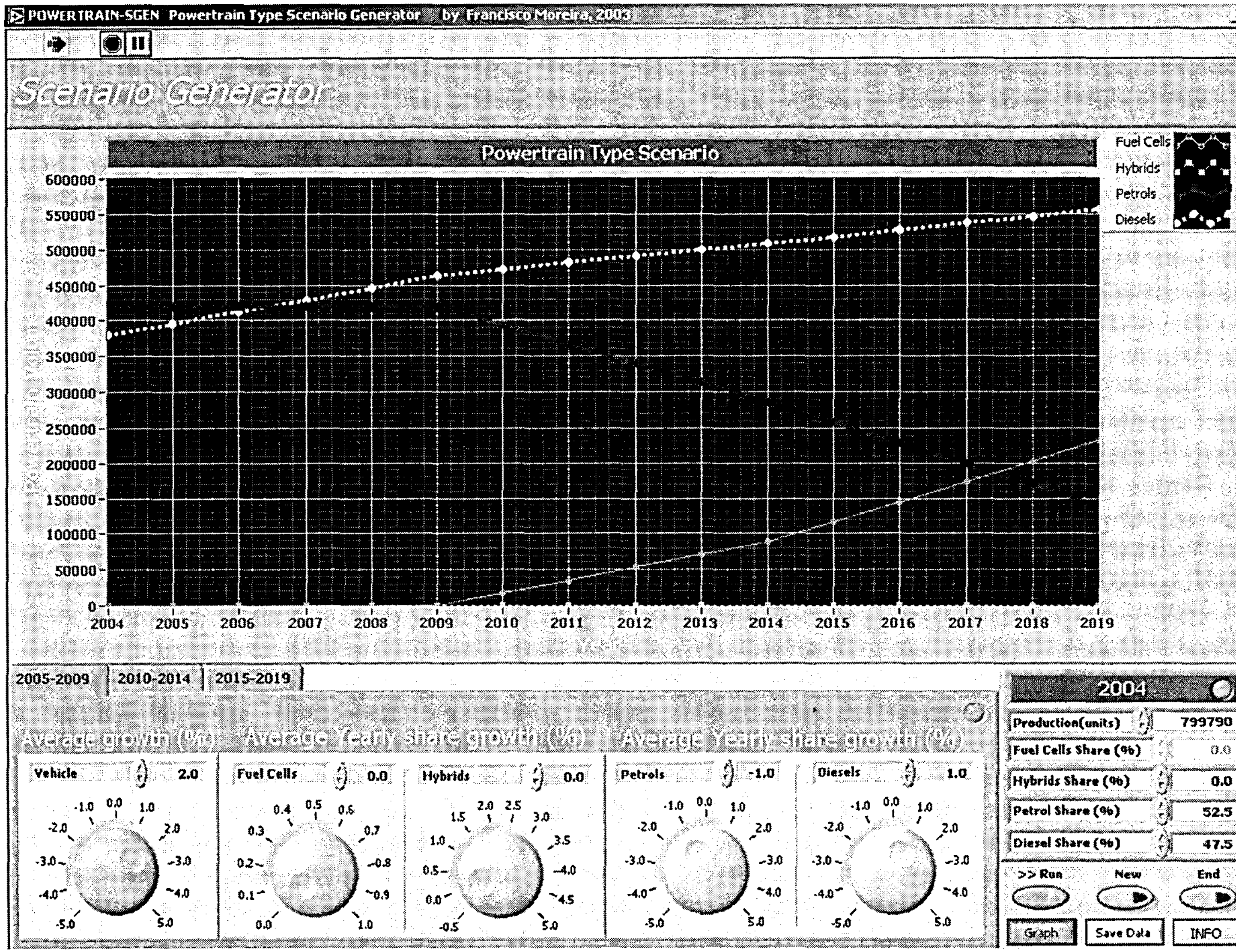
3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**-3.5**	**0.5**	**3.0**	**0.0**	**Smooth**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
600000
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2004
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2016
2017
2018
2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols -1.0
Diesels 1.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 11

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

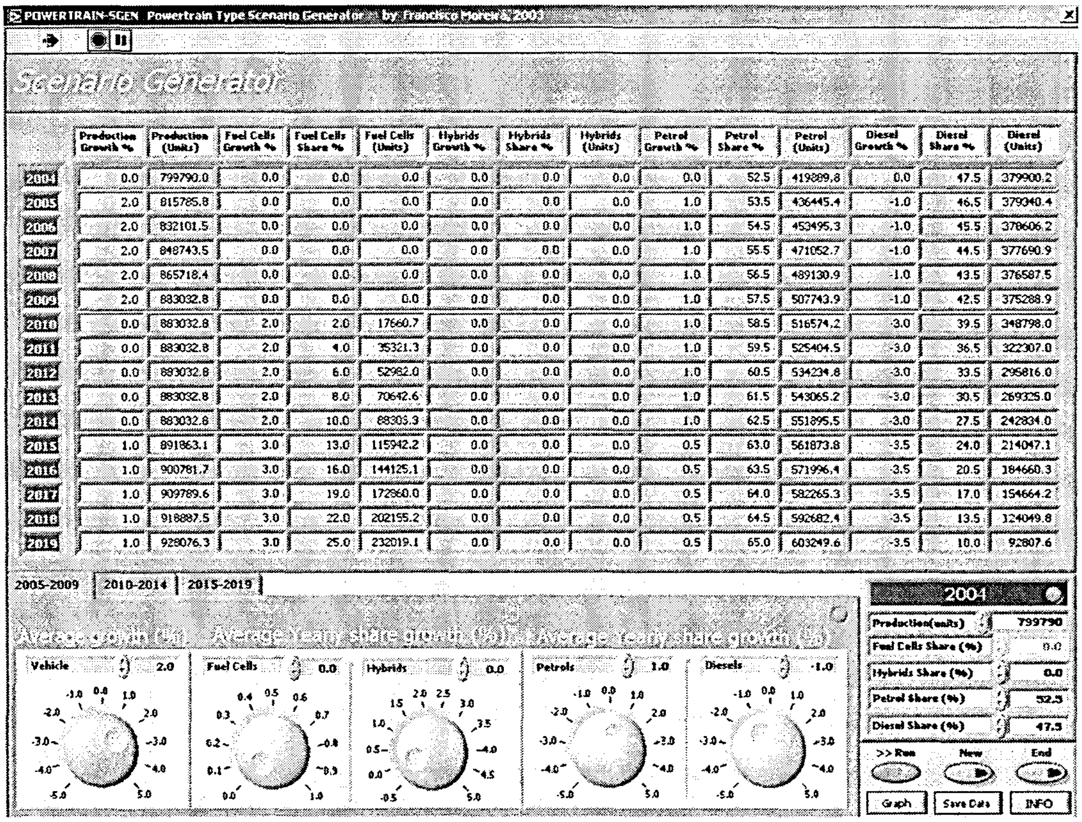
2. Petrols progressively gain market share against Diesel based vehicles.

3. Fuel Cell vehicles gain market share following market introduction around 2010.

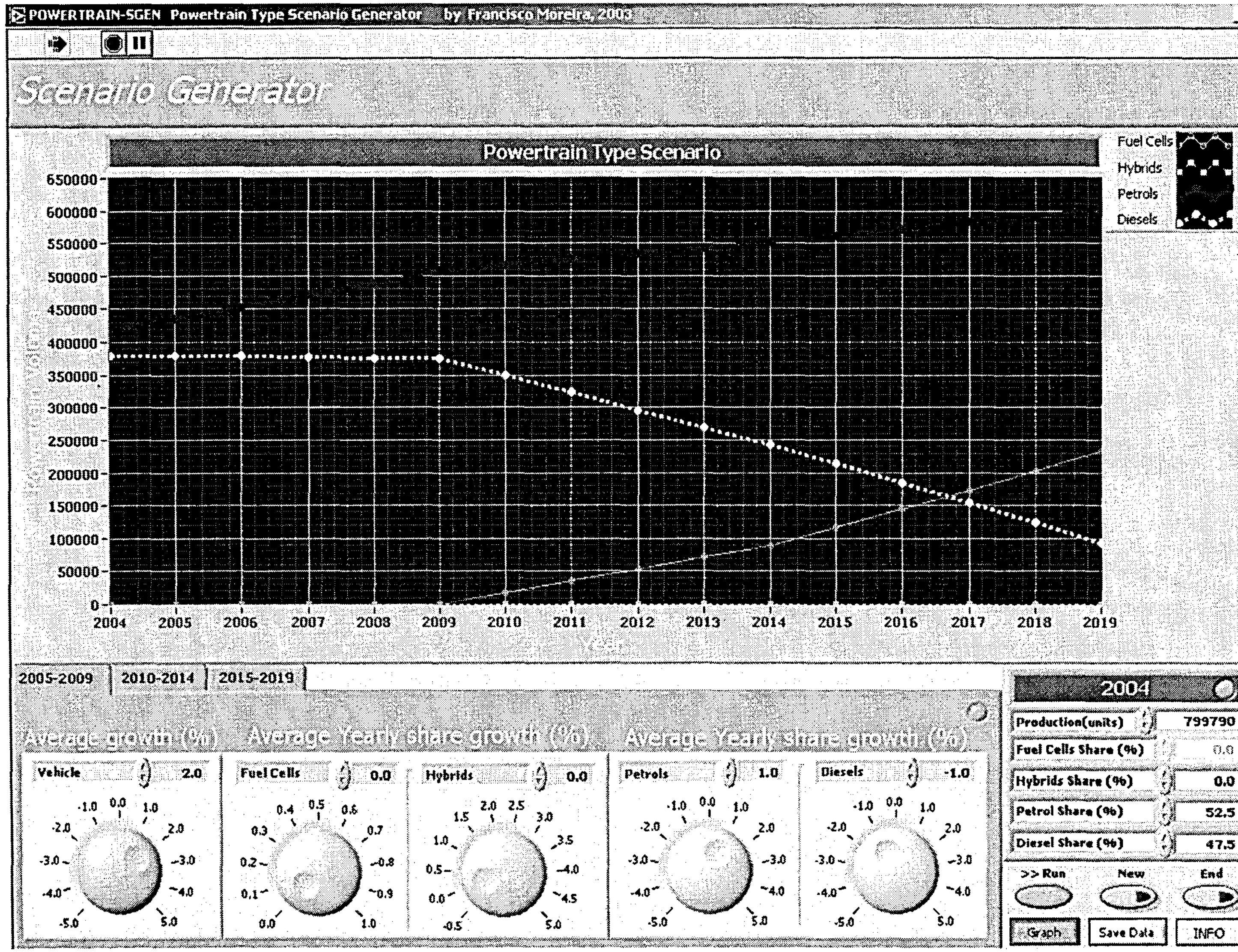
4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**1.0**	**-1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**1.0**	**-3.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**0.5**	**-3.5**	**3.0**	**0.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	1.0	53.5	436445.4	-1.0	46.5	379340.4
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	54.5	453495.3	-1.0	45.5	378606.2
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	55.5	471052.7	-1.0	44.5	377690.9
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	1.0	56.5	489130.9	-1.0	43.5	376587.5
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	1.0	57.5	507743.9	-1.0	42.5	375288.9
2010	0.0	883032.8	2.0	2.0	17660.7	0.0	0.0	0.0	1.0	58.5	516574.2	-3.0	39.5	348798.0
2011	0.0	883032.8	2.0	4.0	35321.3	0.0	0.0	0.0	1.0	59.5	525404.5	-3.0	36.5	322307.0
2012	0.0	883032.8	2.0	6.0	52982.0	0.0	0.0	0.0	1.0	60.5	534234.8	-3.0	33.5	295816.0
2013	0.0	883032.8	2.0	8.0	70642.6	0.0	0.0	0.0	1.0	61.5	543065.2	-3.0	30.5	269325.0
2014	0.0	883032.8	2.0	10.0	88303.3	0.0	0.0	0.0	1.0	62.5	551895.5	-3.0	27.5	242834.0
2015	1.0	891863.1	3.0	13.0	115942.2	0.0	0.0	0.0	0.5	63.0	561873.8	-3.5	24.0	214047.1
2016	1.0	900781.7	3.0	16.0	144125.1	0.0	0.0	0.0	0.5	63.5	571996.4	-3.5	20.5	184660.3
2017	1.0	909789.6	3.0	19.0	172860.0	0.0	0.0	0.0	0.5	64.0	582265.3	-3.5	17.0	154664.2
2018	1.0	918887.5	3.0	22.0	202155.2	0.0	0.0	0.0	0.5	64.5	592682.4	-3.5	13.5	124049.8
2019	1.0	928076.3	3.0	25.0	232019.1	0.0	0.0	0.0	0.5	65.0	603249.6	-3.5	10.0	92807.6


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
650000
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100000
50000
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2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
Year
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols 1.0
Diesels -1.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 12

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

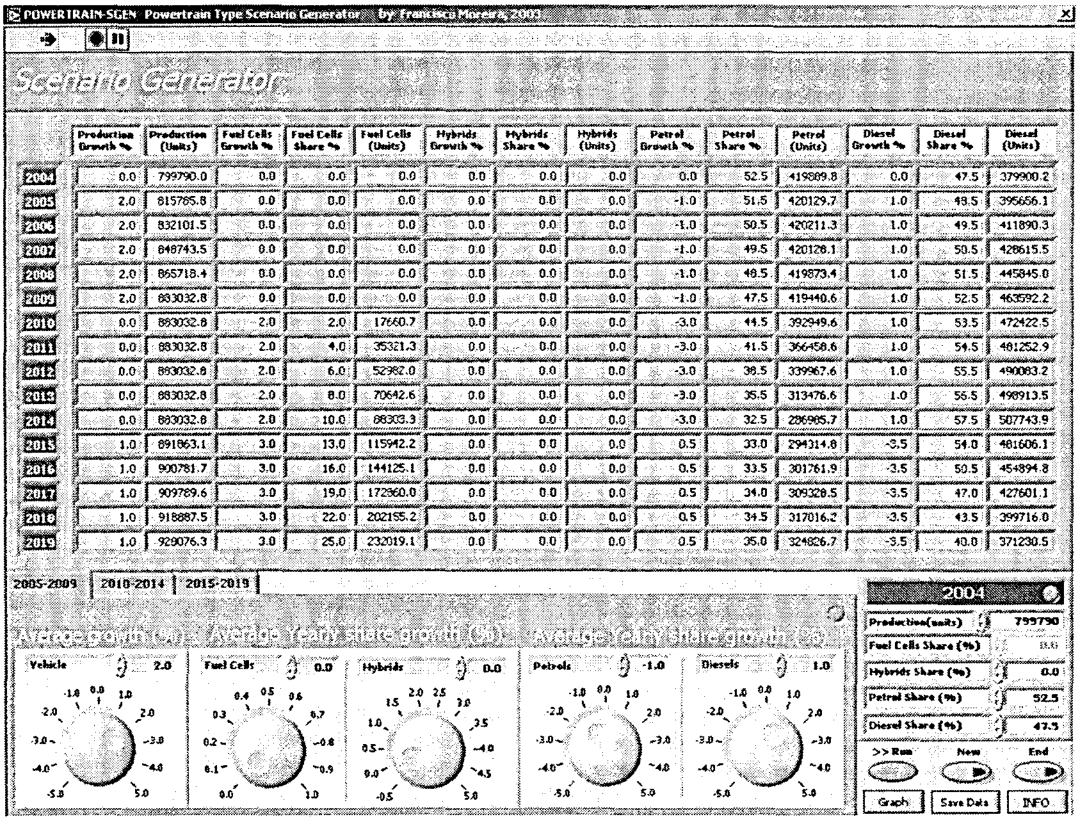
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

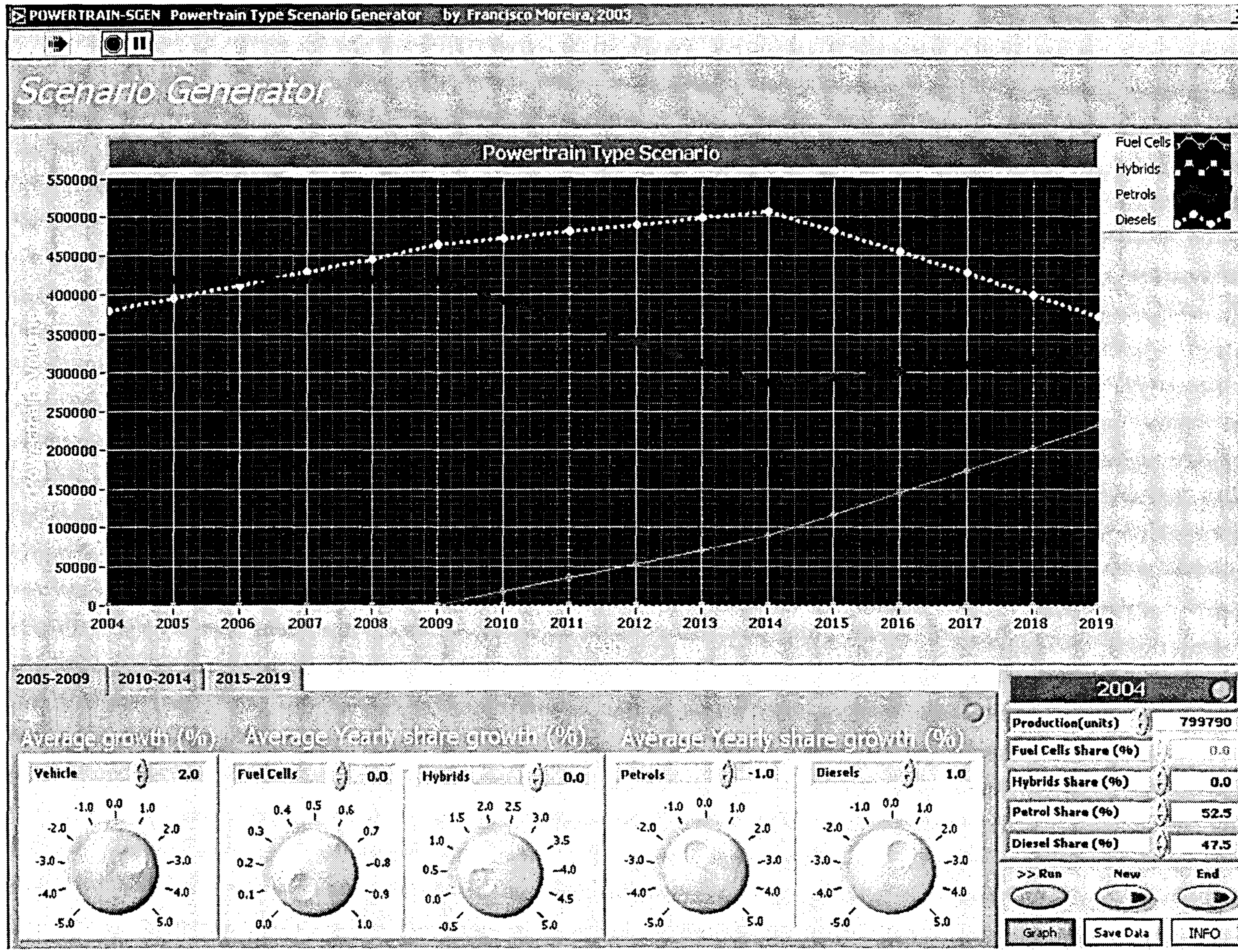
4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**0.5**	**-3.5**	**3.0**	**0.0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815765.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	51.5	420129.7	1.0	48.5	395656.1
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	50.5	420211.3	1.0	49.5	411890.3
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	49.5	420128.1	1.0	50.5	428615.5
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	48.5	419873.4	1.0	51.5	445845.0
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	47.5	419440.6	1.0	52.5	463592.2
2010	0.0	883032.8	2.0	2.0	17660.7	0.0	0.0	0.0	-3.0	44.5	392949.6	1.0	53.5	472422.5
2011	0.0	883032.8	2.0	4.0	35321.3	0.0	0.0	0.0	-3.0	41.5	366458.6	1.0	54.5	481252.9
2012	0.0	883032.8	2.0	6.0	52982.0	0.0	0.0	0.0	-3.0	38.5	339967.6	1.0	55.5	490083.2
2013	0.0	883032.8	2.0	8.0	70642.6	0.0	0.0	0.0	-3.0	35.5	313476.6	1.0	56.5	498913.5
2014	0.0	883032.8	2.0	10.0	88303.3	0.0	0.0	0.0	-3.0	32.5	286985.7	1.0	57.5	507743.9
2015	1.0	891863.1	3.0	13.0	115942.2	0.0	0.0	0.0	0.5	33.0	294314.8	-3.5	54.0	481606.1
2016	1.0	900781.7	3.0	16.0	144125.1	0.0	0.0	0.0	0.5	33.5	301761.9	-3.5	50.5	454894.8
2017	1.0	909789.6	3.0	19.0	172860.0	0.0	0.0	0.0	0.5	34.0	309328.5	-3.5	47.0	427601.1
2018	1.0	918887.5	3.0	22.0	202155.2	0.0	0.0	0.0	0.5	34.5	317016.2	-3.5	43.5	399716.0
2019	1.0	929076.3	3.0	25.0	232019.1	0.0	0.0	0.0	0.5	35.0	324826.7	-3.5	40.0	371230.5


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols -1.0
Diesels 1.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 13

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

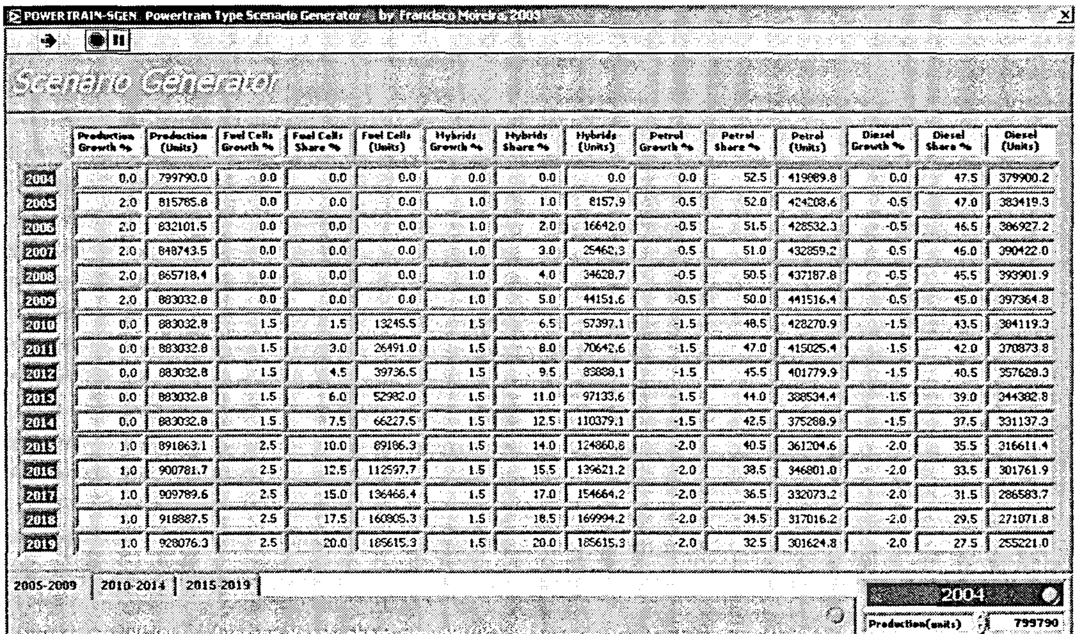
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

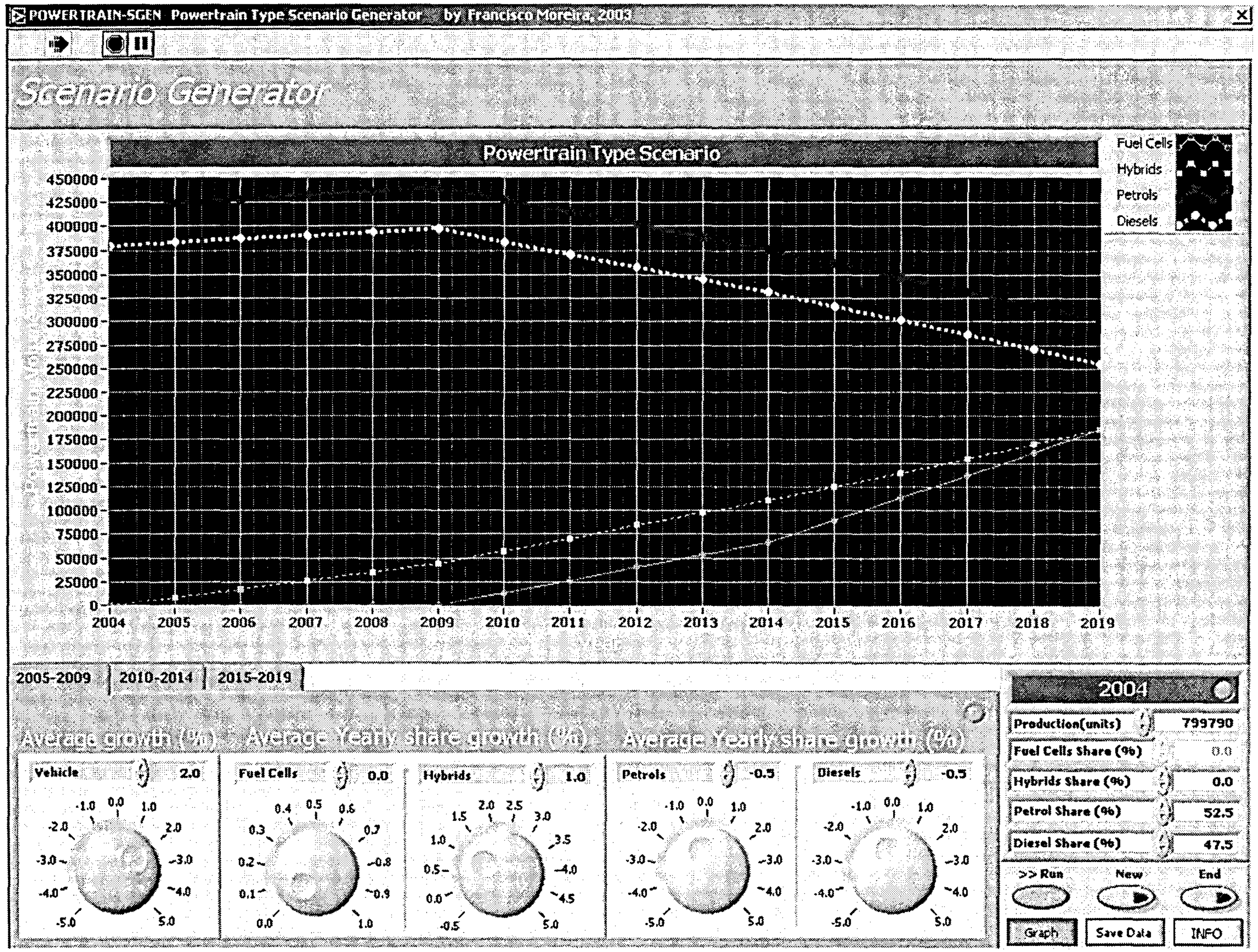
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-0.5**	**-0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-1.5**	**-1.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-2.0**	**-2.0**	**2.5**	**1.5**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-0.5	52.0	424208.6	-0.5	47.0	383419.3
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-0.5	51.5	428532.3	-0.5	46.5	386927.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-0.5	51.0	432859.2	-0.5	46.0	390422.0
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-0.5	50.5	437187.8	-0.5	45.5	393901.9
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-0.5	50.0	441516.4	-0.5	45.0	397364.8
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	-1.5	48.5	428270.9	-1.5	43.5	384119.3
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	-1.5	47.0	415025.4	-1.5	42.0	370873.8
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	-1.5	45.5	401779.9	-1.5	40.5	357628.3
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	-1.5	44.0	388534.4	-1.5	39.0	344382.8
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	-1.5	42.5	375288.9	-1.5	37.5	331137.3
2015	1.0	891863.1	2.5	10.0	89186.3	1.5	14.0	124860.8	-2.0	40.5	361204.6	-2.0	35.5	316611.4
2016	1.0	900781.7	2.5	12.5	112597.7	1.5	15.5	139621.2	-2.0	38.5	346801.0	-2.0	33.5	301761.9
2017	1.0	909789.6	2.5	15.0	136468.4	1.5	17.0	154664.2	-2.0	36.5	332073.2	-2.0	31.5	286583.7
2018	1.0	918887.5	2.5	17.5	160805.3	1.5	18.5	169994.2	-2.0	34.5	317016.2	-2.0	29.5	271071.8
2019	1.0	928076.3	2.5	20.0	185615.3	1.5	20.0	185615.3	-2.0	32.5	301624.8	-2.0	27.5	255221.0



POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
450000
425000
400000
375000
350000
325000
300000
275000
250000
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -0.5
Diesels -0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 14

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

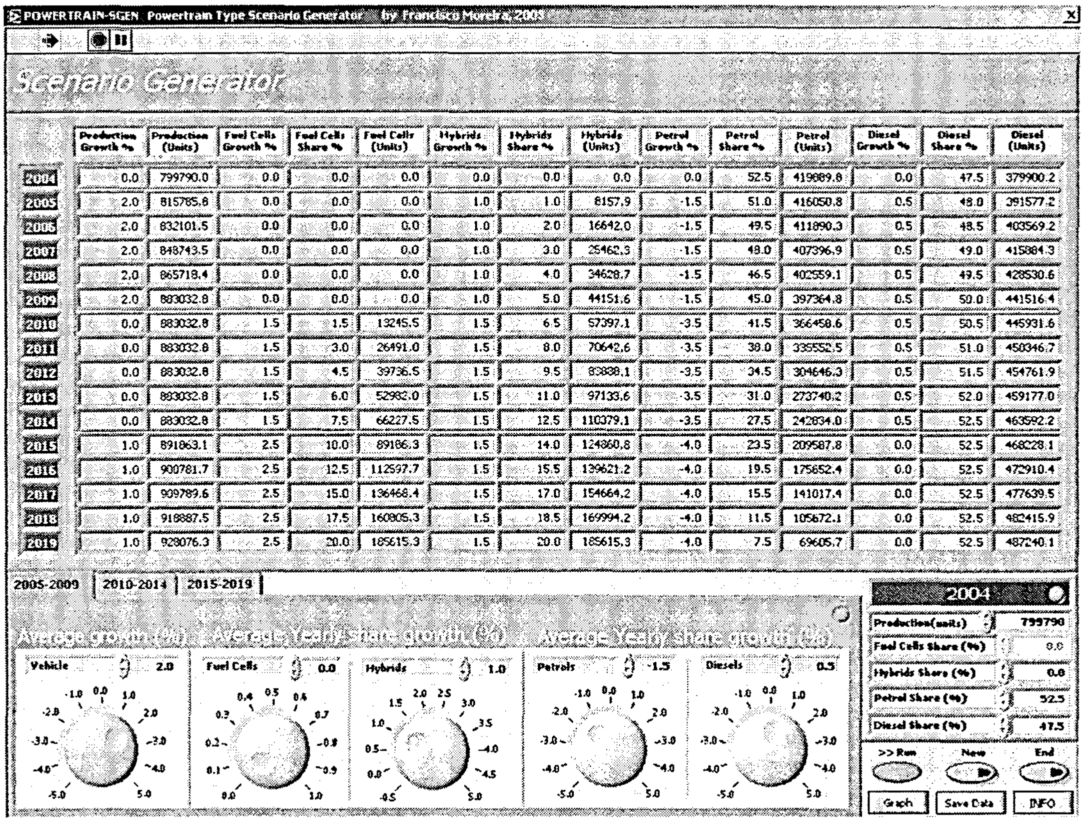
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

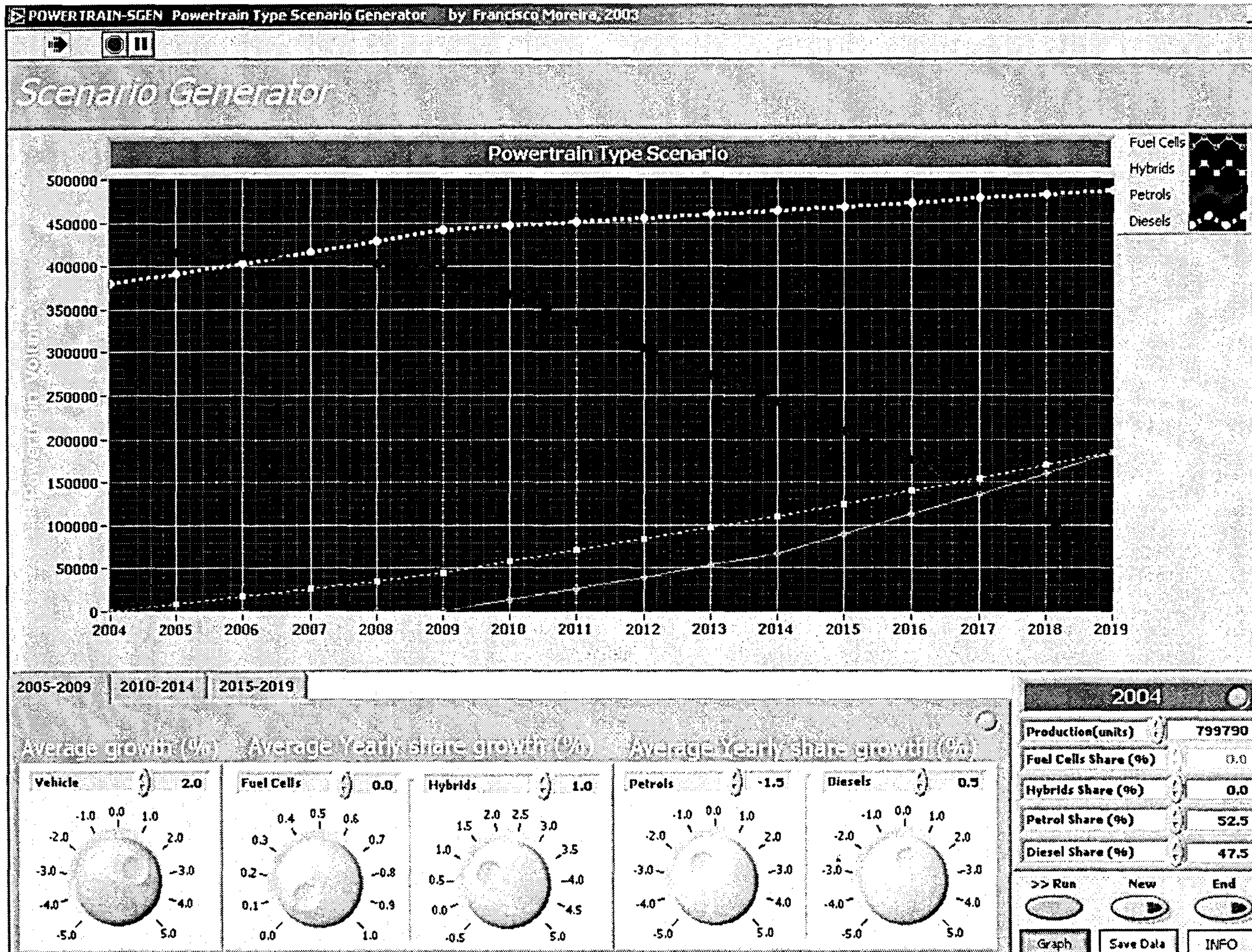
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-4.0**	**0.0**	**2.5**	**1.5**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	-3.5	41.5	366458.6	0.5	50.5	445931.6
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	-3.5	38.0	335552.5	0.5	51.0	450346.7
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	-3.5	34.5	304646.3	0.5	51.5	454761.9
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	-3.5	31.0	273740.2	0.5	52.0	459177.0
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	-3.5	27.5	242834.0	0.5	52.5	463592.2
2015	1.0	891863.1	2.5	10.0	89186.3	1.5	14.0	124860.8	-4.0	23.5	209587.8	0.0	52.5	468228.1
2016	1.0	900781.7	2.5	12.5	112597.7	1.5	15.5	139621.2	-4.0	19.5	175652.4	0.0	52.5	472910.4
2017	1.0	909789.6	2.5	15.0	136468.4	1.5	17.0	154664.2	-4.0	15.5	141017.4	0.0	52.5	477639.5
2018	1.0	918887.5	2.5	17.5	160805.3	1.5	18.5	169994.2	-4.0	11.5	105672.1	0.0	52.5	482415.9
2019	1.0	928076.3	2.5	20.0	185615.3	1.5	20.0	185615.3	-4.0	7.5	69605.7	0.0	52.5	487240.1


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 15

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

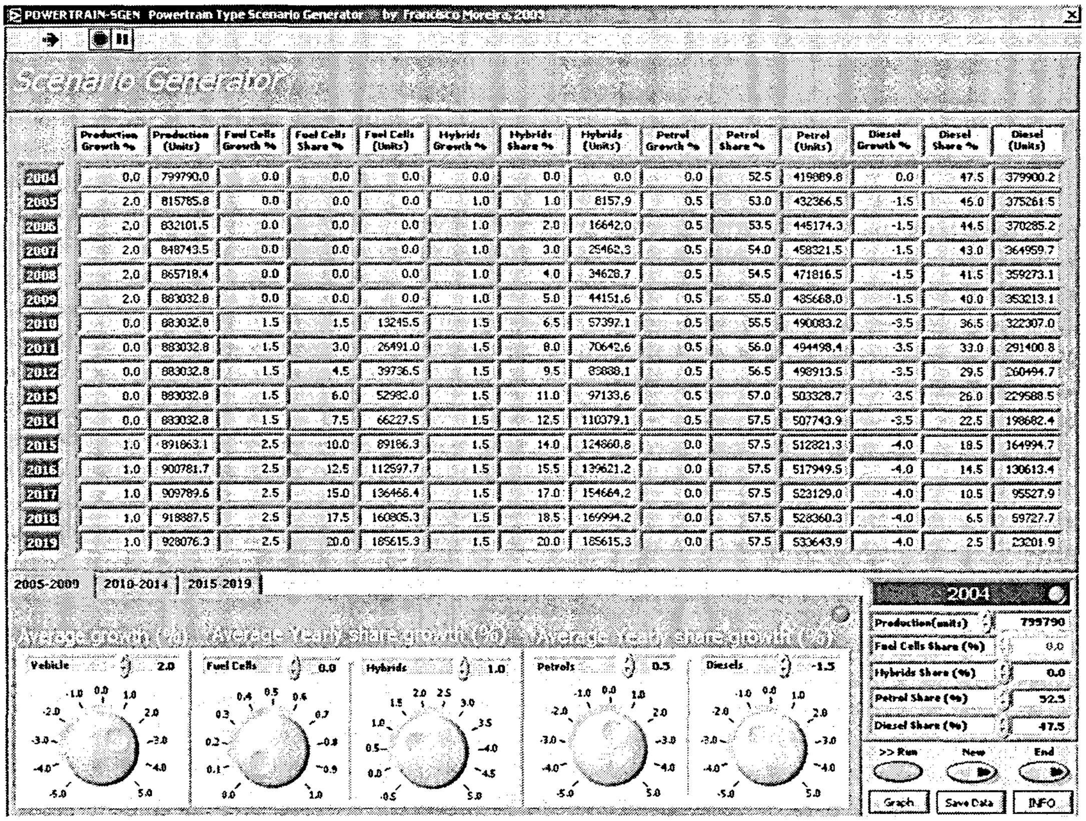
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

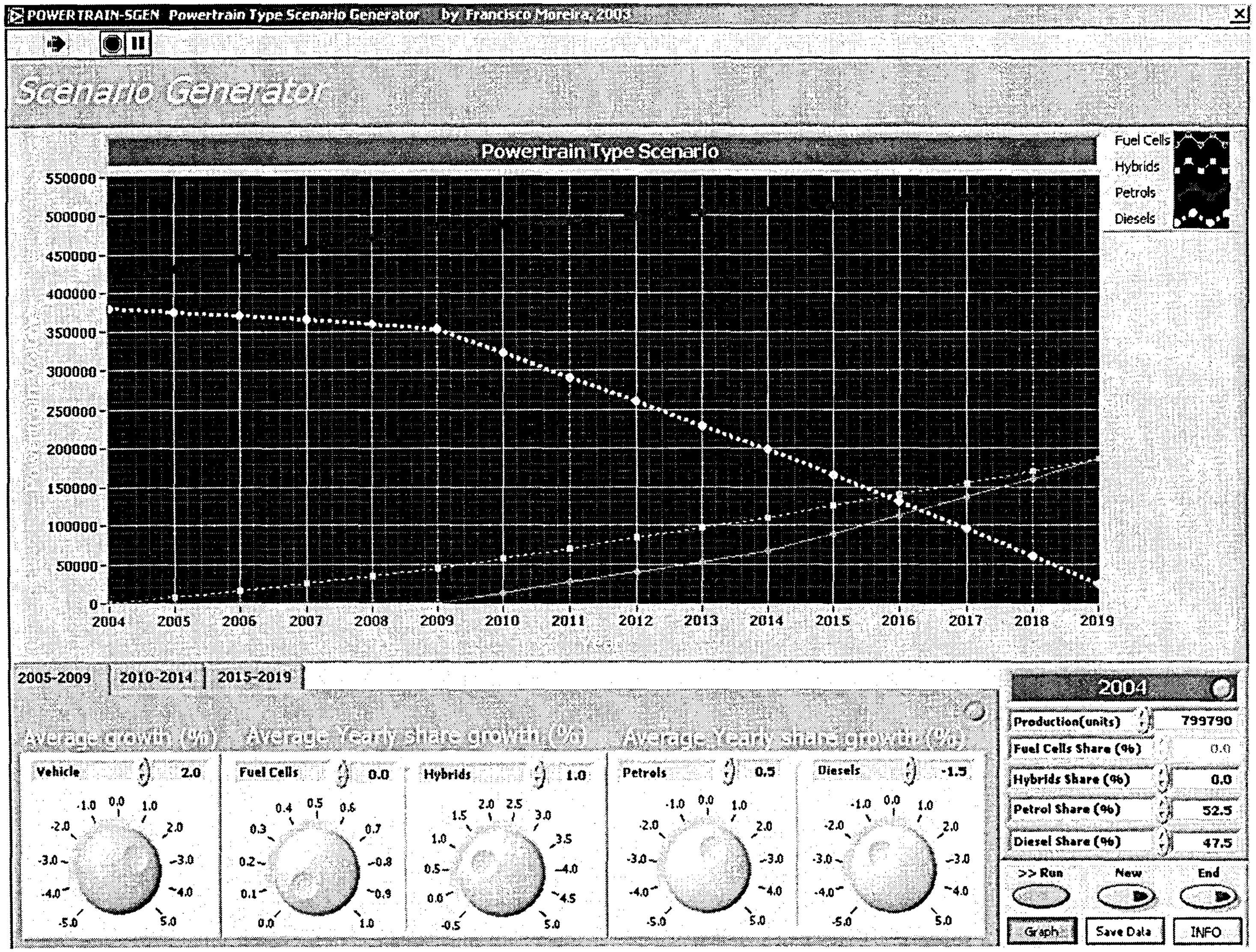
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0.5**	**-1.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**0.5**	**-3.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**0.0**	**-4.0**	**2.5**	**1.5**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	0.5	53.0	432366.5	-1.5	46.0	375261.5
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	0.5	53.5	445174.3	-1.5	44.5	370285.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	0.5	54.0	458321.5	-1.5	43.0	364959.7
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	0.5	54.5	471816.5	-1.5	41.5	359273.1
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	0.5	55.0	485668.0	-1.5	40.0	353213.1
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	0.5	55.5	490083.2	-3.5	36.5	322307.0
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	0.5	56.0	494498.4	-3.5	33.0	291400.8
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	0.5	56.5	498913.5	-3.5	29.5	260494.7
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	0.5	57.0	503328.7	-3.5	26.0	229588.5
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	0.5	57.5	507743.9	-3.5	22.5	198682.4
2015	1.0	891863.1	2.5	10.0	89186.3	1.5	14.0	124860.8	0.0	57.5	512821.3	-4.0	18.5	164994.7
2016	1.0	900781.7	2.5	12.5	112597.7	1.5	15.5	139621.2	0.0	57.5	517949.5	-4.0	14.5	130613.4
2017	1.0	909789.6	2.5	15.0	136468.4	1.5	17.0	154664.2	0.0	57.5	523129.0	-4.0	10.5	95527.9
2018	1.0	918887.5	2.5	17.5	160805.3	1.5	18.5	169994.2	0.0	57.5	528360.3	-4.0	6.5	59727.7
2019	1.0	928076.3	2.5	20.0	185615.3	1.5	20.0	185615.3	0.0	57.5	533643.9	-4.0	2.5	23201.9


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols 0.5
Diesels -1.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 16

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

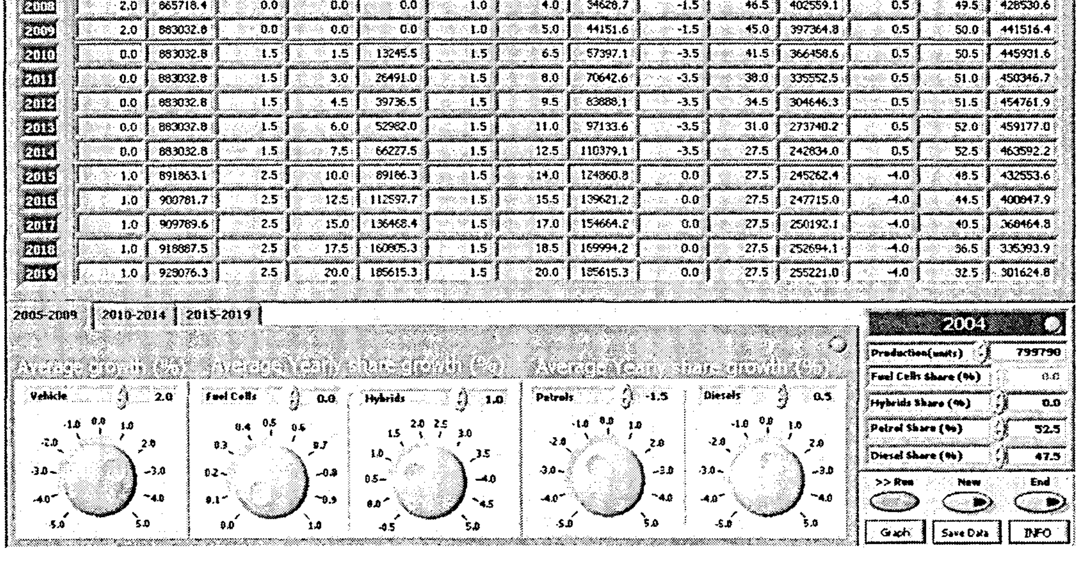
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

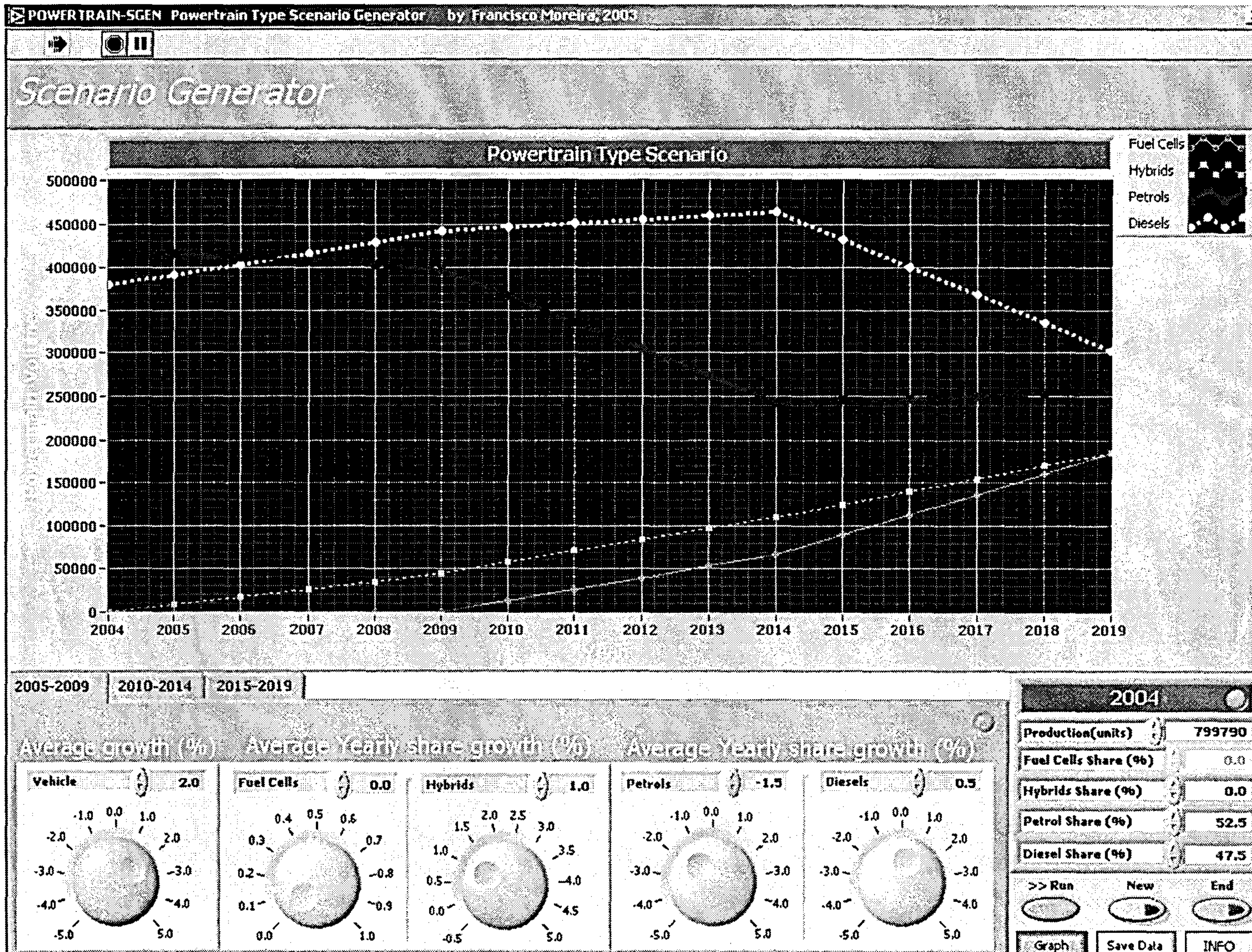
3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**0.0**	**-4.0**	**2.5**	**1.5**	**Smooth**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 17

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

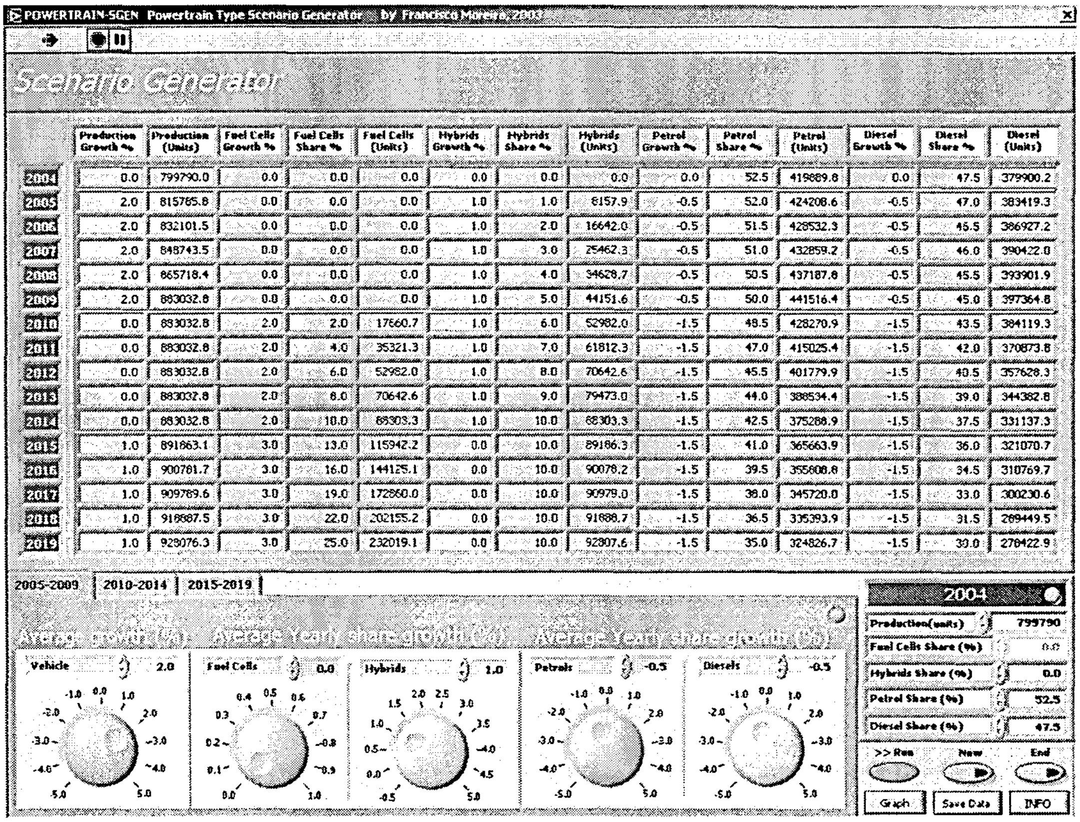
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

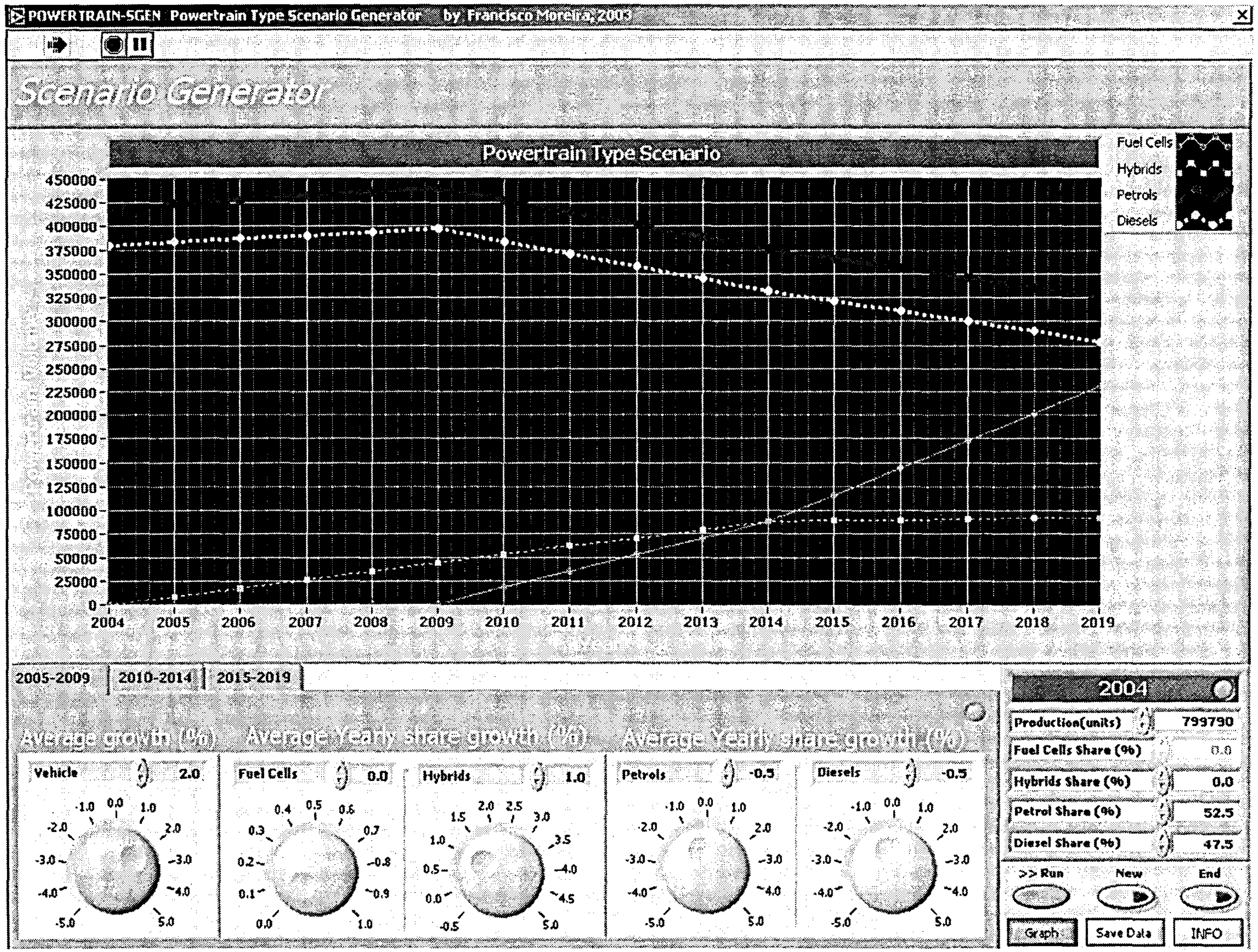
4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-0.5**	**-0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-1.5**	**-1.5**	**2.0**	**1**	**Smooth**
2015-2019	**1.0**	**-1.5**	**-1.5**	**3.0**	**0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-0.5	52.0	424208.6	-0.5	47.0	383419.3
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-0.5	51.5	428532.3	-0.5	46.5	386927.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-0.5	51.0	432859.2	-0.5	46.0	390422.0
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-0.5	50.5	437187.8	-0.5	45.5	393901.9
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-0.5	50.0	441516.4	-0.5	45.0	397364.8
2010	0.0	883032.8	2.0	2.0	17660.7	1.0	6.0	52982.0	-1.5	48.5	428270.9	-1.5	43.5	384119.3
2011	0.0	883032.8	2.0	4.0	35321.3	1.0	7.0	61812.3	-1.5	47.0	415025.4	-1.5	42.0	370873.8
2012	0.0	883032.8	2.0	6.0	52982.0	1.0	8.0	70642.6	-1.5	45.5	401779.9	-1.5	40.5	357628.3
2013	0.0	883032.8	2.0	8.0	70642.6	1.0	9.0	79473.0	-1.5	44.0	388534.4	-1.5	39.0	344382.8
2014	0.0	883032.8	2.0	10.0	88303.3	1.0	10.0	88303.3	-1.5	42.5	375288.9	-1.5	37.5	331137.3
2015	1.0	891863.1	3.0	13.0	115942.2	0.0	10.0	89186.3	-1.5	41.0	365663.9	-1.5	36.0	321070.7
2016	1.0	900781.7	3.0	16.0	144125.1	0.0	10.0	90078.2	-1.5	39.5	355808.8	-1.5	34.5	310769.7
2017	1.0	909789.6	3.0	19.0	172860.0	0.0	10.0	90979.0	-1.5	38.0	345720.0	-1.5	33.0	300230.6
2018	1.0	918887.5	3.0	22.0	202155.2	0.0	10.0	91888.7	-1.5	36.5	335393.9	-1.5	31.5	289449.5
2019	1.0	928076.3	3.0	25.0	232019.1	0.0	10.0	92807.6	-1.5	35.0	324826.7	-1.5	30.0	278422.9


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
450000
425000
400000
375000
350000
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275000
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225000
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175000
150000
125000
100000
75000
50000
25000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -0.5
Diesels -0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 18

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

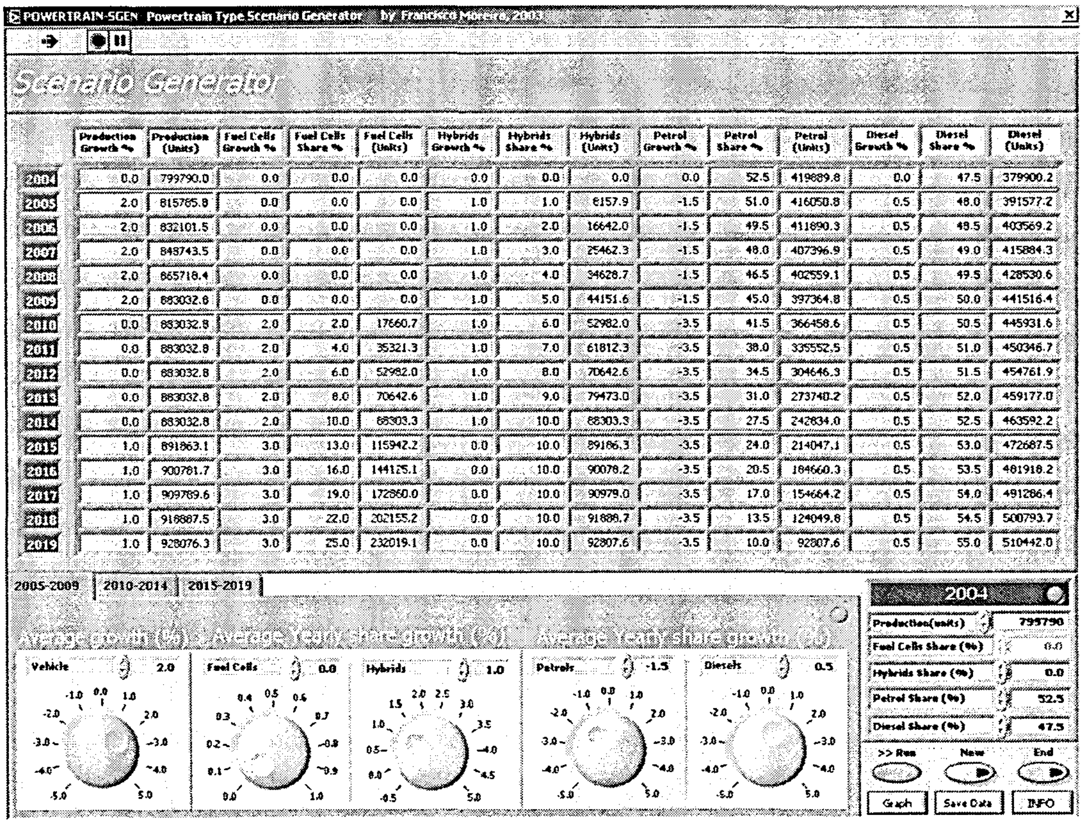
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

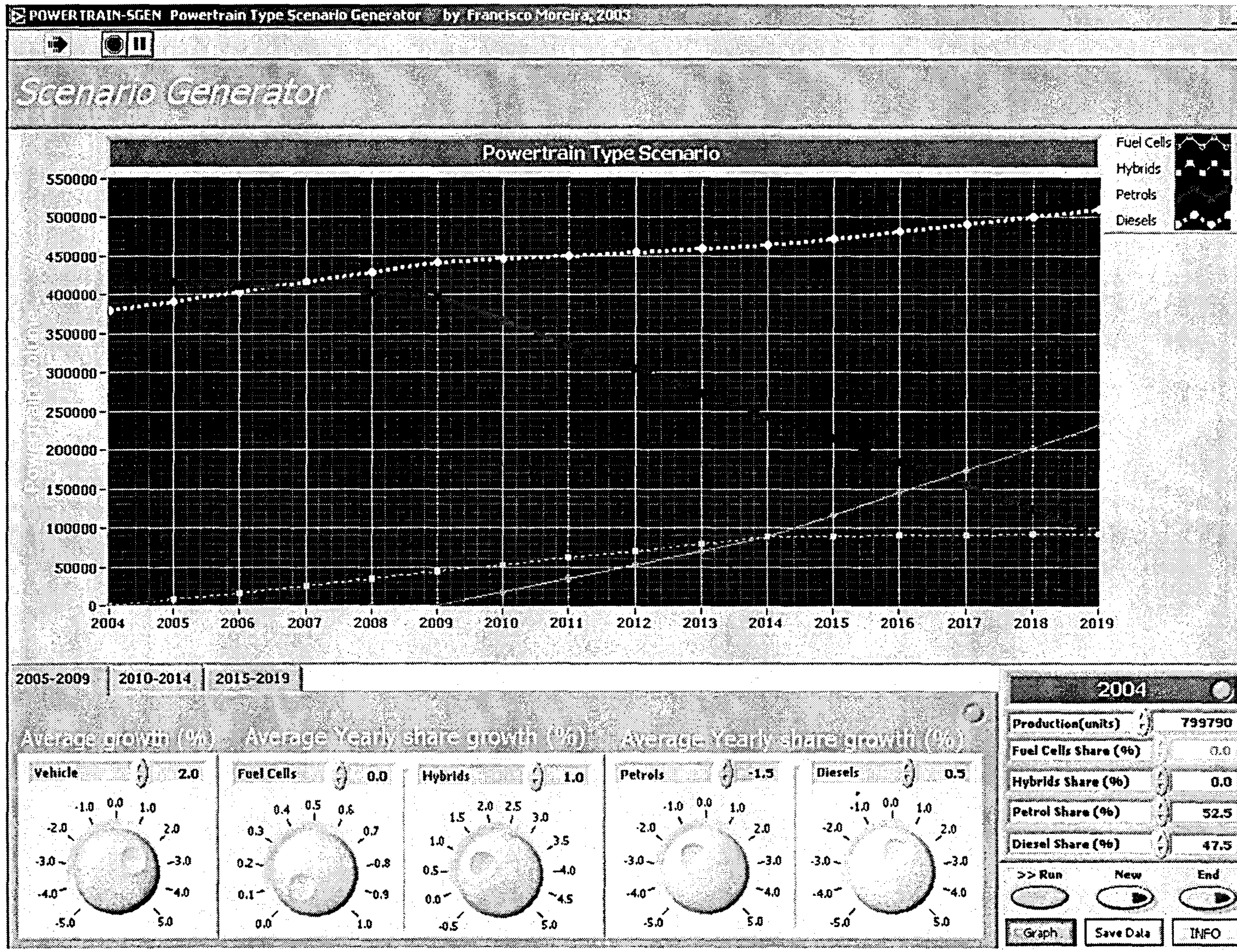
3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**2.0**	**1**	**Smooth**
2015-2019	**1.0**	**-3.5**	**0.5**	**3.0**	**0**	**Smooth**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 19

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

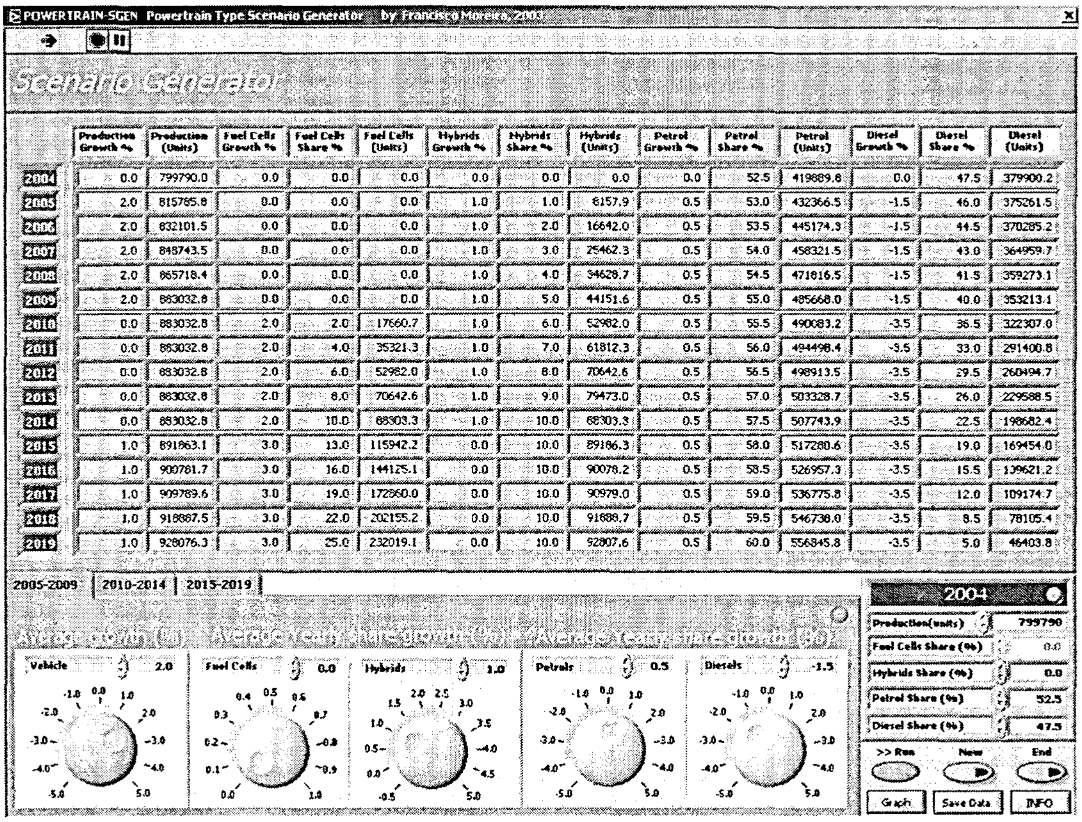
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

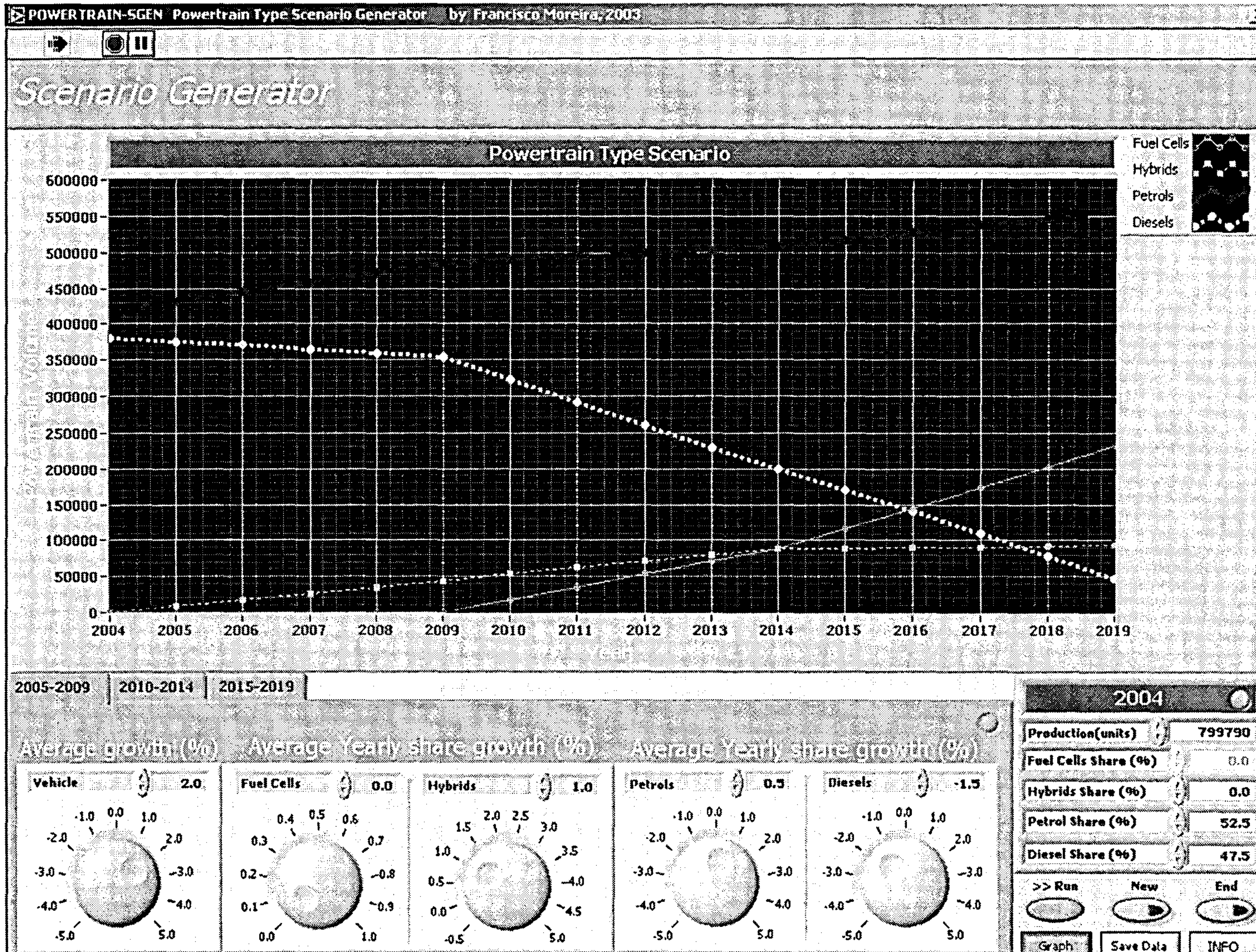
4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0.5**	**-1.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**0.5**	**-3.5**	**2.0**	**1**	**Smooth**
2015-2019	**1.0**	**0.5**	**-3.5**	**3.0**	**0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	0.5	53.0	432366.5	-1.5	46.0	375261.5
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	0.5	53.5	445174.3	-1.5	44.5	370285.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	0.5	54.0	458321.5	-1.5	43.0	364959.7
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	0.5	54.5	471816.5	-1.5	41.5	359273.1
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	0.5	55.0	485668.0	-1.5	40.0	353213.1
2010	0.0	883032.8	2.0	2.0	17660.7	1.0	6.0	52982.0	0.5	55.5	490083.2	-3.5	36.5	322307.0
2011	0.0	883032.8	2.0	4.0	35321.3	1.0	7.0	61812.3	0.5	56.0	494498.4	-3.5	33.0	291400.8
2012	0.0	883032.8	2.0	6.0	52982.0	1.0	8.0	70642.6	0.5	56.5	498913.5	-3.5	29.5	260494.7
2013	0.0	883032.8	2.0	8.0	70642.6	1.0	9.0	79473.0	0.5	57.0	503328.7	-3.5	26.0	229588.5
2014	0.0	883032.8	2.0	10.0	88303.3	1.0	10.0	88303.3	0.5	57.5	507743.9	-3.5	22.5	198682.4
2015	1.0	891863.1	3.0	13.0	115942.2	0.0	10.0	89186.3	0.5	58.0	517280.6	-3.5	19.0	169454.0
2016	1.0	900781.7	3.0	16.0	144125.1	0.0	10.0	90078.2	0.5	58.5	526957.3	-3.5	15.5	139621.2
2017	1.0	909789.6	3.0	19.0	172860.0	0.0	10.0	90979.0	0.5	59.0	536775.8	-3.5	12.0	109174.7
2018	1.0	918887.5	3.0	22.0	202155.2	0.0	10.0	91888.7	0.5	59.5	546738.0	-3.5	8.5	78105.4
2019	1.0	928076.3	3.0	25.0	232019.1	0.0	10.0	92807.6	0.5	60.0	556845.8	-3.5	5.0	46403.8


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira-2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
600000
550000
500000
450000
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350000
300000
250000
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150000
100000
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0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols 0.5
Diesels -1.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 20

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

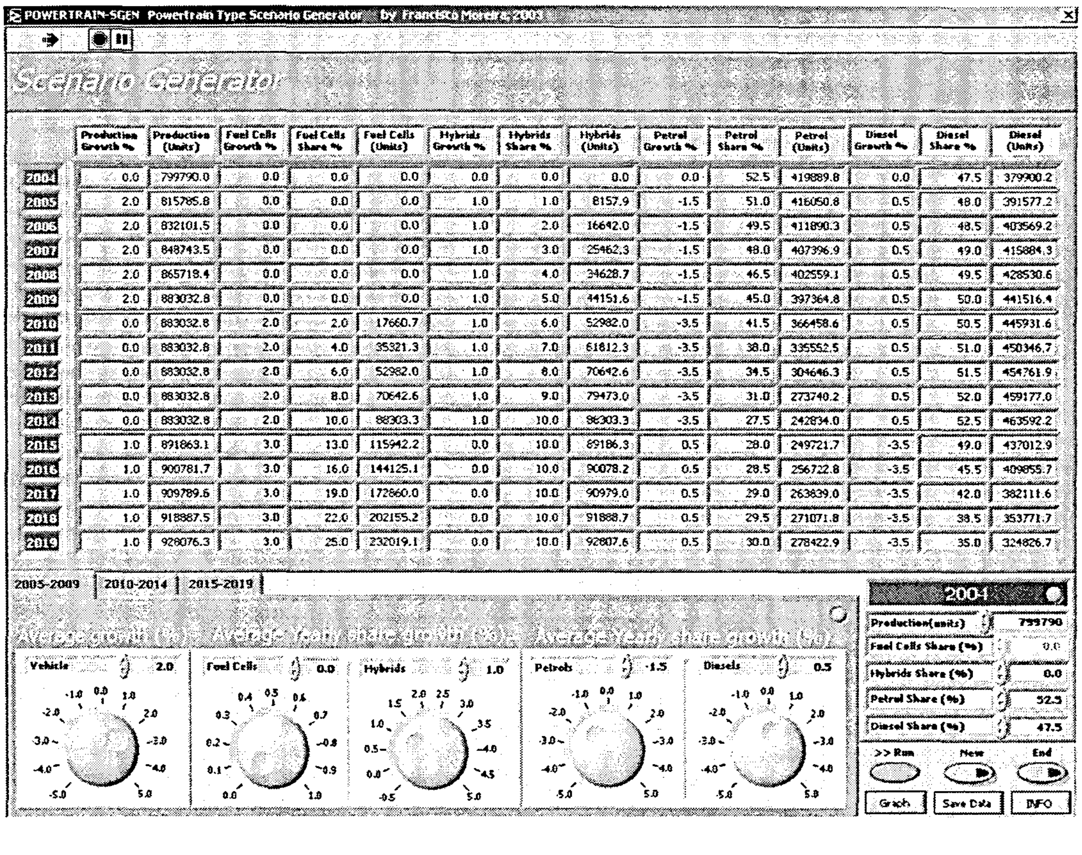
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

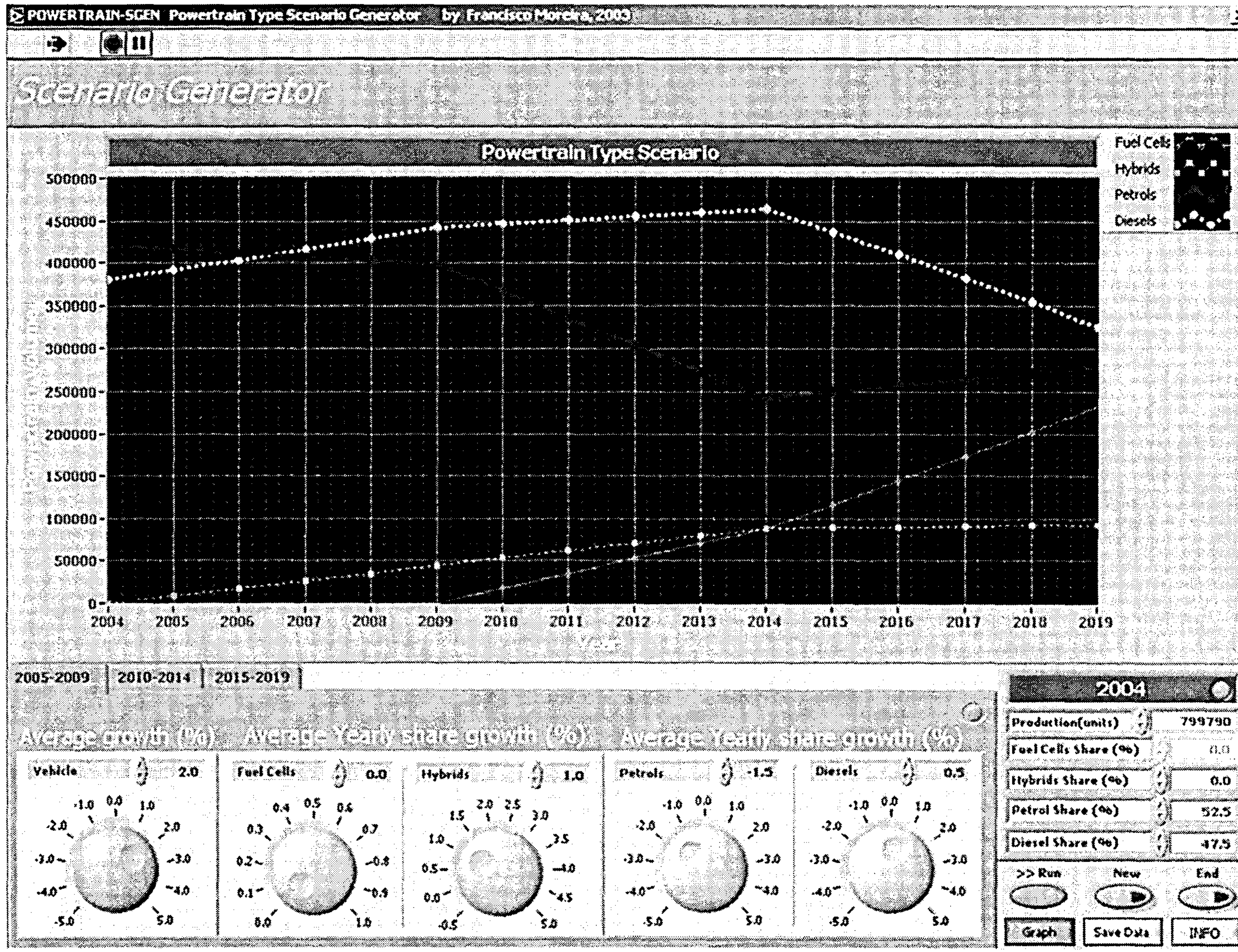
4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. Oil price increase is smooth over the period 2010-2014 and 2015-2019.

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**2.0**	**1**	**Smooth**
2015-2019	**1.0**	**0.5**	**-3.5**	**3.0**	**0**	**Smooth**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	2.0	2.0	17660.7	1.0	6.0	52982.0	-3.5	41.5	366458.6	0.5	50.5	445931.6
2011	0.0	883032.8	2.0	4.0	35321.3	1.0	7.0	61812.3	-3.5	38.0	335552.5	0.5	51.0	450346.7
2012	0.0	883032.8	2.0	6.0	52982.0	1.0	8.0	70642.6	-3.5	34.5	304646.3	0.5	51.5	454761.9
2013	0.0	883032.8	2.0	8.0	70642.6	1.0	9.0	79473.0	-3.5	31.0	273740.2	0.5	52.0	459177.0
2014	0.0	883032.8	2.0	10.0	88303.3	1.0	10.0	88303.3	-3.5	27.5	242834.0	0.5	52.5	463592.2
2015	1.0	891863.1	3.0	13.0	115942.2	0.0	10.0	89186.3	0.5	28.0	249721.7	-3.5	49.0	437012.9
2016	1.0	900781.7	3.0	16.0	144125.1	0.0	10.0	90078.2	0.5	28.5	256722.8	-3.5	45.5	409855.7
2017	1.0	909789.6	3.0	19.0	172860.0	0.0	10.0	90979.0	0.5	29.0	263839.0	-3.5	42.0	382111.6
2018	1.0	918887.5	3.0	22.0	202155.2	0.0	10.0	91888.7	0.5	29.5	271071.8	-3.5	38.5	353771.7
2019	1.0	928076.3	3.0	25.0	232019.1	0.0	10.0	92807.6	0.5	30.0	278422.9	-3.5	35.0	324826.7


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
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500000
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2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 21

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

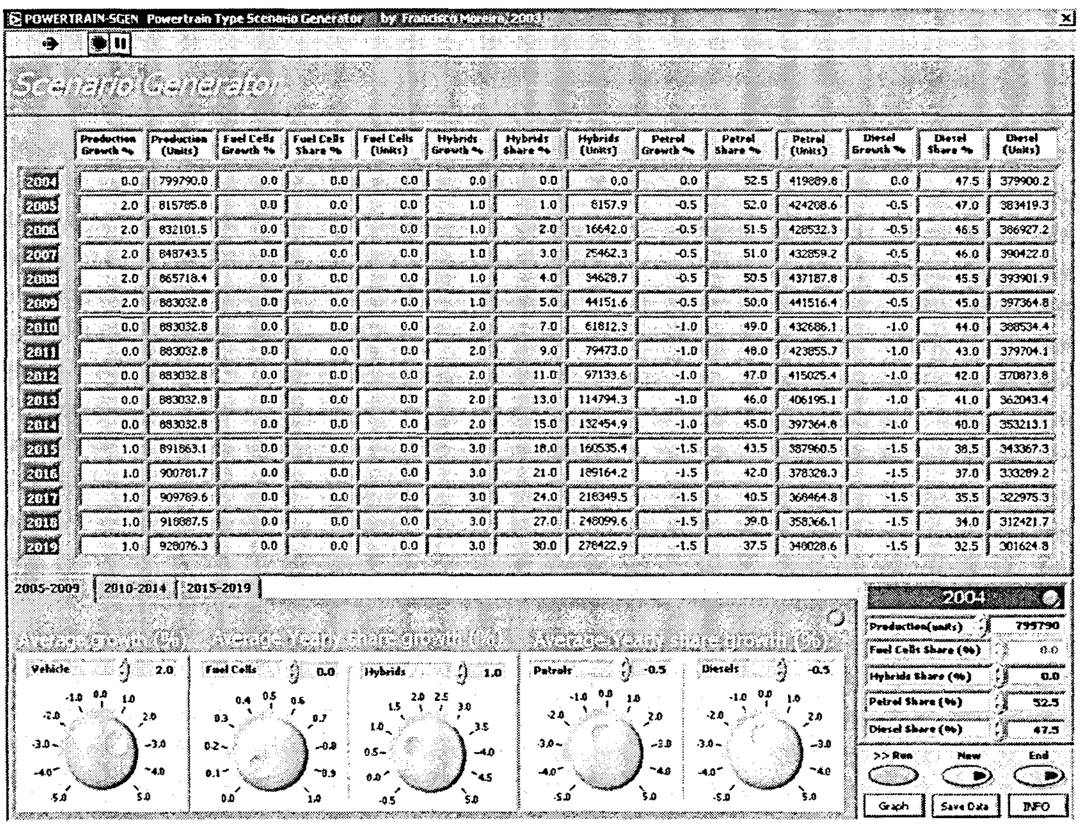
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**

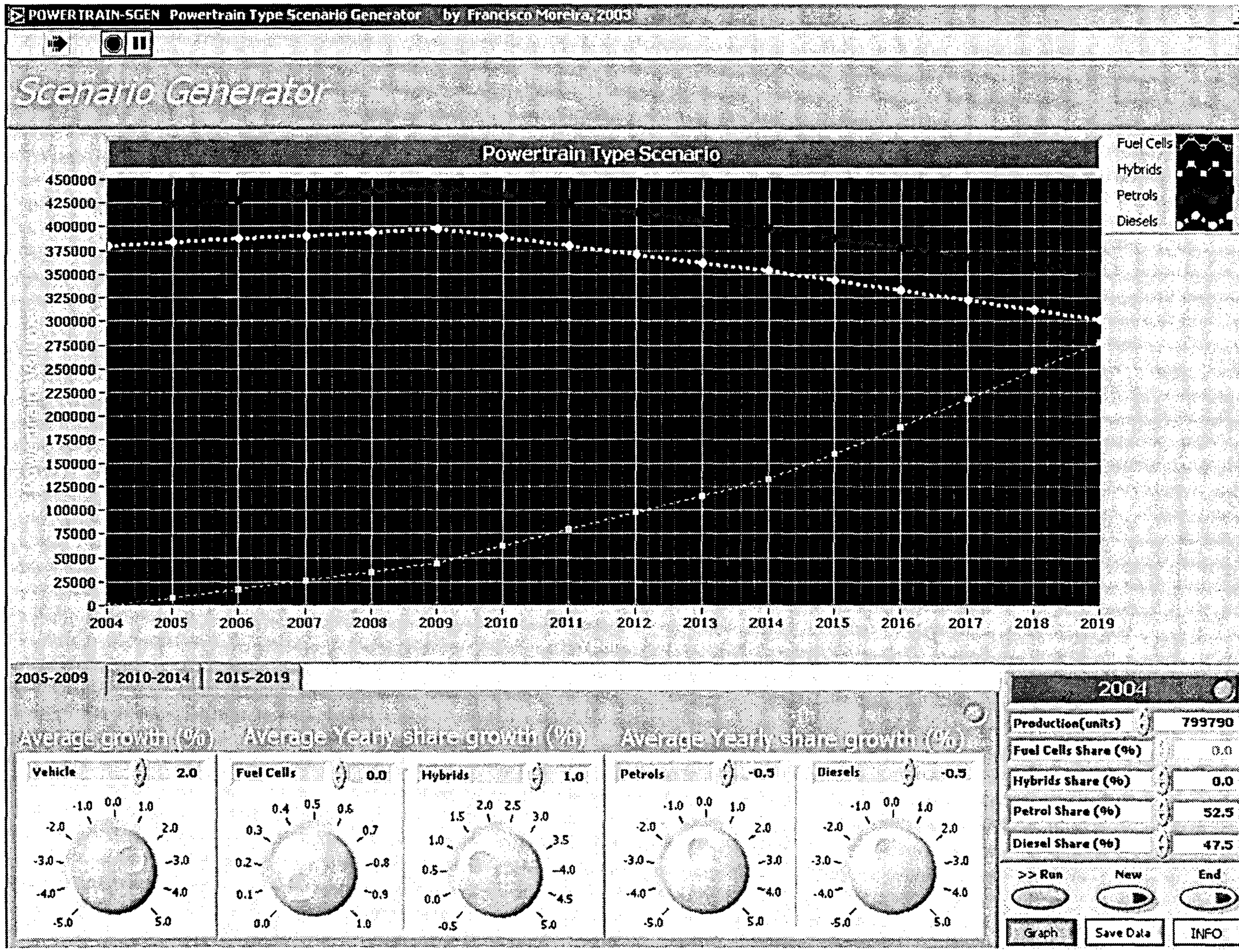
3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-0.5**	**-0.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**-1.0**	**-1.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**-1.5**	**-1.5**	**0.0**	**3.0**	**Fast**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
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150000
125000
100000
75000
50000
25000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -0.5
Diesels -0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 22

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

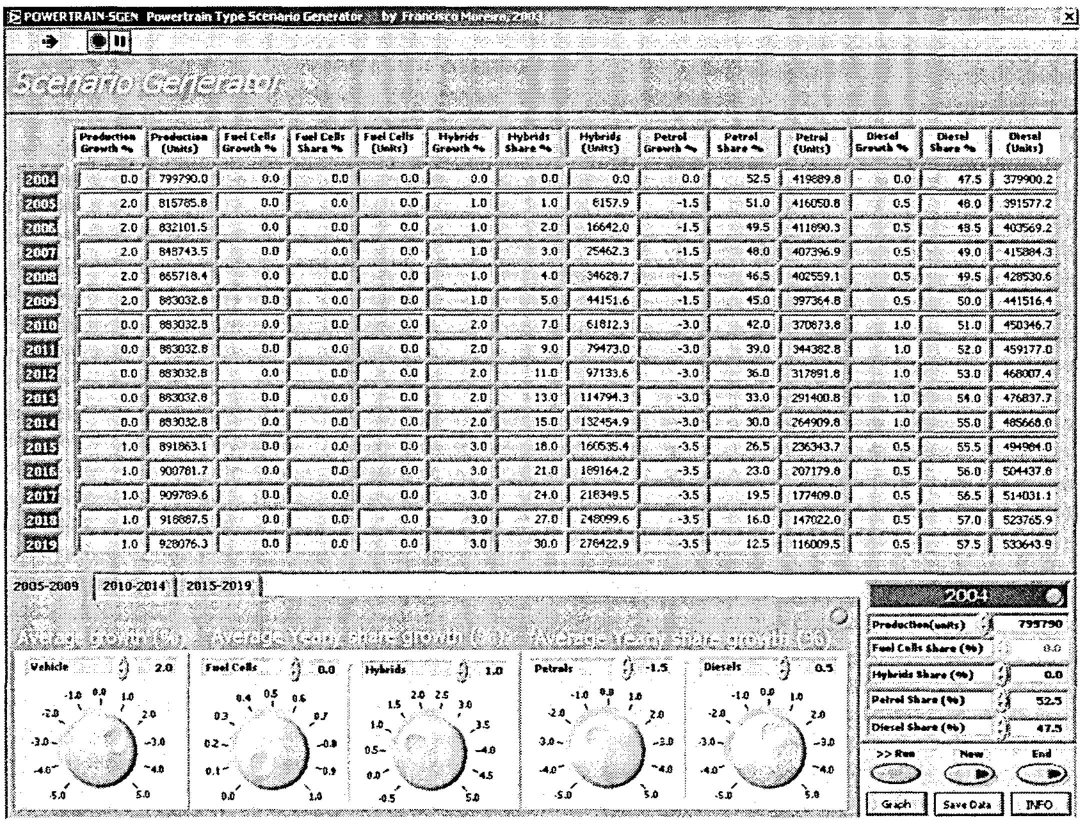
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

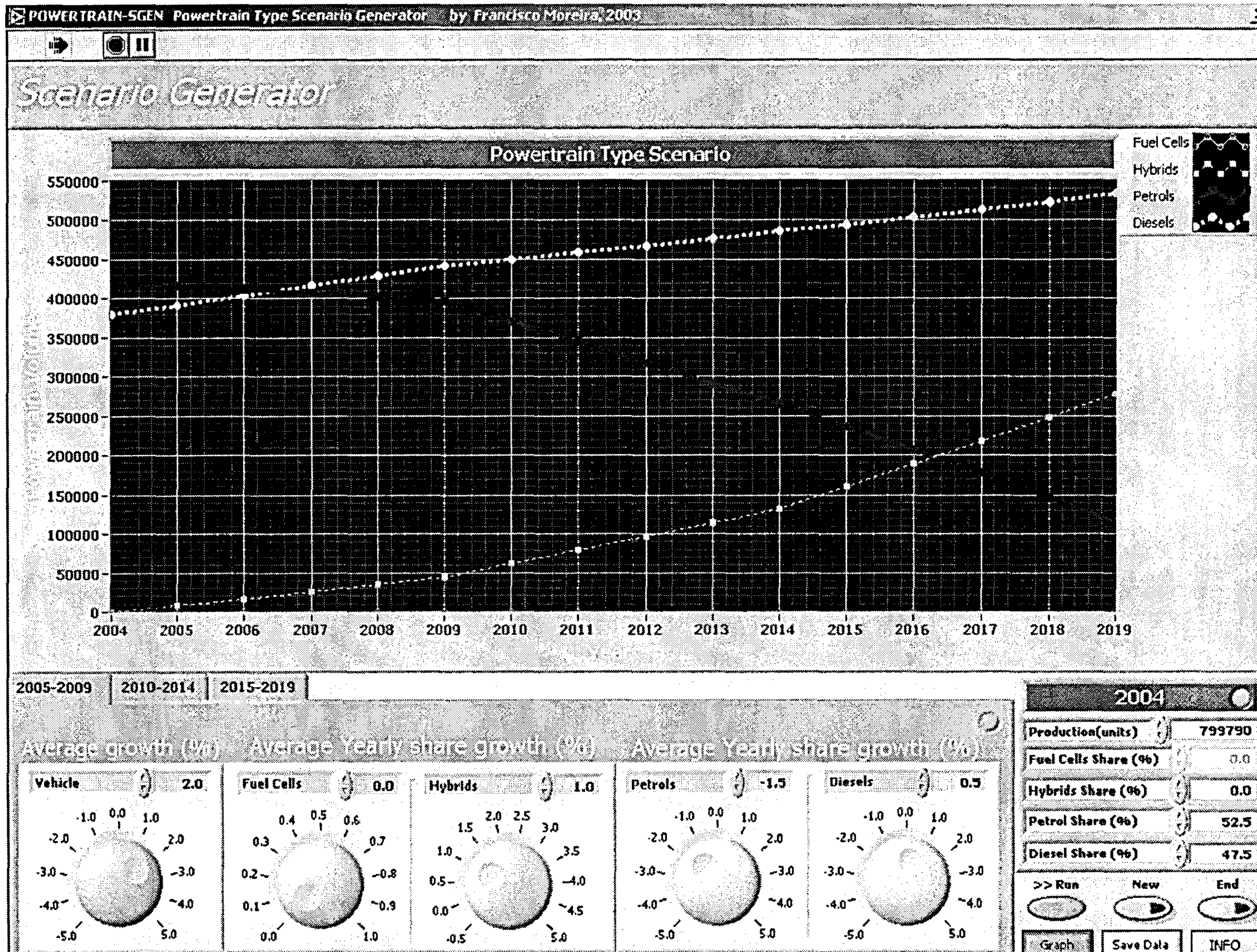
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**-3.5**	**0.5**	**0.0**	**3.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	0.0	0.0	0.0	2.0	7.0	61812.3	-3.0	42.0	370873.8	1.0	51.0	450346.7
2011	0.0	883032.8	0.0	0.0	0.0	2.0	9.0	79473.0	-3.0	39.0	344382.8	1.0	52.0	459177.0
2012	0.0	883032.8	0.0	0.0	0.0	2.0	11.0	97133.6	-3.0	36.0	317891.8	1.0	53.0	468007.4
2013	0.0	883032.8	0.0	0.0	0.0	2.0	13.0	114794.3	-3.0	33.0	291400.8	1.0	54.0	476837.7
2014	0.0	883032.8	0.0	0.0	0.0	2.0	15.0	132454.9	-3.0	30.0	264909.8	1.0	55.0	485668.0
2015	1.0	891863.1	0.0	0.0	0.0	3.0	18.0	160535.4	-3.5	26.5	236343.7	0.5	55.5	494984.0
2016	1.0	900781.7	0.0	0.0	0.0	3.0	21.0	189164.2	-3.5	23.0	207179.8	0.5	56.0	504437.8
2017	1.0	909789.6	0.0	0.0	0.0	3.0	24.0	218349.5	-3.5	19.5	177409.0	0.5	56.5	514031.1
2018	1.0	918887.5	0.0	0.0	0.0	3.0	27.0	248099.6	-3.5	16.0	147022.0	0.5	57.0	523765.9
2019	1.0	928076.3	0.0	0.0	0.0	3.0	30.0	278422.9	-3.5	12.5	116009.5	0.5	57.5	533643.9


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
550000
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2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 23

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

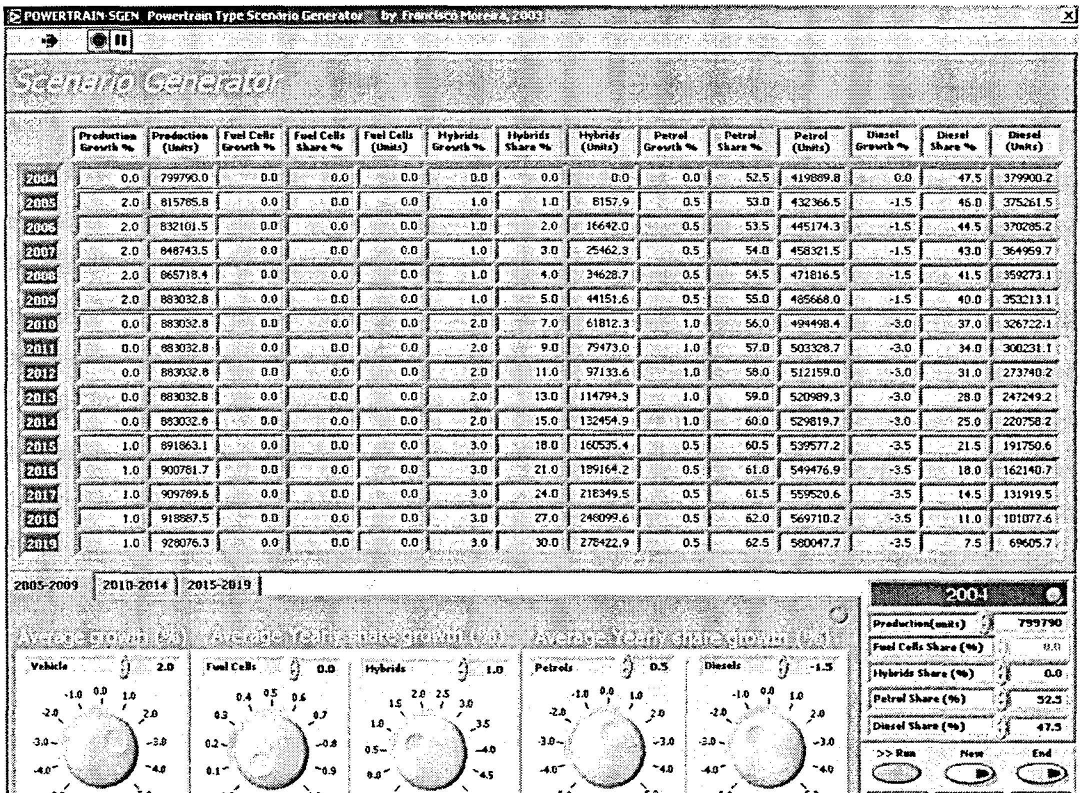
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

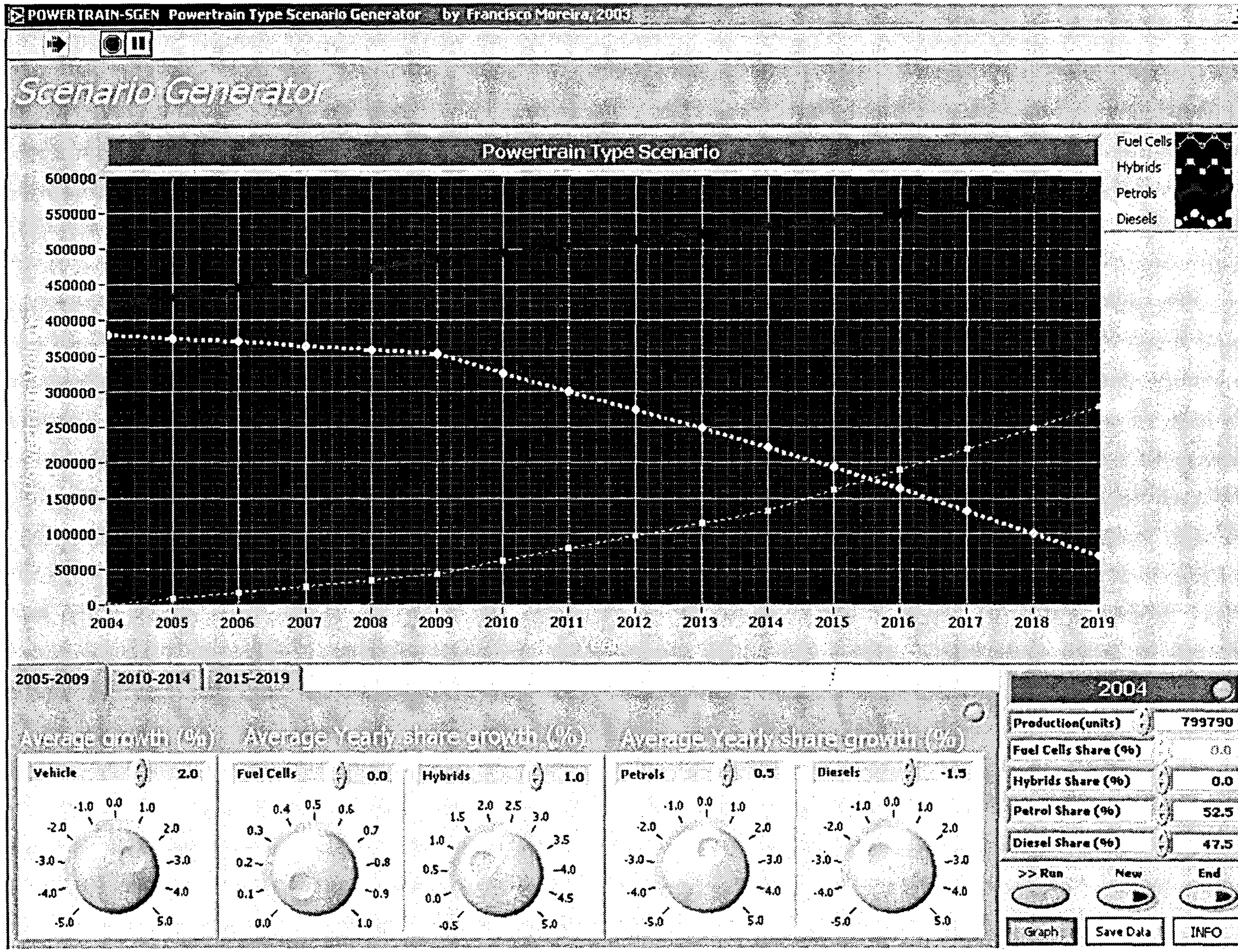
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0.5**	**-1.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**1.0**	**-3.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**0.5**	**-3.5**	**0.0**	**3.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	0.5	53.0	432366.5	-1.5	46.0	375261.5
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	0.5	53.5	445174.3	-1.5	44.5	370285.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	0.5	54.0	458321.5	-1.5	43.0	364959.7
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	0.5	54.5	471816.5	-1.5	41.5	359273.1
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	0.5	55.0	485668.0	-1.5	40.0	353213.1
2010	0.0	883032.8	0.0	0.0	0.0	2.0	7.0	61812.3	1.0	56.0	494498.4	-3.0	37.0	326722.1
2011	0.0	883032.8	0.0	0.0	0.0	2.0	9.0	79473.0	1.0	57.0	503328.7	-3.0	34.0	300231.1
2012	0.0	883032.8	0.0	0.0	0.0	2.0	11.0	97133.6	1.0	58.0	512159.0	-3.0	31.0	273740.2
2013	0.0	883032.8	0.0	0.0	0.0	2.0	13.0	114794.3	1.0	59.0	520989.3	-3.0	28.0	247249.2
2014	0.0	883032.8	0.0	0.0	0.0	2.0	15.0	132454.9	1.0	60.0	529819.7	-3.0	25.0	220758.2
2015	1.0	891863.1	0.0	0.0	0.0	3.0	18.0	160535.4	0.5	60.5	539577.2	-3.5	21.5	191750.6
2016	1.0	900781.7	0.0	0.0	0.0	3.0	21.0	189164.2	0.5	61.0	549476.9	-3.5	18.0	162140.7
2017	1.0	909789.6	0.0	0.0	0.0	3.0	24.0	218349.5	0.5	61.5	559520.6	-3.5	14.5	131919.5
2018	1.0	918887.5	0.0	0.0	0.0	3.0	27.0	248099.6	0.5	62.0	569710.2	-3.5	11.0	101077.6
2019	1.0	928076.3	0.0	0.0	0.0	3.0	30.0	278422.9	0.5	62.5	580047.7	-3.5	7.5	69605.7


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
600000
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100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
Year
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols 0.5
Diesels -1.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 24

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

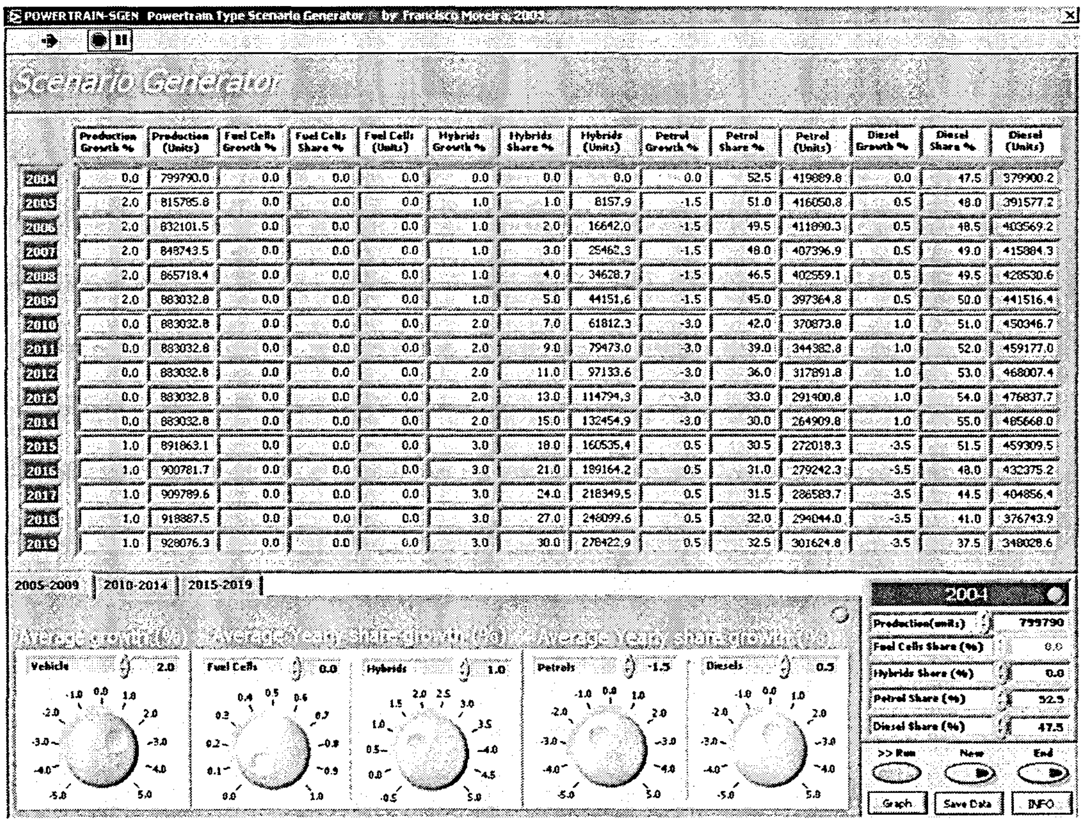
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

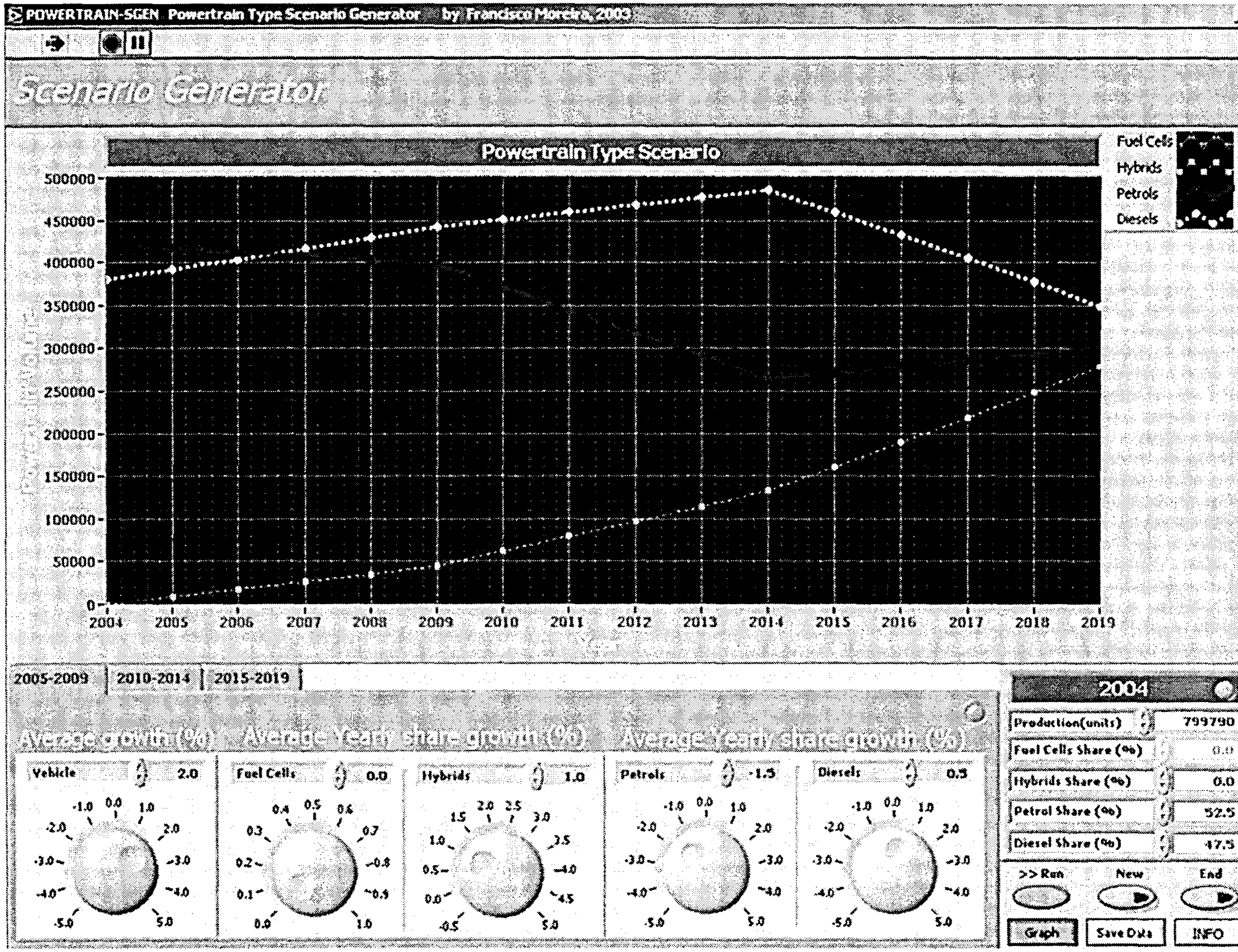
3. Fuel Cell vehicles fail to gain market share following market introduction around 2010.

4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**0.0**	**2.0**	**Smooth**
2015-2019	**1.0**	**0.5**	**-3.5**	**0.0**	**3.0**	**Fast**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 25

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

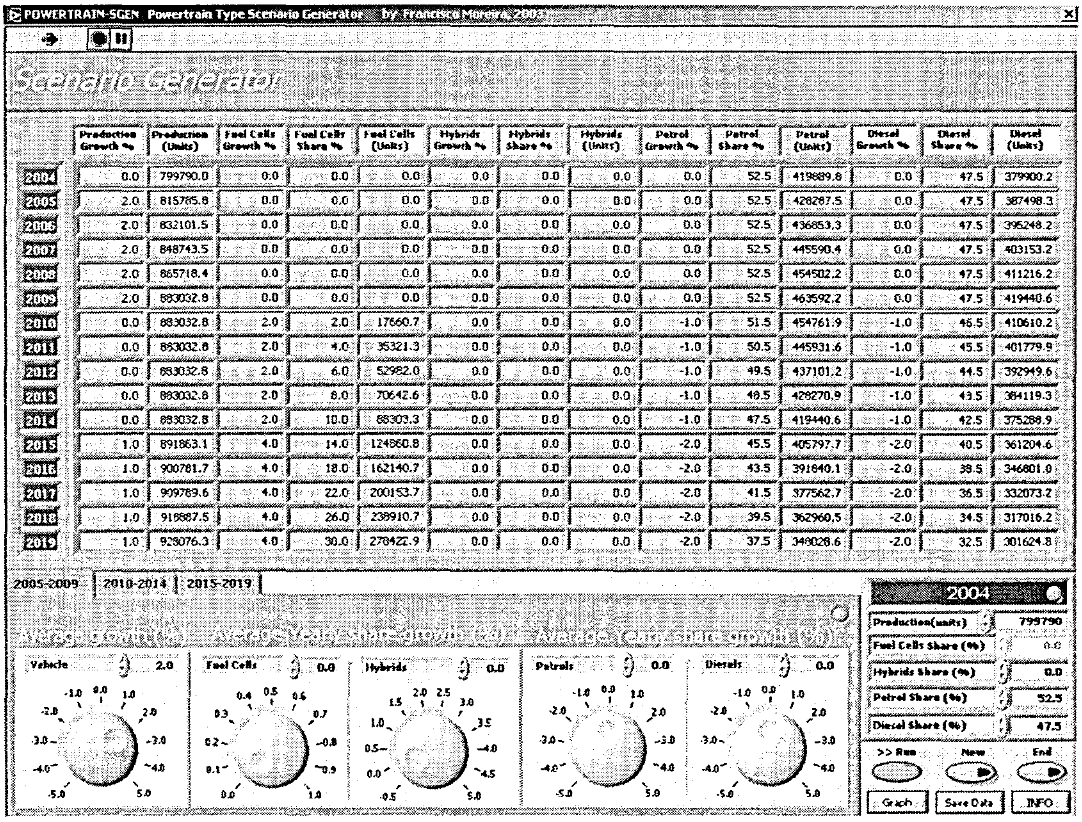
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

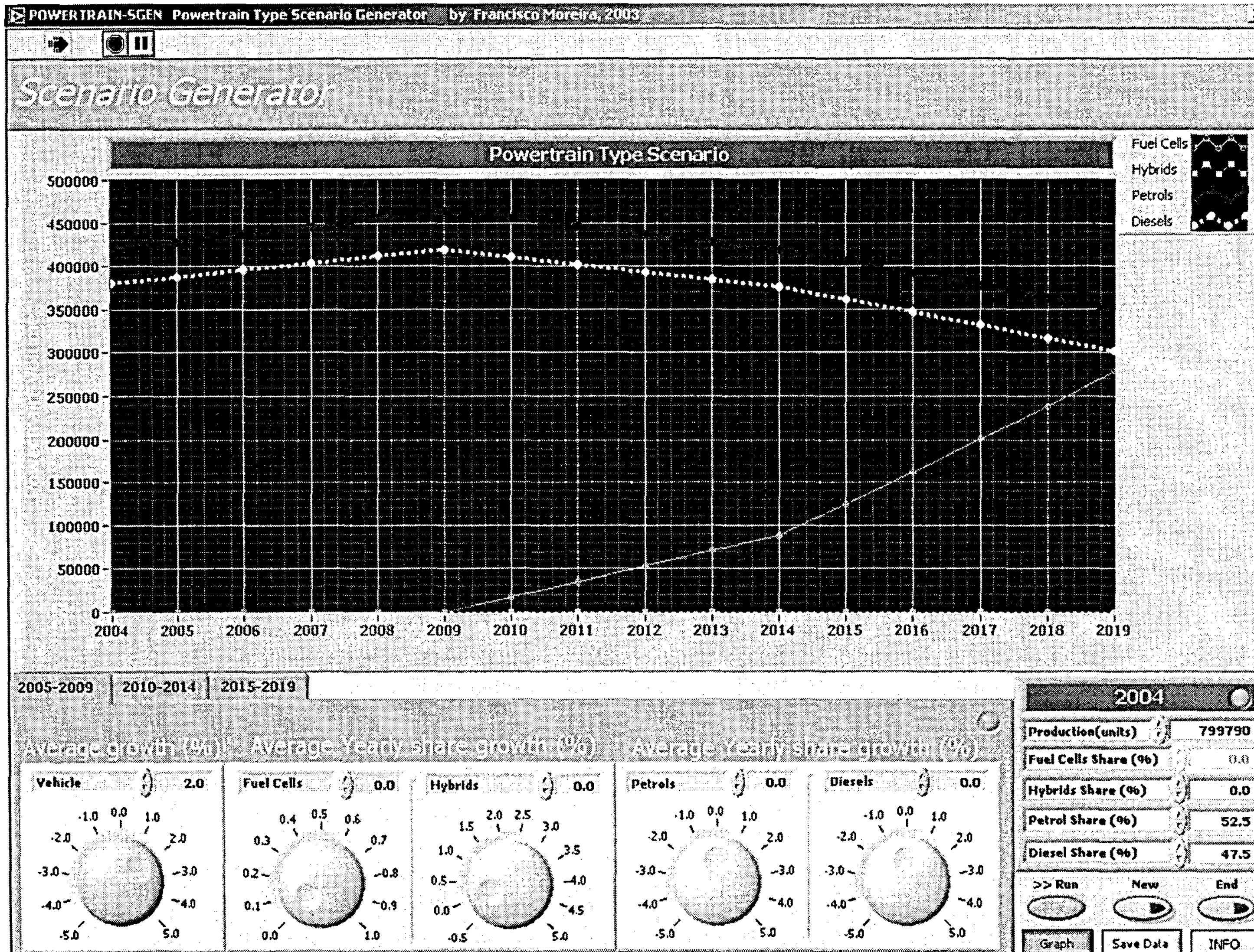
4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0**	**0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-1.0**	**-1.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**-2.0**	**-2.0**	**4.0**	**0.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	428287.5	0.0	47.5	387498.3
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	436853.3	0.0	47.5	395248.2
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	445590.4	0.0	47.5	403153.2
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	454502.2	0.0	47.5	411216.2
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	463592.2	0.0	47.5	419440.6
2010	0.0	883032.8	2.0	2.0	17660.7	0.0	0.0	0.0	-1.0	51.5	454761.9	-1.0	46.5	410610.2
2011	0.0	883032.8	2.0	4.0	35321.3	0.0	0.0	0.0	-1.0	50.5	445931.6	-1.0	45.5	401779.9
2012	0.0	883032.8	2.0	6.0	52982.0	0.0	0.0	0.0	-1.0	49.5	437101.2	-1.0	44.5	392949.6
2013	0.0	883032.8	2.0	8.0	70642.6	0.0	0.0	0.0	-1.0	48.5	428270.9	-1.0	43.5	384119.3
2014	0.0	883032.8	2.0	10.0	88303.3	0.0	0.0	0.0	-1.0	47.5	419440.6	-1.0	42.5	375288.9
2015	1.0	891863.1	4.0	14.0	124860.8	0.0	0.0	0.0	-2.0	45.5	405797.7	-2.0	40.5	361204.6
2016	1.0	900781.7	4.0	18.0	162140.7	0.0	0.0	0.0	-2.0	43.5	391840.1	-2.0	38.5	346801.0
2017	1.0	909789.6	4.0	22.0	200153.7	0.0	0.0	0.0	-2.0	41.5	377562.7	-2.0	36.5	332073.2
2018	1.0	918887.5	4.0	26.0	238910.7	0.0	0.0	0.0	-2.0	39.5	362960.5	-2.0	34.5	317016.2
2019	1.0	928076.3	4.0	30.0	278422.9	0.0	0.0	0.0	-2.0	37.5	348028.6	-2.0	32.5	301624.8


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
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2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols 0.0
Diesels 0.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 26

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

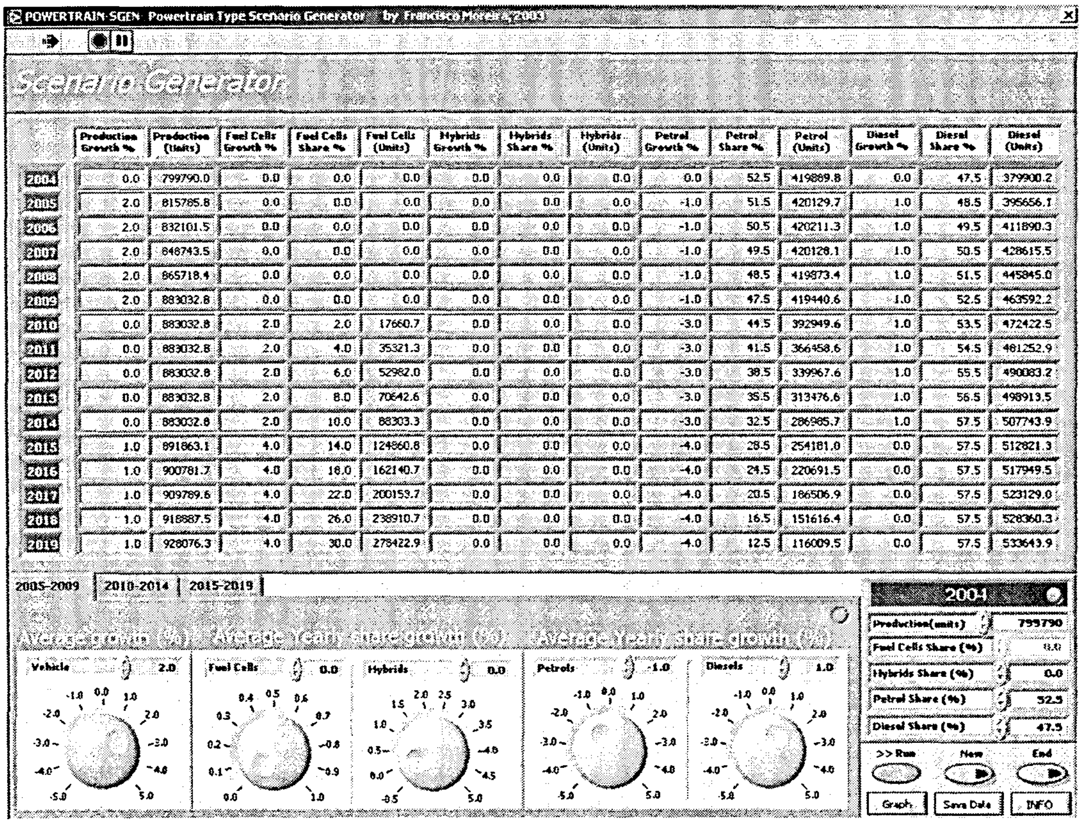
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

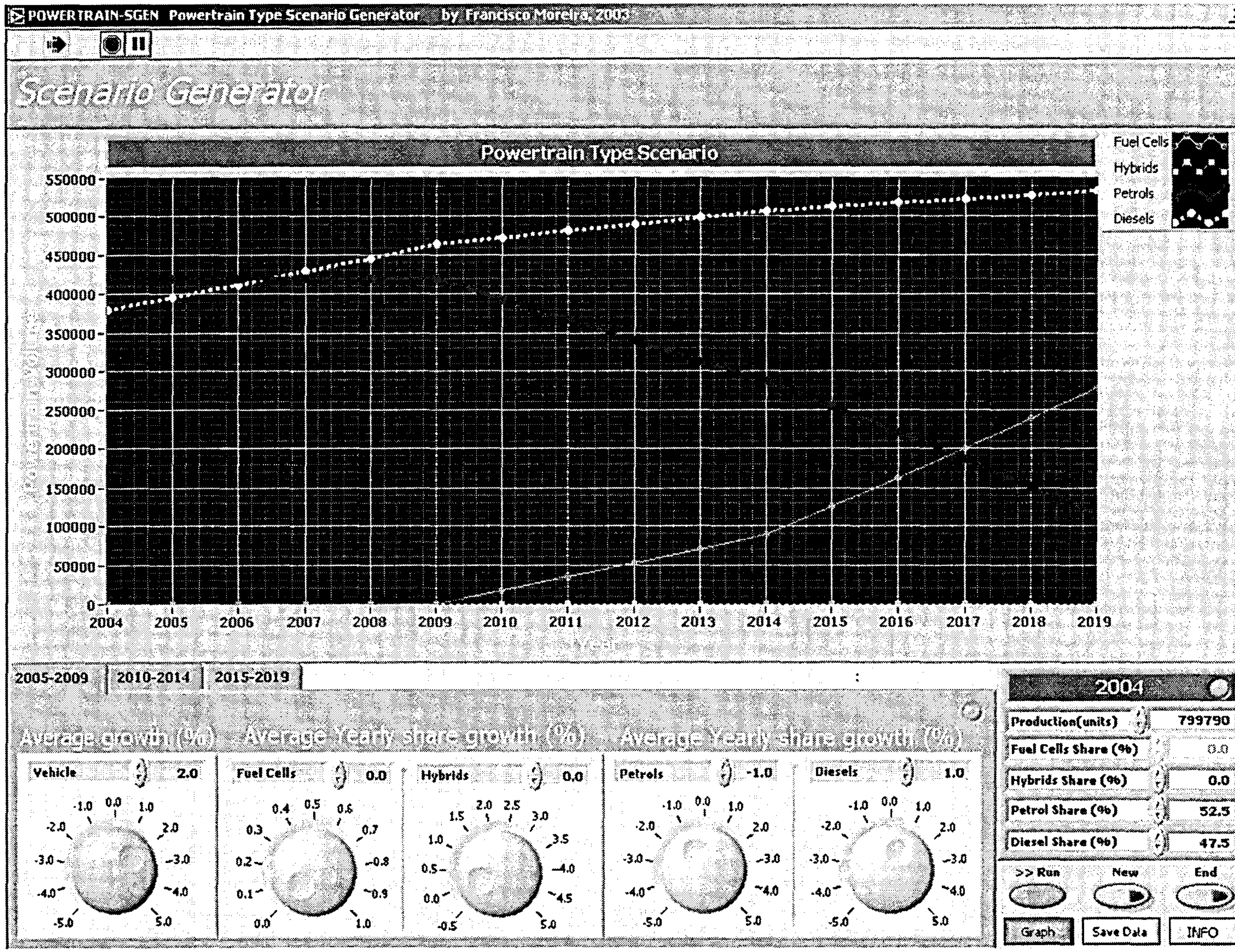
4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**-4.0**	**0**	**4.0**	**0.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	51.5	420129.7	1.0	48.5	395656.1
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	50.5	420211.3	1.0	49.5	411890.3
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	49.5	420128.1	1.0	50.5	428615.5
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	48.5	419873.4	1.0	51.5	445845.0
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	47.5	419440.6	1.0	52.5	463592.2
2010	0.0	883032.8	2.0	2.0	17660.7	0.0	0.0	0.0	-3.0	44.5	392949.6	1.0	53.5	472422.5
2011	0.0	883032.8	2.0	4.0	35321.3	0.0	0.0	0.0	-3.0	41.5	366458.6	1.0	54.5	481252.9
2012	0.0	883032.8	2.0	6.0	52982.0	0.0	0.0	0.0	-3.0	38.5	339967.6	1.0	55.5	490083.2
2013	0.0	883032.8	2.0	8.0	70642.6	0.0	0.0	0.0	-3.0	35.5	313476.6	1.0	56.5	498913.5
2014	0.0	883032.8	2.0	10.0	88303.3	0.0	0.0	0.0	-3.0	32.5	286985.7	1.0	57.5	507743.9
2015	1.0	891863.1	4.0	14.0	124860.8	0.0	0.0	0.0	-4.0	28.5	254181.0	0.0	57.5	512821.3
2016	1.0	900781.7	4.0	18.0	162140.7	0.0	0.0	0.0	-4.0	24.5	220691.5	0.0	57.5	517949.5
2017	1.0	909789.6	4.0	22.0	200153.7	0.0	0.0	0.0	-4.0	20.5	186506.9	0.0	57.5	523129.0
2018	1.0	918887.5	4.0	26.0	238910.7	0.0	0.0	0.0	-4.0	16.5	151616.4	0.0	57.5	528360.3
2019	1.0	928076.3	4.0	30.0	278422.9	0.0	0.0	0.0	-4.0	12.5	116009.5	0.0	57.5	533643.9


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
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2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
Year
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols -1.0
Diesels 1.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 27

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

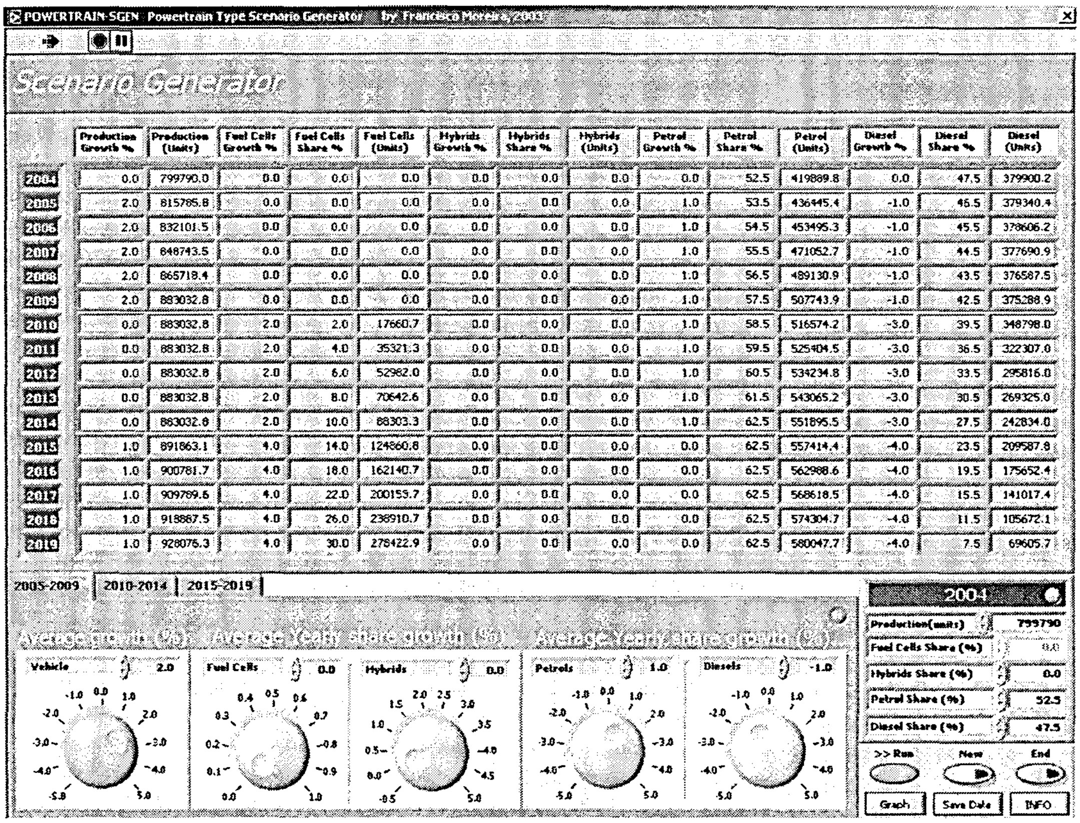
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

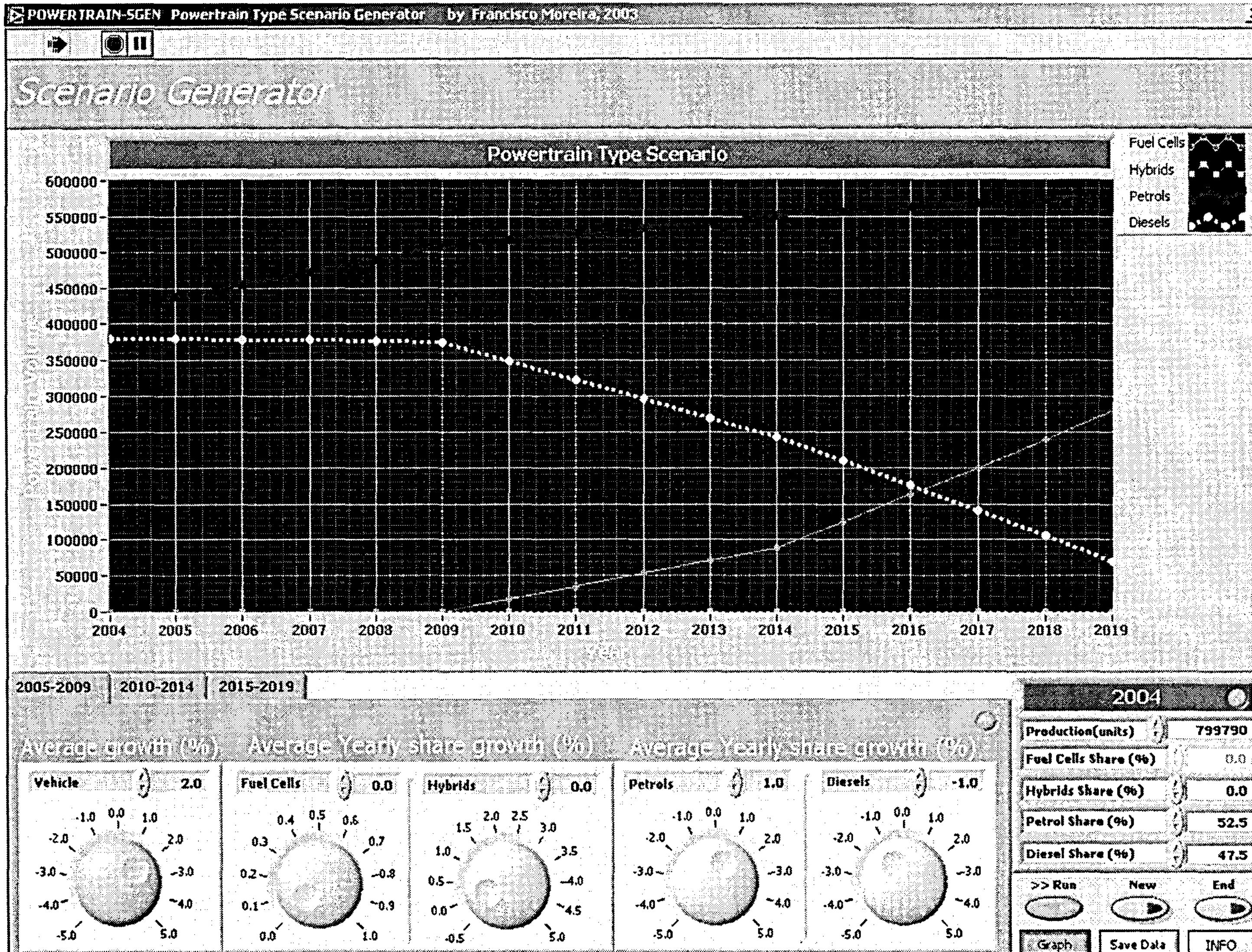
4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**1.0**	**-1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**1.0**	**-3.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**0.0**	**-4**	**4.0**	**0.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	0.0	0.0	0.0	1.0	53.5	436445.4	-1.0	46.5	379340.4
2006	2.0	832101.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	54.5	453495.3	-1.0	45.5	378606.2
2007	2.0	848743.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	55.5	471052.7	-1.0	44.5	377690.9
2008	2.0	865718.4	0.0	0.0	0.0	0.0	0.0	0.0	1.0	56.5	489130.9	-1.0	43.5	376587.5
2009	2.0	883032.8	0.0	0.0	0.0	0.0	0.0	0.0	1.0	57.5	507743.9	-1.0	42.5	375288.9
2010	0.0	883032.8	2.0	2.0	17660.7	0.0	0.0	0.0	1.0	58.5	516574.2	-3.0	39.5	348798.0
2011	0.0	883032.8	2.0	4.0	35321.3	0.0	0.0	0.0	1.0	59.5	525404.5	-3.0	36.5	322307.0
2012	0.0	883032.8	2.0	6.0	52982.0	0.0	0.0	0.0	1.0	60.5	534234.8	-3.0	33.5	295816.0
2013	0.0	883032.8	2.0	8.0	70642.6	0.0	0.0	0.0	1.0	61.5	543065.2	-3.0	30.5	269325.0
2014	0.0	883032.8	2.0	10.0	88303.3	0.0	0.0	0.0	1.0	62.5	551895.5	-3.0	27.5	242834.0
2015	1.0	891863.1	4.0	14.0	124860.8	0.0	0.0	0.0	0.0	62.5	557414.4	-4.0	23.5	209587.8
2016	1.0	900781.7	4.0	18.0	162140.7	0.0	0.0	0.0	0.0	62.5	562988.6	-4.0	19.5	175652.4
2017	1.0	909789.6	4.0	22.0	200153.7	0.0	0.0	0.0	0.0	62.5	568618.5	-4.0	15.5	141017.4
2018	1.0	918887.5	4.0	26.0	238910.7	0.0	0.0	0.0	0.0	62.5	574304.7	-4.0	11.5	105672.1
2019	1.0	928076.3	4.0	30.0	278422.9	0.0	0.0	0.0	0.0	62.5	580047.7	-4.0	7.5	69605.7



POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
600000
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500000
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2004
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2006
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2014
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2017
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2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols 1.0
Diesels -1.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 28

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

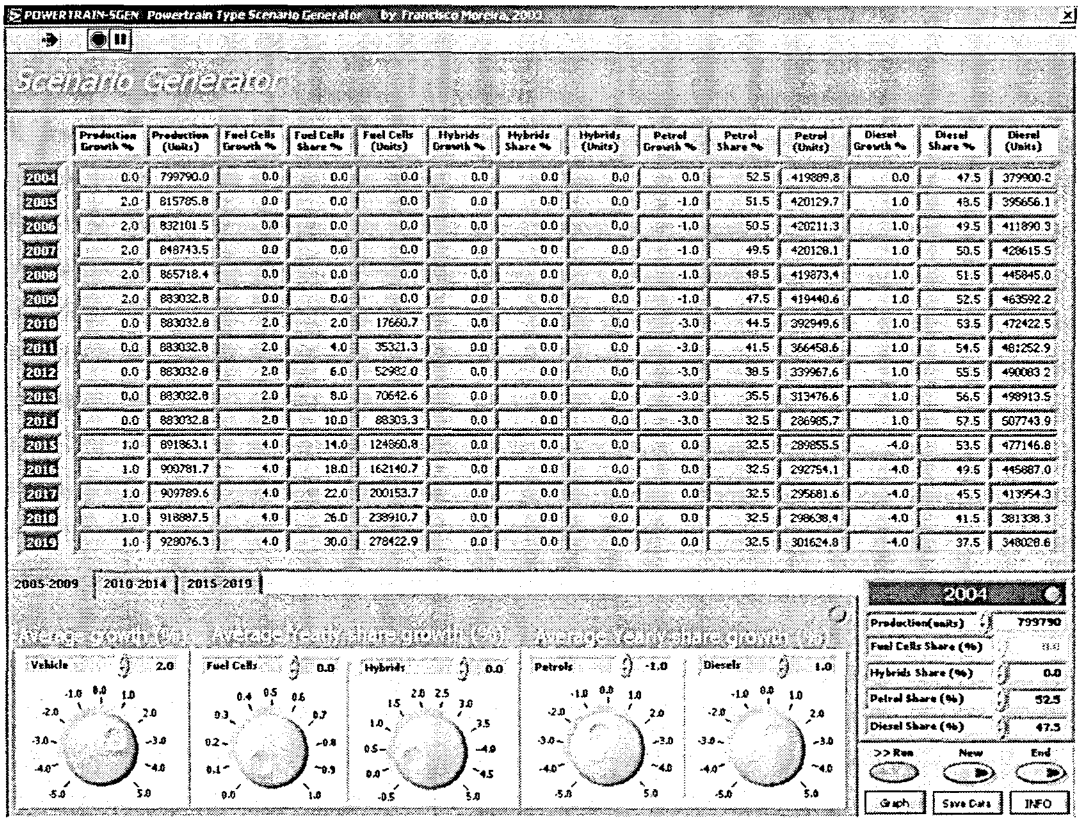
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

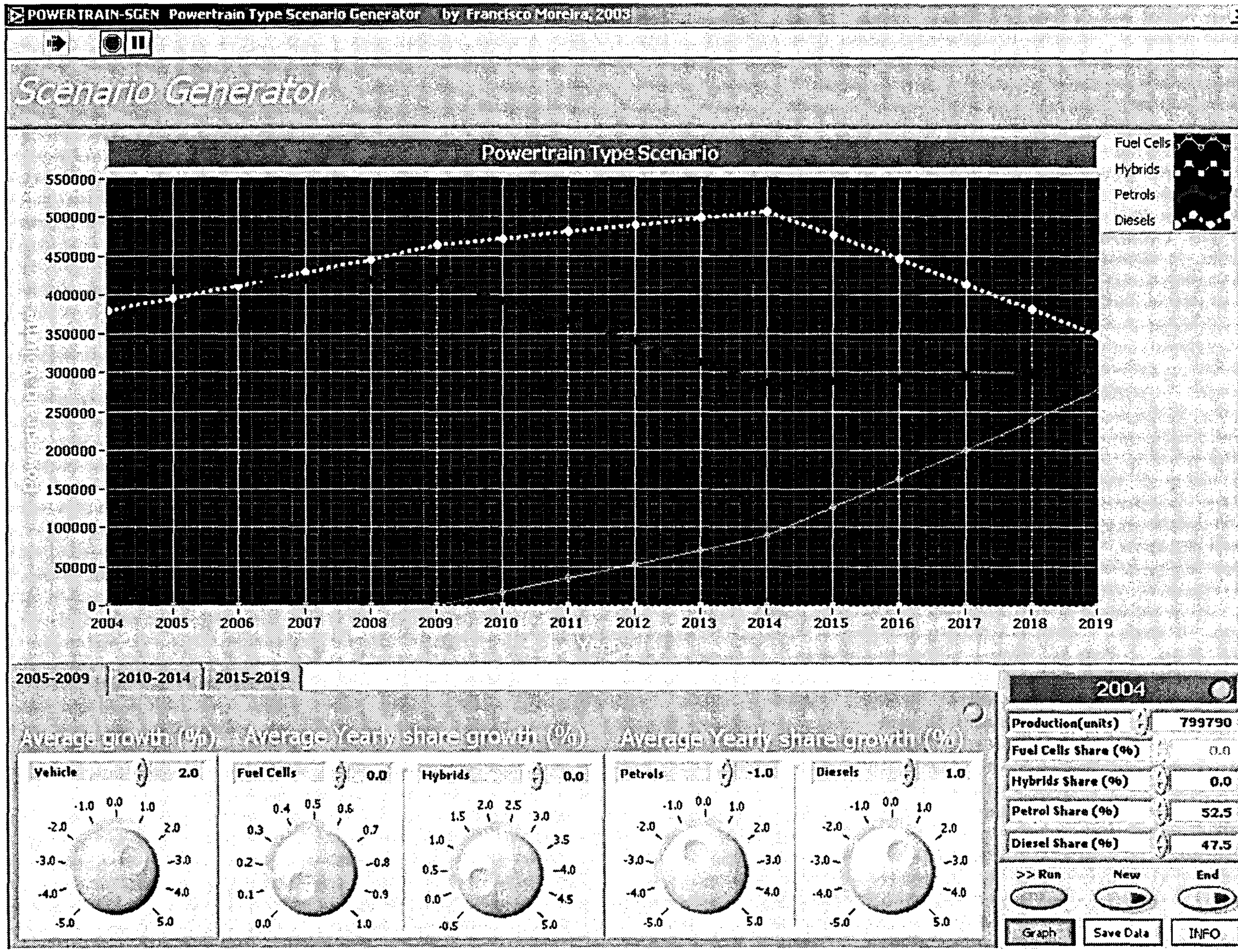
3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

4. Hybrid vehicles fail to gain market share following market introduction around 2005.

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.0**	**1.0**	**0.0**	**0.0**	**No change**
2010-2014	**0.0**	**-3.0**	**1.0**	**2.0**	**0.0**	**Smooth**
2015-2019	**1.0**	**0.0**	**-4.0**	**4.0**	**0.0**	**Fast**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 0.0
Petrols -1.0
Diesels 1.0
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 29

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

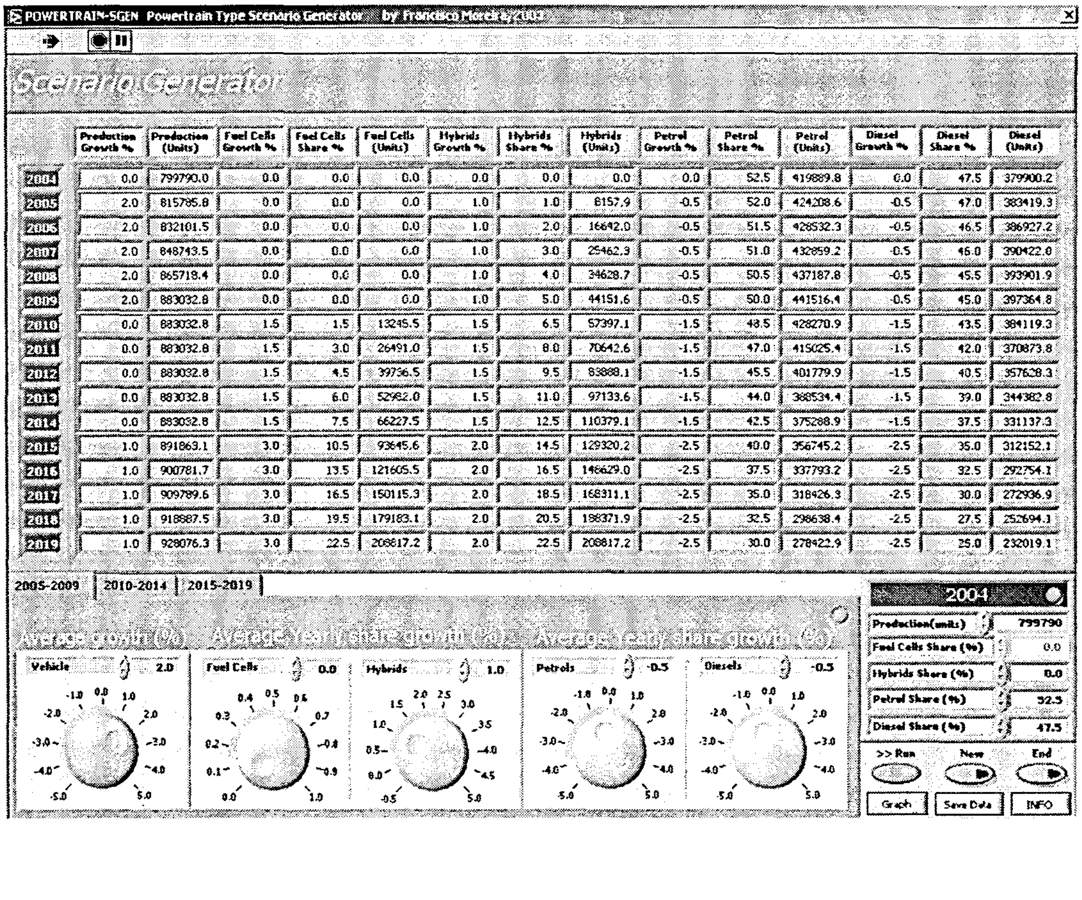
2. **The proportional share of Petrols/Diesels remain essentially unchanged.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

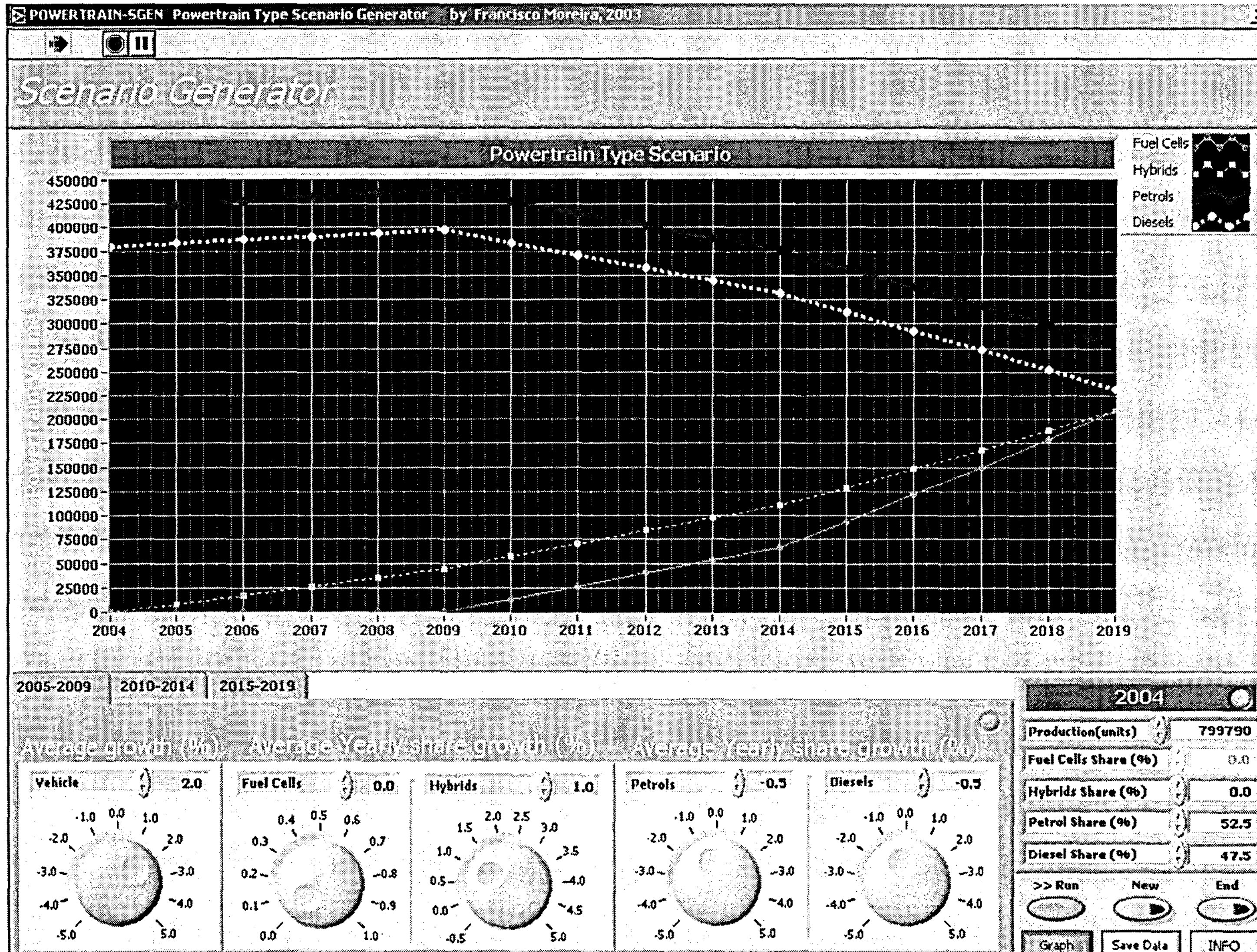
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-0.5**	**-0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-1.5**	**-1.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-2.5**	**-2.5**	**3.0**	**2.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-0.5	52.0	424208.6	-0.5	47.0	383419.3
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-0.5	51.5	428532.3	-0.5	46.5	386927.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-0.5	51.0	432859.2	-0.5	46.0	390422.0
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-0.5	50.5	437187.8	-0.5	45.5	393901.9
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-0.5	50.0	441516.4	-0.5	45.0	397364.8
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	-1.5	48.5	428270.9	-1.5	43.5	384119.3
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	-1.5	47.0	415025.4	-1.5	42.0	370873.8
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	-1.5	45.5	401779.9	-1.5	40.5	357628.3
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	-1.5	44.0	388534.4	-1.5	39.0	344382.8
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	-1.5	42.5	375288.9	-1.5	37.5	331137.3
2015	1.0	891863.1	3.0	10.5	93645.6	2.0	14.5	129320.2	-2.5	40.0	356745.2	-2.5	35.0	312152.1
2016	1.0	900781.7	3.0	13.5	121605.5	2.0	16.5	148629.0	-2.5	37.5	337793.2	-2.5	32.5	292754.1
2017	1.0	909789.6	3.0	16.5	150115.3	2.0	18.5	168311.1	-2.5	35.0	318426.3	-2.5	30.0	272936.9
2018	1.0	918887.5	3.0	19.5	179183.1	2.0	20.5	188371.9	-2.5	32.5	298638.4	-2.5	27.5	252694.1
2019	1.0	928076.3	3.0	22.5	208817.2	2.0	22.5	208817.2	-2.5	30.0	278422.9	-2.5	25.0	232019.1


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
450000
425000
400000
375000
350000
325000
300000
275000
250000
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -0.5
Diesels -0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 30

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

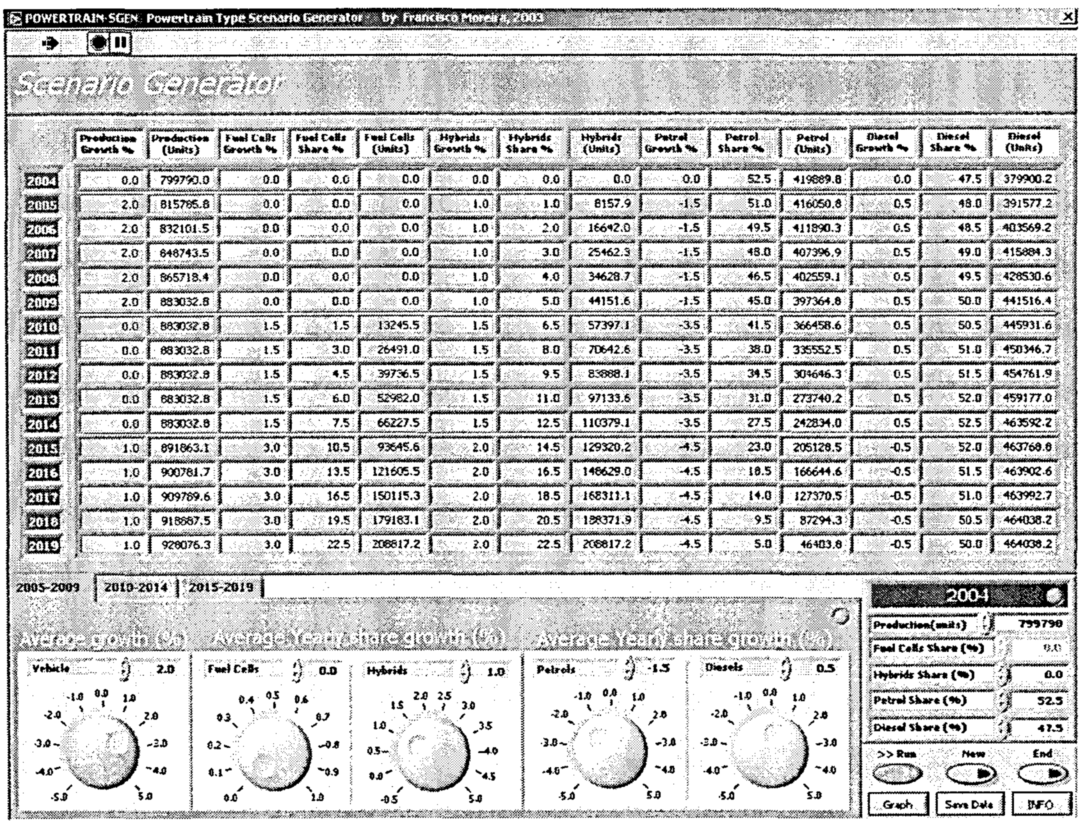
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

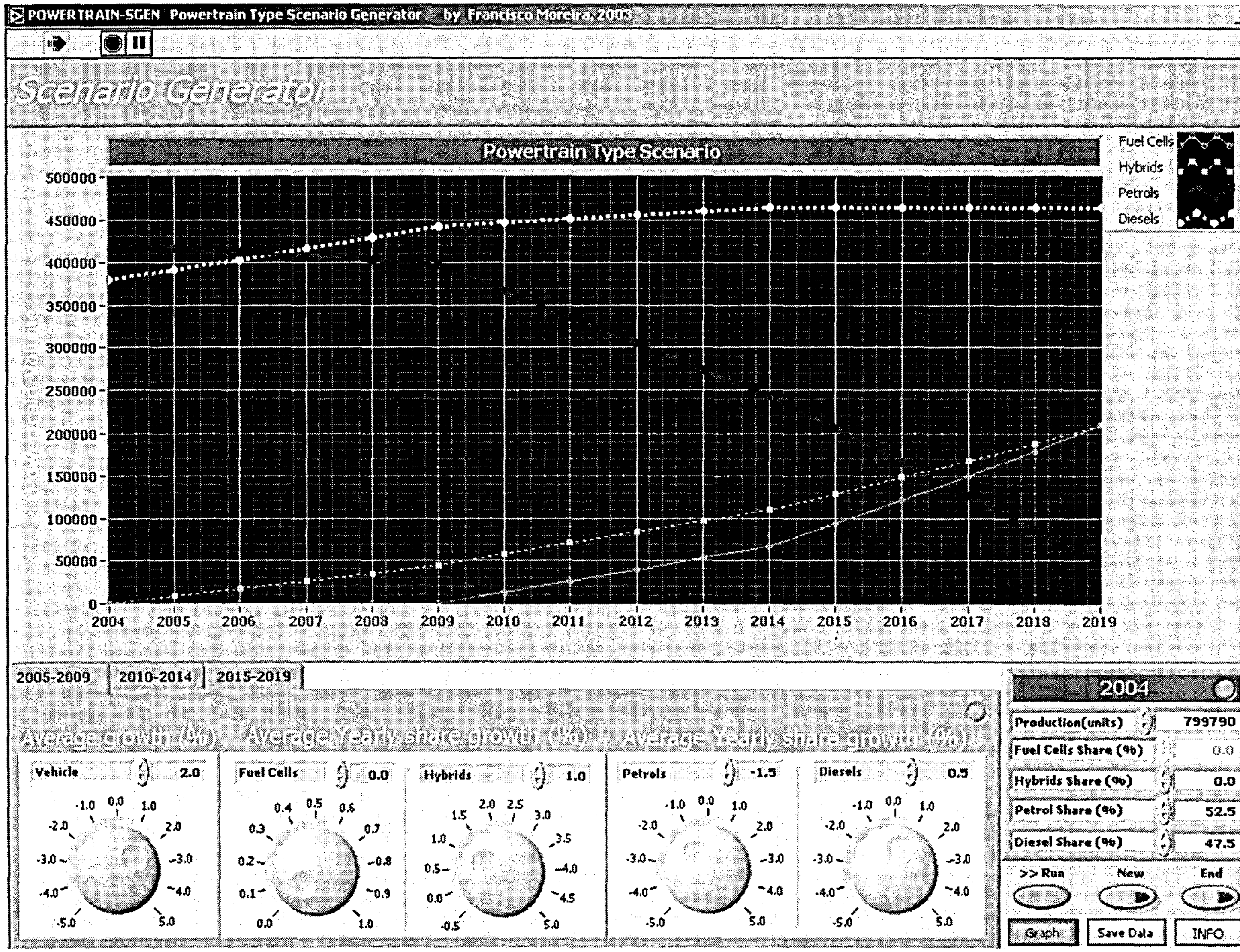
3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-4.5**	**-0.5**	**3.0**	**2.0**	**Fast**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
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350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 31

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

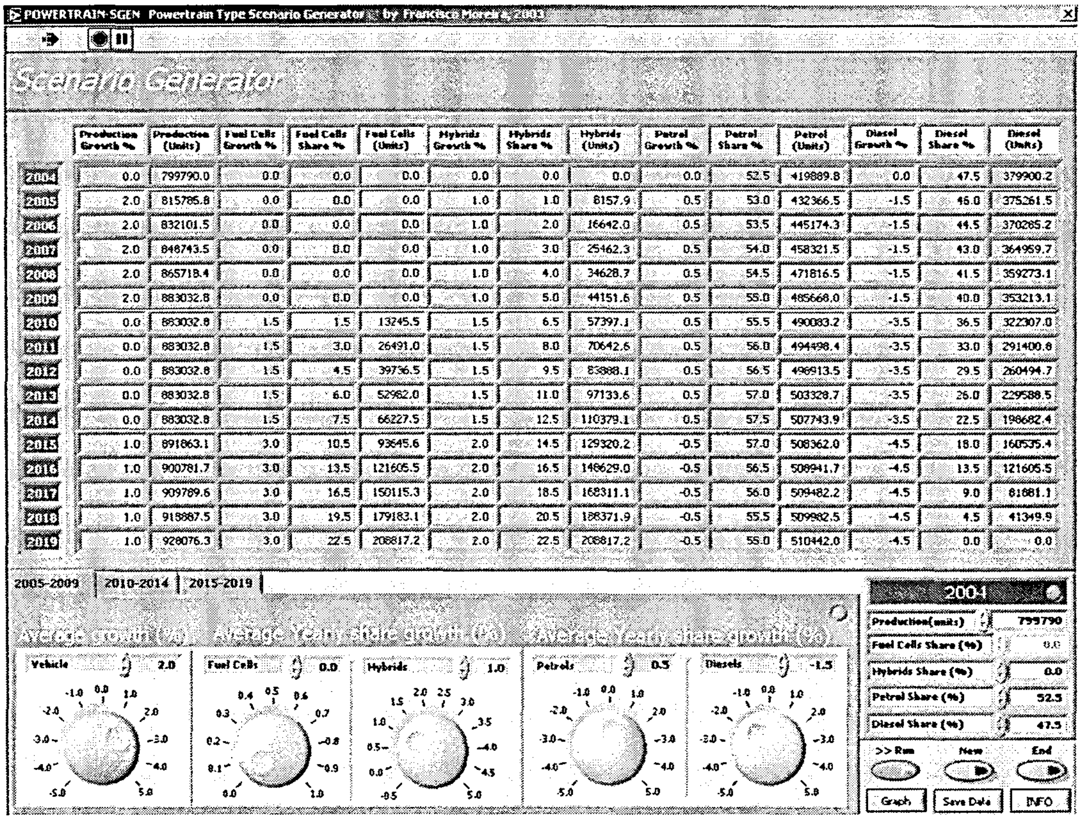
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

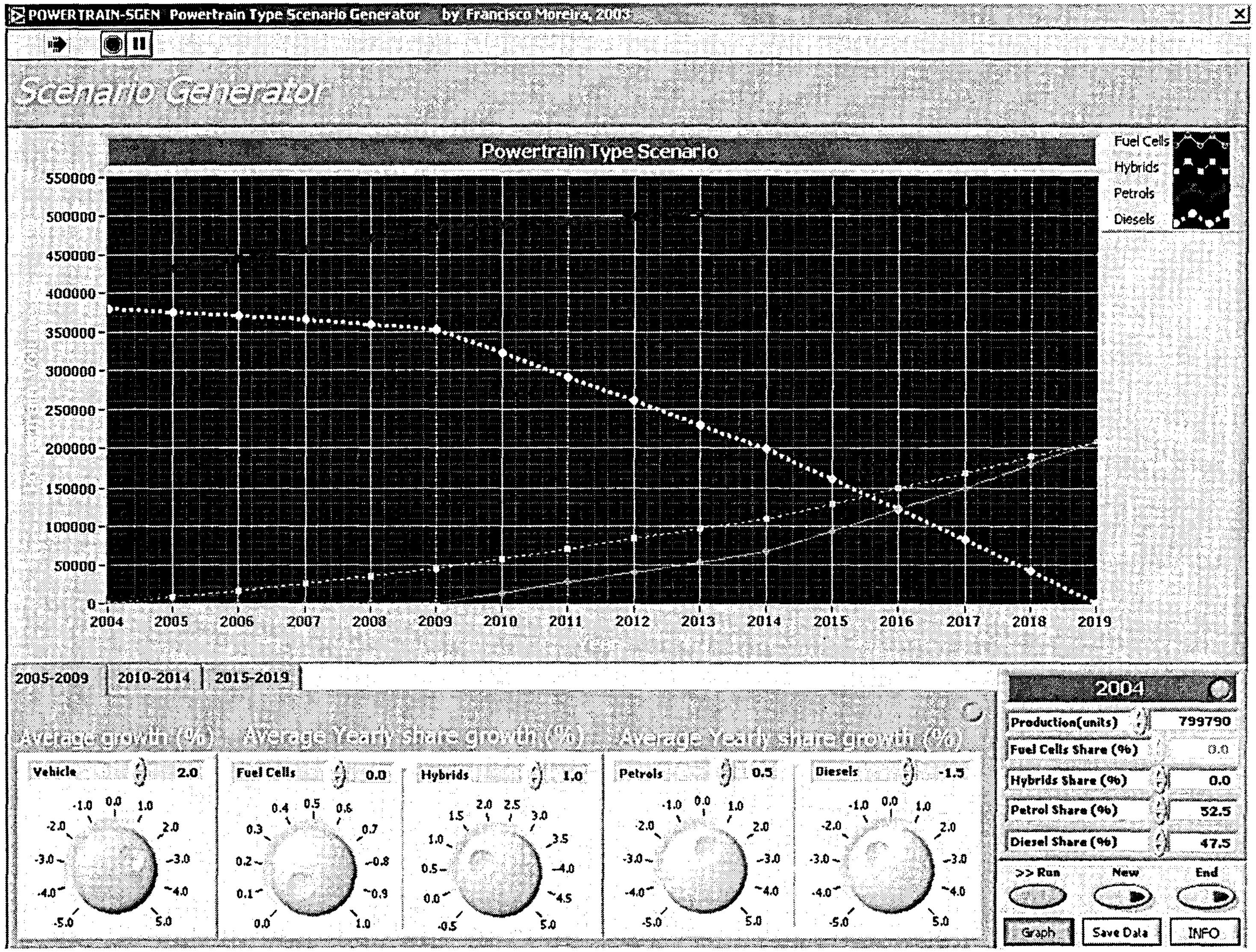
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0.5**	**-1.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**0.5**	**-3.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-0.5**	**-4.5**	**3.0**	**2.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	0.5	53.0	432366.5	-1.5	46.0	375261.5
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	0.5	53.5	445174.3	-1.5	44.5	370265.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	0.5	54.0	458321.5	-1.5	43.0	364959.7
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	0.5	54.5	471816.5	-1.5	41.5	359273.1
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	0.5	55.0	485668.0	-1.5	40.0	353213.1
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	0.5	55.5	490083.2	-3.5	36.5	322307.0
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	0.5	56.0	494498.4	-3.5	33.0	291400.8
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	0.5	56.5	496913.5	-3.5	29.5	260494.7
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	0.5	57.0	503328.7	-3.5	26.0	229588.5
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	0.5	57.5	507743.9	-3.5	22.5	198682.4
2015	1.0	891863.1	3.0	10.5	93645.6	2.0	14.5	129320.2	-0.5	57.0	508362.0	-4.5	18.0	160535.4
2016	1.0	900781.7	3.0	13.5	121605.5	2.0	16.5	148629.0	-0.5	56.5	508941.7	-4.5	13.5	121605.5
2017	1.0	909789.6	3.0	16.5	150115.3	2.0	18.5	168311.1	-0.5	56.0	509482.2	-4.5	9.0	81881.1
2018	1.0	918887.5	3.0	19.5	179183.1	2.0	20.5	188371.9	-0.5	55.5	509982.5	-4.5	4.5	41349.9
2019	1.0	928076.3	3.0	22.5	208817.2	2.0	22.5	208817.2	-0.5	55.0	510442.0	-4.5	0.0	0.0


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
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400000
350000
300000
250000
200000
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2005
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2007
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2015
2016
2017
2018
2019
Year
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols 0.5
Diesels -1.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 32

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

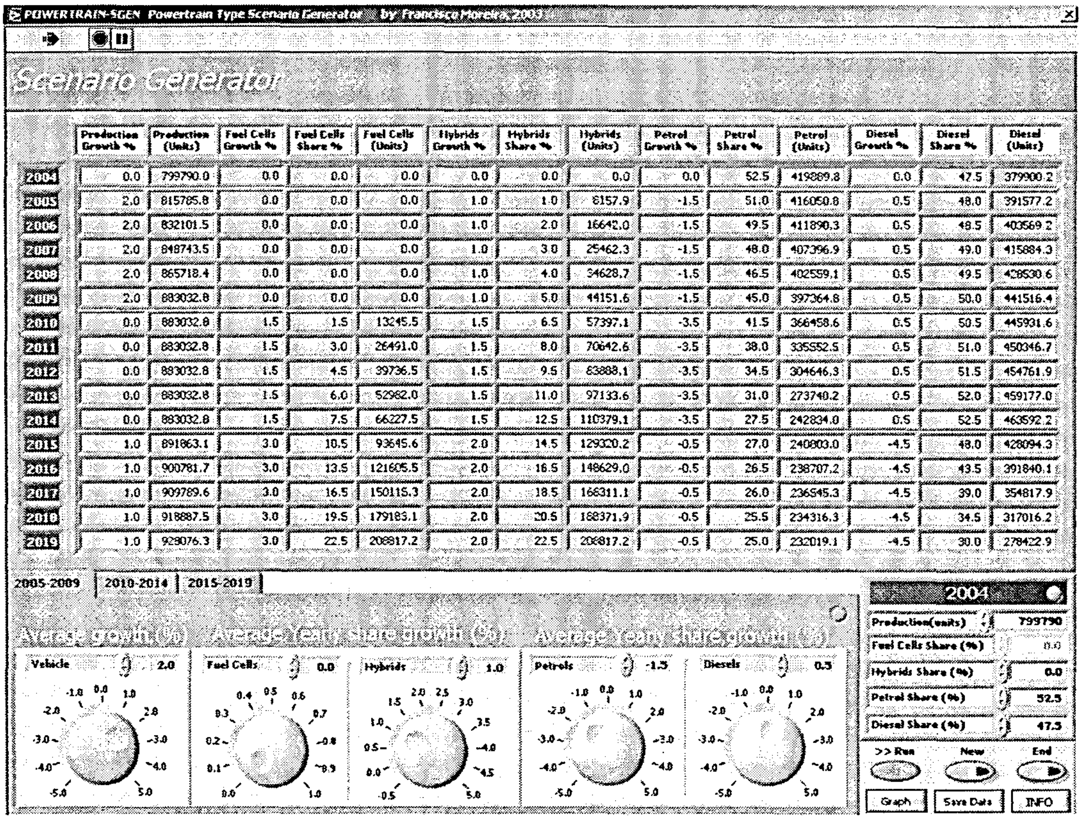
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

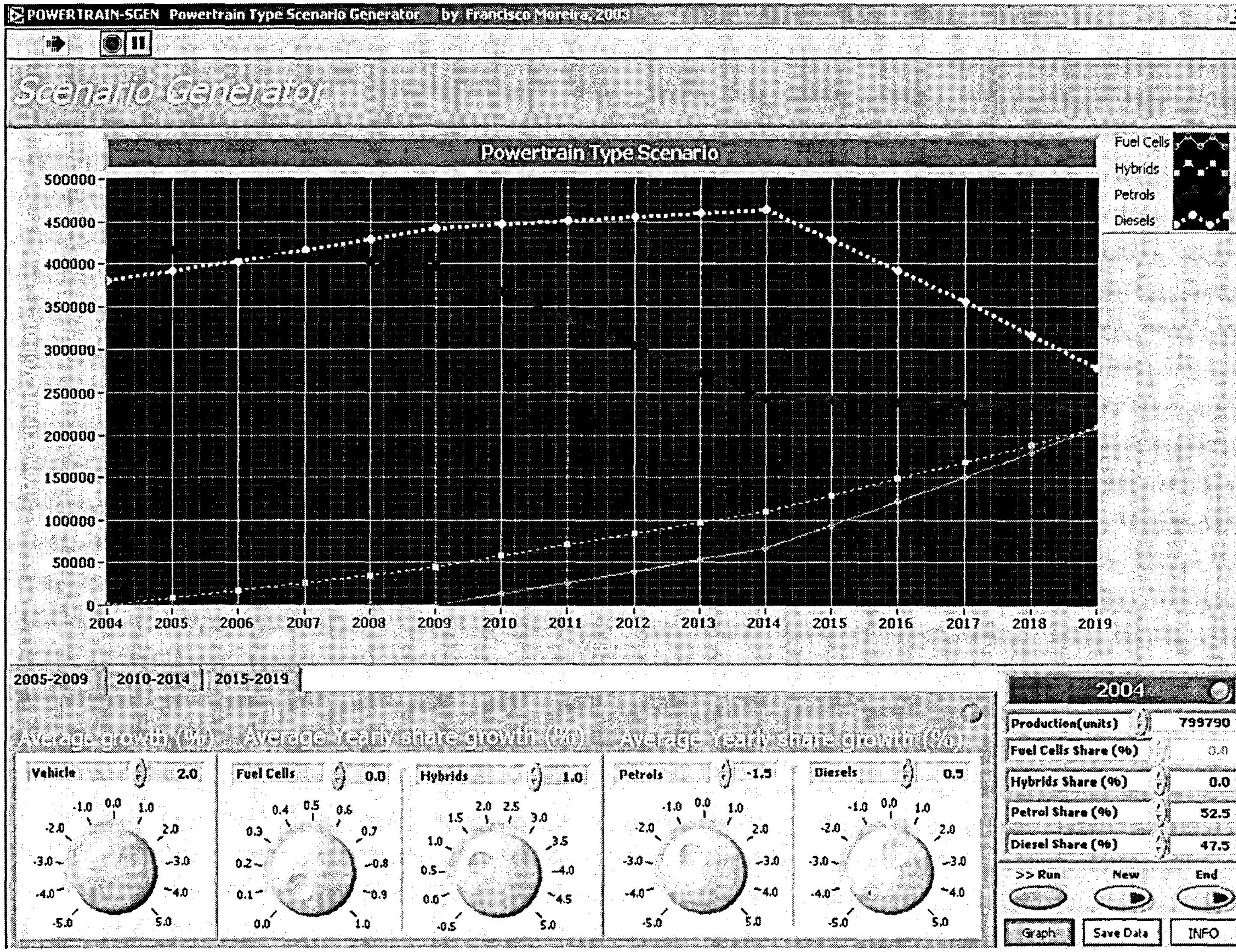
4. **Hybrid vehicles gain market share following market introduction around 2005.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-0.5**	**-4.5**	**3.0**	**2.0**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	-3.5	41.5	366458.6	0.5	50.5	445931.6
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	-3.5	38.0	335552.5	0.5	51.0	450346.7
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	-3.5	34.5	304646.3	0.5	51.5	454761.9
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	-3.5	31.0	273740.2	0.5	52.0	459177.0
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	-3.5	27.5	242834.0	0.5	52.5	463592.2
2015	1.0	891863.1	3.0	10.5	93645.6	2.0	14.5	129320.2	-0.5	27.0	240803.0	-4.5	48.0	428094.3
2016	1.0	900781.7	3.0	13.5	121605.5	2.0	16.5	148629.0	-0.5	26.5	238707.2	-4.5	43.5	391840.1
2017	1.0	909789.6	3.0	16.5	150115.3	2.0	18.5	168311.1	-0.5	26.0	236545.3	-4.5	39.0	354817.9
2018	1.0	918887.5	3.0	19.5	179183.1	2.0	20.5	188371.9	-0.5	25.5	234316.3	-4.5	34.5	317016.2
2019	1.0	928076.3	3.0	22.5	208817.2	2.0	22.5	208817.2	-0.5	25.0	232019.1	-4.5	30.0	278422.9


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
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300000
250000
200000
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2016
2017
2018
2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 33

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

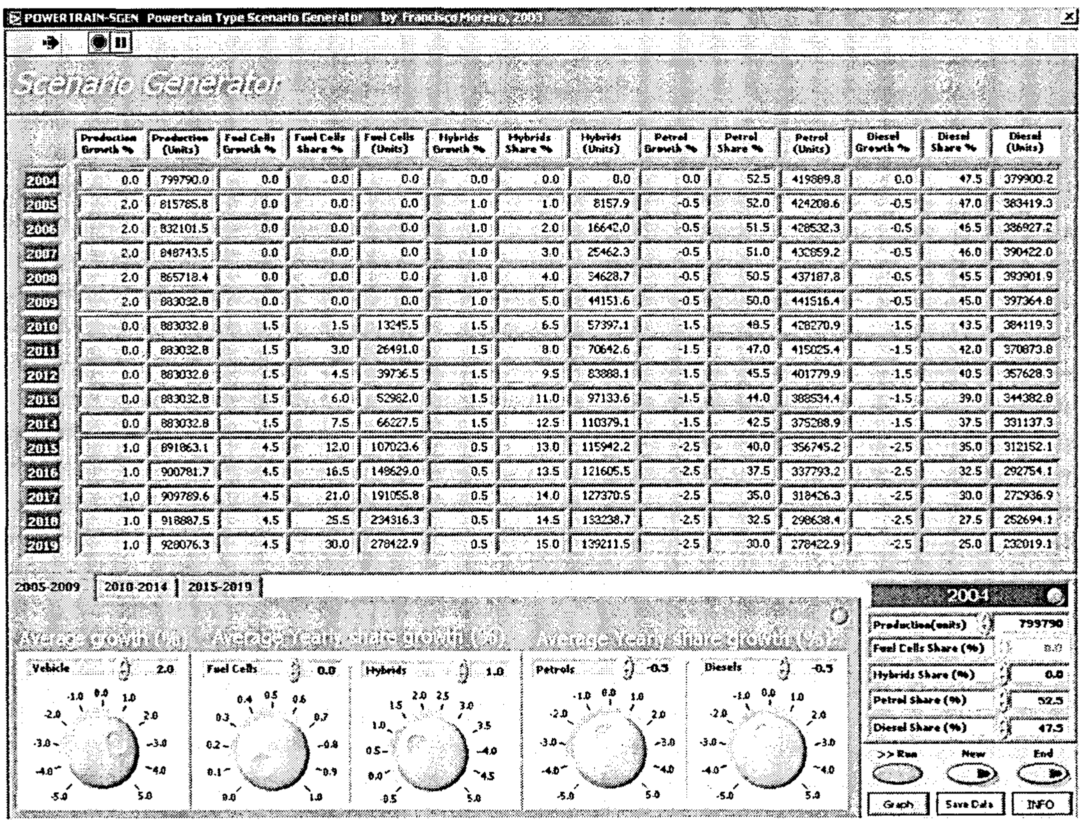
2. **The proportional share of Petrols/Diesels remains essentially unchanged.**

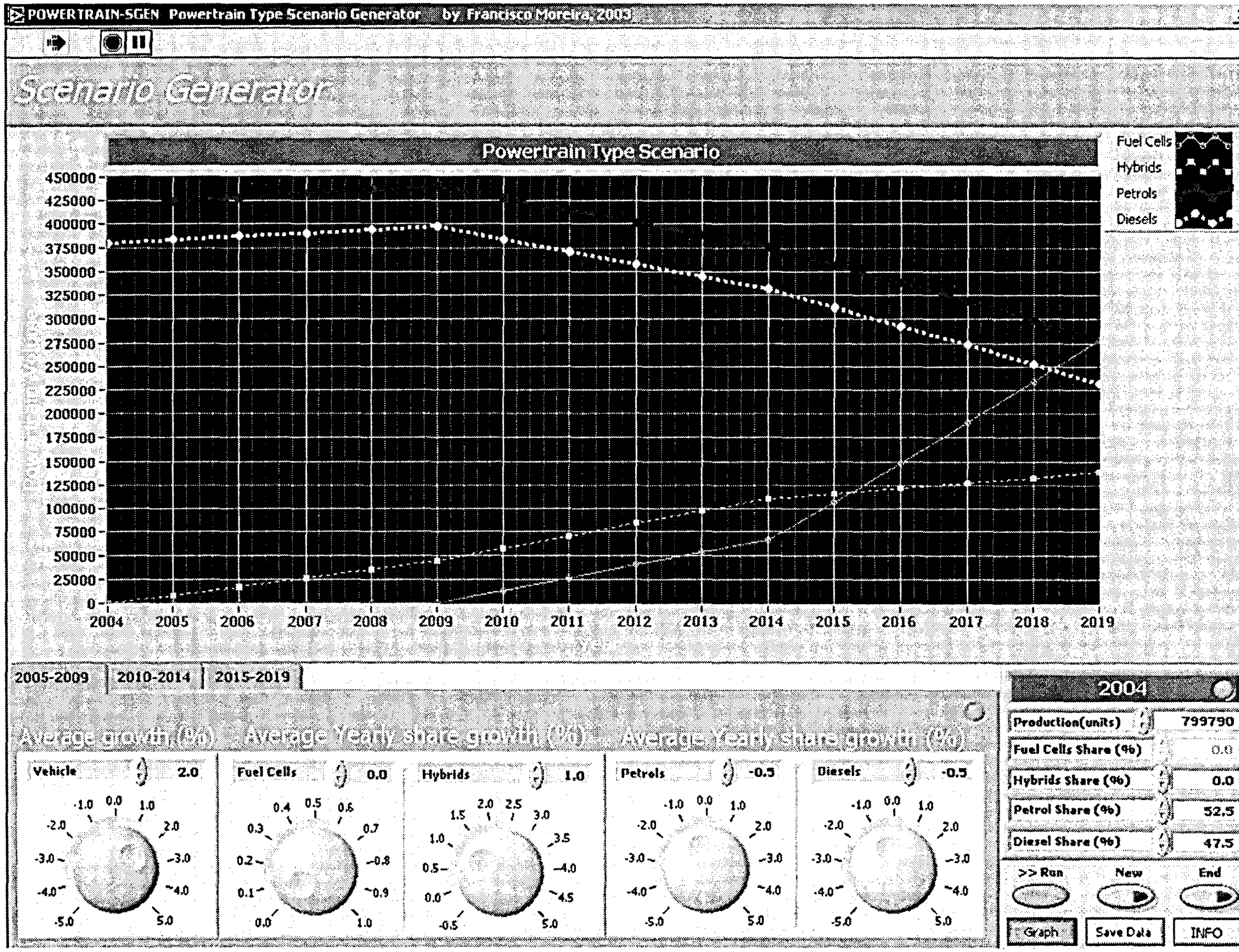
3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-0.5**	**-0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-1.5**	**-1.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-2.5**	**-2.5**	**4.5**	**0.5**	**Fast**




POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
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400000
375000
350000
325000
300000
275000
250000
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -0.5
Diesels -0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 34

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

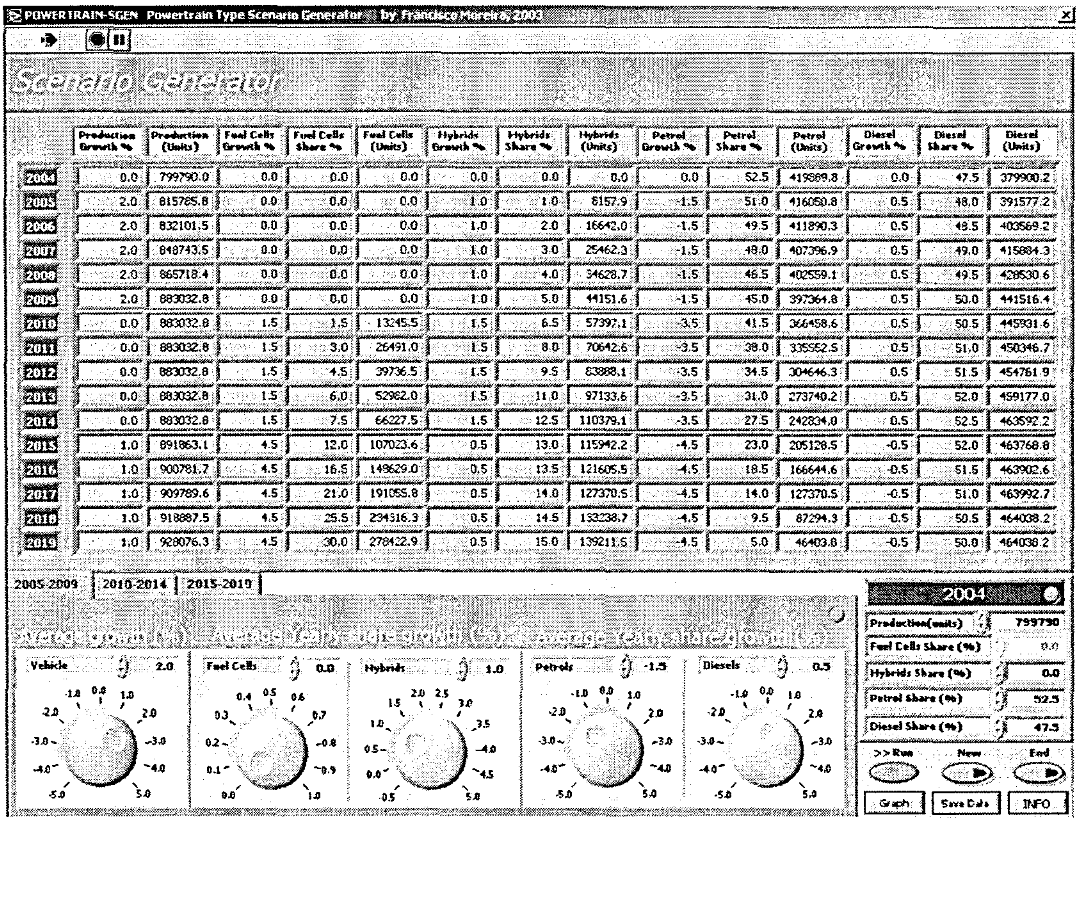
2. **Diesels progressively gain market share against Petrol based vehicles (present trend).**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

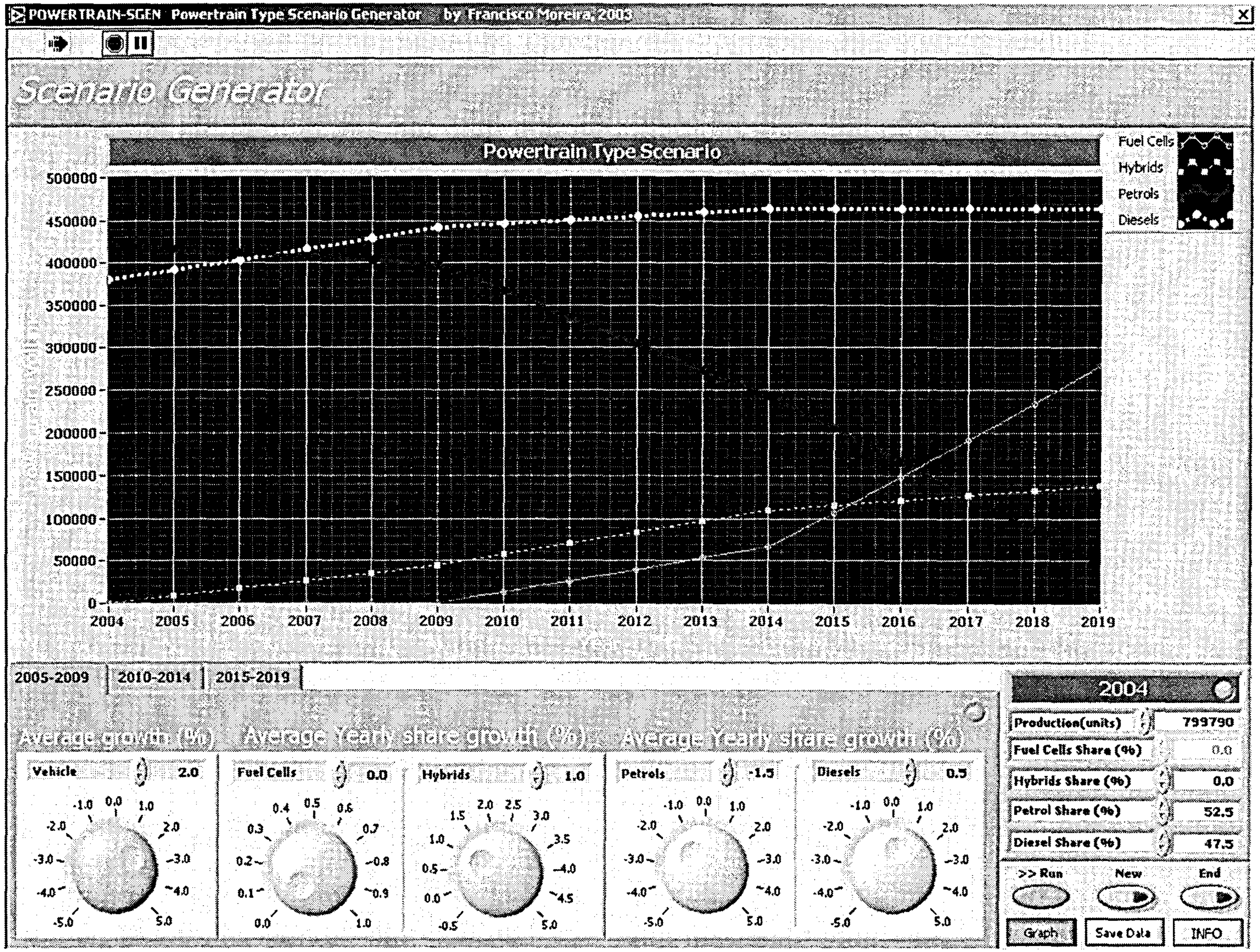
4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-4.5**	**-0.5**	**4.5**	**0.5**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	-3.5	41.5	366458.6	0.5	50.5	445931.6
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	-3.5	38.0	335552.5	0.5	51.0	450346.7
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	-3.5	34.5	304646.3	0.5	51.5	454761.9
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	-3.5	31.0	273740.2	0.5	52.0	459177.0
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	-3.5	27.5	242834.0	0.5	52.5	463592.2
2015	1.0	891863.1	4.5	12.0	107023.6	0.5	13.0	115942.2	-4.5	23.0	205128.5	-0.5	52.0	463768.8
2016	1.0	900781.7	4.5	16.5	148629.0	0.5	13.5	121605.5	-4.5	18.5	166644.6	-0.5	51.5	463902.6
2017	1.0	909789.6	4.5	21.0	191055.8	0.5	14.0	127370.5	-4.5	14.0	127370.5	-0.5	51.0	463992.7
2018	1.0	918887.5	4.5	25.5	234316.3	0.5	14.5	133238.7	-4.5	9.5	87294.3	-0.5	50.5	464038.2
2019	1.0	928076.3	4.5	30.0	278422.9	0.5	15.0	139211.5	-4.5	5.0	46403.8	-0.5	50.0	464038.2


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 35

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

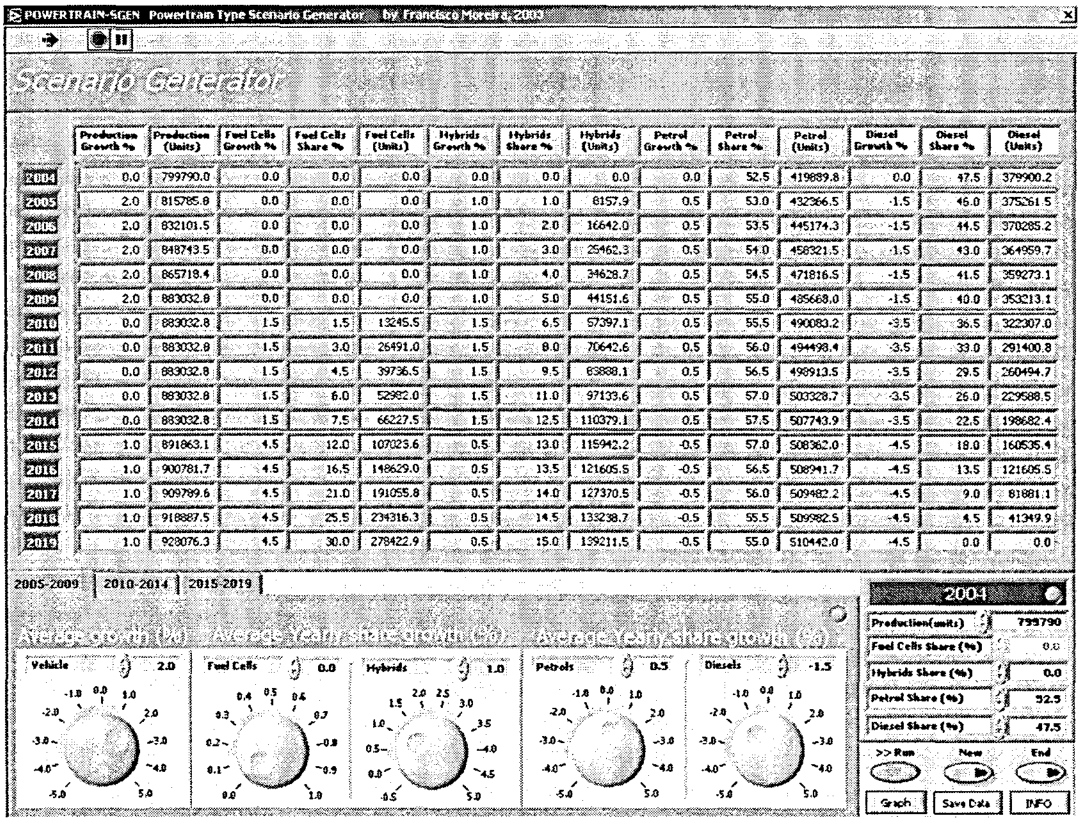
2. **Petrols progressively gain market share against Diesel based vehicles.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

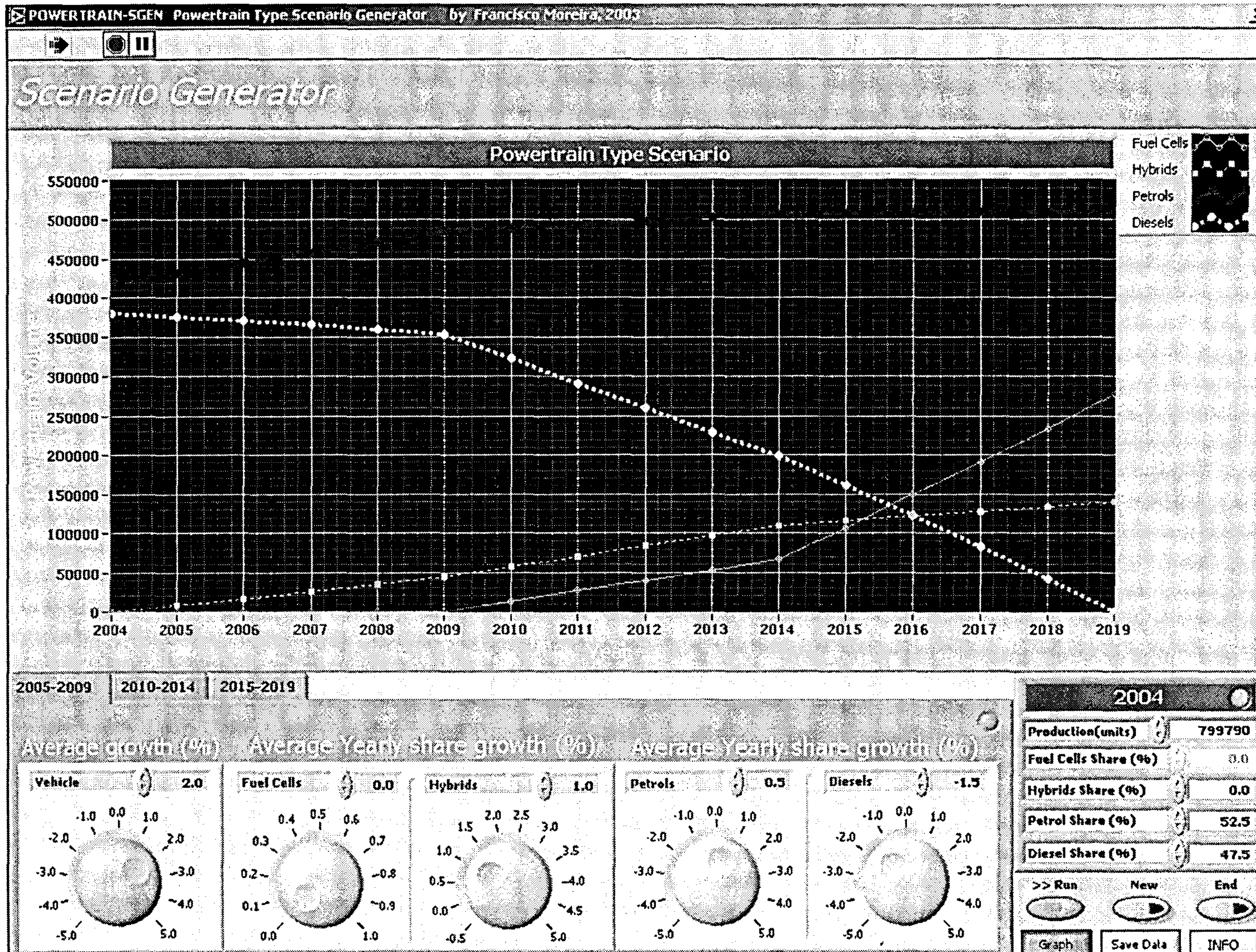
4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**0.5**	**-1.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**0.5**	**-3.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-0.5**	**-4.5**	**4.5**	**0.5**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	0.5	53.0	432366.5	-1.5	46.0	375261.5
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	0.5	53.5	445174.3	-1.5	44.5	370285.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	0.5	54.0	458321.5	-1.5	43.0	364959.7
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	0.5	54.5	471816.5	-1.5	41.5	359273.1
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	0.5	55.0	485668.0	-1.5	40.0	353213.1
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	0.5	55.5	490083.2	-3.5	36.5	322307.0
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	0.5	56.0	494498.4	-3.5	33.0	291400.8
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	0.5	56.5	498913.5	-3.5	29.5	260494.7
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	0.5	57.0	503328.7	-3.5	26.0	229588.5
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	0.5	57.5	507743.9	-3.5	22.5	198682.4
2015	1.0	891863.1	4.5	12.0	107023.6	0.5	13.0	115942.2	-0.5	57.0	508362.0	-4.5	18.0	160535.4
2016	1.0	900781.7	4.5	16.5	148629.0	0.5	13.5	121605.5	-0.5	56.5	508941.7	-4.5	13.5	121605.5
2017	1.0	909789.6	4.5	21.0	191055.8	0.5	14.0	127370.5	-0.5	56.0	509482.2	-4.5	9.0	81881.1
2018	1.0	918887.5	4.5	25.5	234316.3	0.5	14.5	133238.7	-0.5	55.5	509982.5	-4.5	4.5	41349.9
2019	1.0	928076.3	4.5	30.0	278422.9	0.5	15.0	139211.5	-0.5	55.0	510442.0	-4.5	0.0	0.0



POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
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2004
2005
2006
2007
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2011
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2013
2014
2015
2016
2017
2018
2019
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols 0.5
Diesels -1.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

SCENARIO 36

1. Vehicle production volume grows on average at rates of 2%; 0% and 1% in respective periods 2005-2009; 2010-2014 and 2015-2019.

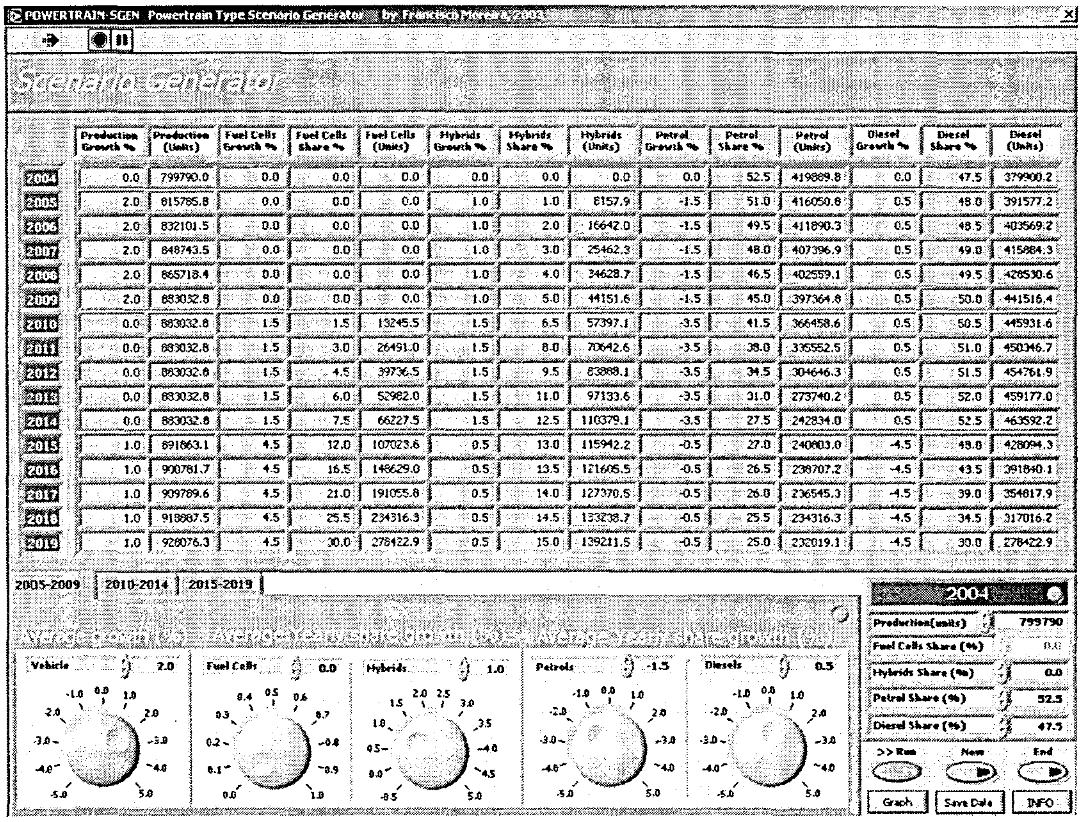
2. **Diesels progressively gain market share against Petrol based vehicles (current trend) however there is an inversion on this trend in 2015-2019.**

3. **Fuel Cell vehicles gain market share following market introduction around 2010.**

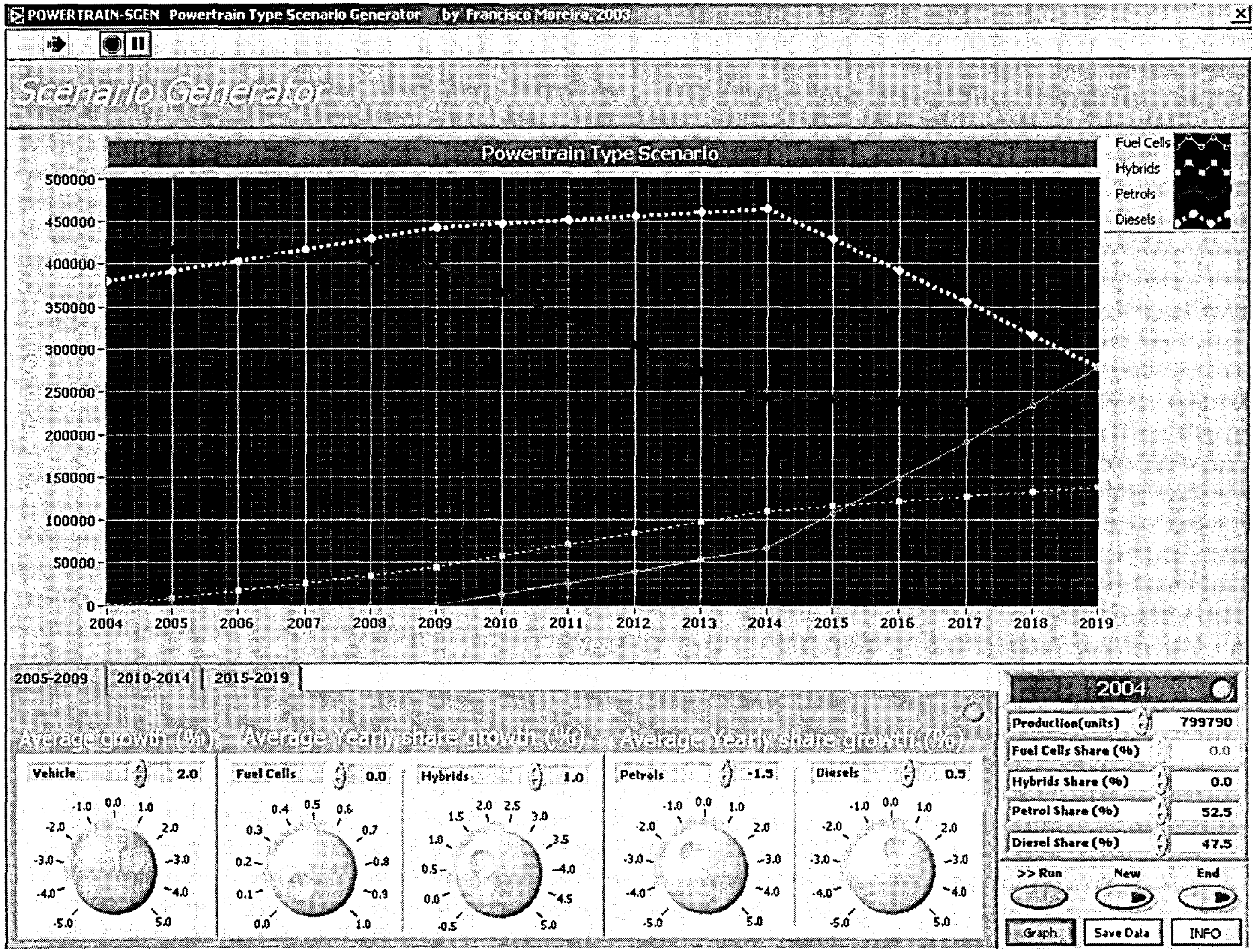
4. **Hybrid vehicles gain market share following market introduction around 2005 but loose it after Fuel Cells market acceptance.**

5. **Oil price increase is smooth over the period 2010-2014 and fast over the period 2015-2019.**

Avg. yearly growth	Vehicle (%)	Petrol share (%)	Diesel share (%)	FCV share (%)	Hybrids share (%)	Oil price increase
2005-2009	**2.0**	**-1.5**	**0.5**	**0.0**	**1**	**No change**
2010-2014	**0.0**	**-3.5**	**0.5**	**1.5**	**1.5**	**Smooth**
2015-2019	**1.0**	**-0.5**	**-4.5**	**4.5**	**0.5**	**Fast**



	Production Growth %	Production (Units)	Fuel Cells Growth %	Fuel Cells Share %	Fuel Cells (Units)	Hybrids Growth %	Hybrids Share %	Hybrids (Units)	Petrol Growth %	Petrol Share %	Petrol (Units)	Diesel Growth %	Diesel Share %	Diesel (Units)
2004	0.0	799790.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.5	419889.8	0.0	47.5	379900.2
2005	2.0	815785.8	0.0	0.0	0.0	1.0	1.0	8157.9	-1.5	51.0	416050.8	0.5	48.0	391577.2
2006	2.0	832101.5	0.0	0.0	0.0	1.0	2.0	16642.0	-1.5	49.5	411890.3	0.5	48.5	403569.2
2007	2.0	848743.5	0.0	0.0	0.0	1.0	3.0	25462.3	-1.5	48.0	407396.9	0.5	49.0	415884.3
2008	2.0	865718.4	0.0	0.0	0.0	1.0	4.0	34628.7	-1.5	46.5	402559.1	0.5	49.5	428530.6
2009	2.0	883032.8	0.0	0.0	0.0	1.0	5.0	44151.6	-1.5	45.0	397364.8	0.5	50.0	441516.4
2010	0.0	883032.8	1.5	1.5	13245.5	1.5	6.5	57397.1	-3.5	41.5	366458.6	0.5	50.5	445931.6
2011	0.0	883032.8	1.5	3.0	26491.0	1.5	8.0	70642.6	-3.5	38.0	335552.5	0.5	51.0	450346.7
2012	0.0	883032.8	1.5	4.5	39736.5	1.5	9.5	83888.1	-3.5	34.5	304646.3	0.5	51.5	454761.9
2013	0.0	883032.8	1.5	6.0	52982.0	1.5	11.0	97133.6	-3.5	31.0	273740.2	0.5	52.0	459177.0
2014	0.0	883032.8	1.5	7.5	66227.5	1.5	12.5	110379.1	-3.5	27.5	242834.0	0.5	52.5	463592.2
2015	1.0	891863.1	4.5	12.0	107023.6	0.5	13.0	115942.2	-0.5	27.0	240803.0	-4.5	48.0	428094.3
2016	1.0	900781.7	4.5	16.5	148629.0	0.5	13.5	121605.5	-0.5	26.5	238707.2	-4.5	43.5	391840.1
2017	1.0	909789.6	4.5	21.0	191055.8	0.5	14.0	127370.5	-0.5	26.0	236545.3	-4.5	39.0	354817.9
2018	1.0	918887.5	4.5	25.5	234316.3	0.5	14.5	133238.7	-0.5	25.5	234316.3	-4.5	34.5	317016.2
2019	1.0	928076.3	4.5	30.0	278422.9	0.5	15.0	139211.5	-0.5	25.0	232019.1	-4.5	30.0	278422.9


POWERTRAIN-SGEN Powertrain Type Scenario Generator by Francisco Moreira, 2003
Scenario Generator
Powertrain Type Scenario
Fuel Cells
Hybrids
Petrols
Diesels
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
Year
2005-2009
2010-2014
2015-2019
Average growth (%)
Average Yearly share growth (%)
Average Yearly share growth (%)
Vehicle 2.0
Fuel Cells 0.0
Hybrids 1.0
Petrols -1.5
Diesels 0.5
2004
Production(units) 799790
Fuel Cells Share (%) 0.0
Hybrids Share (%) 0.0
Petrol Share (%) 52.5
Diesel Share (%) 47.5
>> Run
New
End
Graph
Save Data
INFO

APPENDIX H

SIMULATION RESULTS OBTAINED IN RESPECT OF THE 36 POWERTRAIN SHARES FUTURE SCENARIOS

The following tabulates results obtained for the 36 future scenarios for propulsion systems when using the Powertrain-SGen tool. Each scenario predicts yearly vehicle units demand over a 15-year period. Also tabulated are predicted share volumes of engine units belonging to the four prime engine configurations that are expected to propel commercial vehicles over that timeframe.

The algorithmic nature of the scenarios is defined in section 6.1.2 of this thesis.

1	Vehicle Units	Fuel Cell Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	428,288	387,498
2006	832,102	0	0	436,853	395,248
2007	848,744	0	0	445,590	403,153
2008	865,718	0	0	454,502	411,216
2009	883,033	0	0	463,592	419,441
2010	883,033	0	0	463,592	419,441
2011	883,033	0	0	463,592	419,441
2012	883,033	0	0	463,592	419,441
2013	883,033	0	0	463,592	419,441
2014	883,033	0	0	463,592	419,441
2015	891,863	0	0	468,228	423,635
2016	900,782	0	0	472,910	427,871
2017	909,790	0	0	477,640	432,150
2018	918,888	0	0	482,416	436,472
2019	928,076	0	0	487,240	440,836
2	Vehicle Units	Fuel Cell Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	420,130	395,656
2006	832,102	0	0	420,211	411,890
2007	848,744	0	0	420,128	428,616
2008	865,718	0	0	419,873	445,845
2009	883,033	0	0	419,441	463,592
2010	883,033	0	0	401,780	481,253
2011	883,033	0	0	384,119	498,914
2012	883,033	0	0	366,459	516,574
2013	883,033	0	0	348,798	534,235
2014	883,033	0	0	331,137	551,896
2015	891,863	0	0	316,611	575,252
2016	900,782	0	0	301,762	599,020
2017	909,790	0	0	286,584	623,206
2018	918,888	0	0	271,072	647,816
2019	928,076	0	0	255,221	672,855
3	Vehicle Units	Fuel Cell Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	436,445	379,340
2006	832,102	0	0	453,495	378,606
2007	848,744	0	0	471,053	377,691
2008	865,718	0	0	489,131	376,588
2009	883,033	0	0	507,744	375,289
2010	883,033	0	0	525,405	357,628
2011	883,033	0	0	543,065	339,968
2012	883,033	0	0	560,726	322,307
2013	883,033	0	0	578,387	304,646
2014	883,033	0	0	596,047	286,986
2015	891,863	0	0	619,845	272,018
2016	900,782	0	0	644,059	256,723
2017	909,790	0	0	668,695	241,094
2018	918,888	0	0	693,760	225,127
2019	928,076	0	0	719,259	208,817

4	*Vehicle Units*	*Fuel Cell Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	420,130	395,656
2006	832,102	0	0	420,211	411,890
2007	848,744	0	0	420,128	428,616
2008	865,718	0	0	419,873	445,845
2009	883,033	0	0	419,441	463,592
2010	883,033	0	0	401,780	481,253
2011	883,033	0	0	384,119	498,914
2012	883,033	0	0	366,459	516,574
2013	883,033	0	0	348,798	534,235
2014	883,033	0	0	331,137	551,896
2015	891,863	0	0	352,286	539,577
2016	900,782	0	0	373,824	526,957
2017	909,790	0	0	395,759	514,031
2018	918,888	0	0	418,094	500,794
2019	928,076	0	0	440,836	487,240
5	*Vehicle Units*	*Fuel Cell Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	424,209	383,419
2006	832,102	0	16,642	428,532	386,927
2007	848,744	0	25,462	432,859	390,422
2008	865,718	0	34,629	437,188	393,902
2009	883,033	0	44,152	441,516	397,365
2010	883,033	0	61,812	432,686	388,534
2011	883,033	0	79,473	423,856	379,704
2012	883,033	0	97,134	415,025	370,874
2013	883,033	0	114,794	406,195	362,043
2014	883,033	0	132,455	397,365	353,213
2015	891,863	0	151,617	392,420	347,827
2016	900,782	0	171,149	387,336	342,297
2017	909,790	0	191,056	382,112	336,622
2018	918,888	0	211,344	376,744	330,800
2019	928,076	0	232,019	371,231	324,827
6	*Vehicle Units*	*Fuel Cell Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	0	61,812	370,874	450,347
2011	883,033	0	79,473	344,383	459,177
2012	883,033	0	97,134	317,892	468,007
2013	883,033	0	114,794	291,401	476,838
2014	883,033	0	132,455	264,910	485,668
2015	891,863	0	151,617	240,803	499,443
2016	900,782	0	171,149	216,188	513,446
2017	909,790	0	191,056	191,056	527,678
2018	918,888	0	211,344	165,400	542,144
2019	928,076	0	232,019	139,211	556,846

7	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	432,367	375,262
2006	832,102	0	16,642	445,174	370,285
2007	848,744	0	25,462	458,322	364,960
2008	865,718	0	34,629	471,817	359,273
2009	883,033	0	44,152	485,668	353,213
2010	883,033	0	61,812	494,498	326,722
2011	883,033	0	79,473	503,329	300,231
2012	883,033	0	97,134	512,159	273,740
2013	883,033	0	114,794	520,989	247,249
2014	883,033	0	132,455	529,820	220,758
2015	891,863	0	151,617	544,037	196,210
2016	900,782	0	171,149	558,485	171,149
2017	909,790	0	191,056	573,167	145,566
2018	918,888	0	211,344	588,088	119,455
2019	928,076	0	232,019	603,250	92,808
8	***Vehicle Units***	***Fuel Cells Units***	***Hybrid Units***	***Petrol Units***	***Diesel Units***
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	0	61,812	370,874	450,347
2011	883,033	0	79,473	344,383	459,177
2012	883,033	0	97,134	317,892	468,007
2013	883,033	0	114,794	291,401	476,838
2014	883,033	0	132,455	264,910	485,668
2015	891,863	0	151,617	276,478	463,769
2016	900,782	0	171,149	288,250	441,383
2017	909,790	0	191,056	300,231	418,503
2018	918,888	0	211,344	312,422	395,122
2019	928,076	0	232,019	324,827	371,231
9	***Vehicle Units***	***Fuel Cells Units***	***Hybrid Units***	***Petrol Units***	***Diesel Units***
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	428,288	387,498
2006	832,102	0	0	436,853	395,248
2007	848,744	0	0	445,590	403,153
2008	865,718	0	0	454,502	411,216
2009	883,033	0	0	463,592	419,441
2010	883,033	17,661	0	454,762	410,610
2011	883,033	35,321	0	445,932	401,780
2012	883,033	52,982	0	437,101	392,950
2013	883,033	70,643	0	428,271	384,119
2014	883,033	88,303	0	419,441	375,289
2015	891,863	115,942	0	410,257	365,664
2016	900,782	144,125	0	400,848	355,809
2017	909,790	172,860	0	391,210	345,720
2018	918,888	202,155	0	381,338	335,394
2019	928,076	232,019	0	371,231	324,827

10	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	420,130	395,656
2006	832,102	0	0	420,211	411,890
2007	848,744	0	0	420,128	428,616
2008	865,718	0	0	419,873	445,845
2009	883,033	0	0	419,441	463,592
2010	883,033	17,661	0	392,950	472,423
2011	883,033	35,321	0	366,459	481,253
2012	883,033	52,982	0	339,968	490,083
2013	883,033	70,643	0	313,477	498,914
2014	883,033	88,303	0	286,986	507,744
2015	891,863	115,942	0	258,640	517,281
2016	900,782	144,125	0	229,699	526,957
2017	909,790	172,860	0	200,154	536,776
2018	918,888	202,155	0	169,994	546,738
2019	928,076	232,019	0	139,211	556,846
11	**Vehicle Units**	**Fuel Cells Units**	**Hybrid Units**	**Petrol Units**	**Diesel Units**
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	436,445	379,340
2006	832,102	0	0	453,495	378,606
2007	848,744	0	0	471,053	377,691
2008	865,718	0	0	489,131	376,588
2009	883,033	0	0	507,744	375,289
2010	883,033	17,661	0	516,574	348,798
2011	883,033	35,321	0	525,405	322,307
2012	883,033	52,982	0	534,235	295,816
2013	883,033	70,643	0	543,065	269,325
2014	883,033	88,303	0	551,896	242,834
2015	891,863	115,942	0	561,874	214,047
2016	900,782	144,125	0	571,996	184,660
2017	909,790	172,860	0	582,265	154,664
2018	918,888	202,155	0	592,682	124,050
2019	928,076	232,019	0	603,250	92,808
12	**Vehicle Units**	**Fuel Cells Units**	**Hybrid Units**	**Petrol Units**	**Diesel Units**
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	420,130	395,656
2006	832,102	0	0	420,211	411,890
2007	848,744	0	0	420,128	428,616
2008	865,718	0	0	419,873	445,845
2009	883,033	0	0	419,441	463,592
2010	883,033	17,661	0	392,950	472,423
2011	883,033	35,321	0	366,459	481,253
2012	883,033	52,982	0	339,968	490,083
2013	883,033	70,643	0	313,477	498,914
2014	883,033	88,303	0	286,986	507,744
2015	891,863	115,942	0	294,315	481,606
2016	900,782	144,125	0	301,762	454,895
2017	909,790	172,860	0	309,329	427,601
2018	918,888	202,155	0	317,016	399,716
2019	928,076	232,019	0	324,827	371,231

13	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	424,209	383,419
2006	832,102	0	16,642	428,532	386,927
2007	848,744	0	25,462	432,859	390,422
2008	865,718	0	34,629	437,188	393,902
2009	883,033	0	44,152	441,516	397,365
2010	883,033	13,246	57,397	428,271	384,119
2011	883,033	26,491	70,643	415,025	370,874
2012	883,033	39,737	83,888	401,780	357,628
2013	883,033	52,982	97,134	388,534	344,383
2014	883,033	66,228	110,379	375,289	331,137
2015	891,863	89,186	124,861	361,205	316,611
2016	900,782	112,598	139,621	346,801	301,762
2017	909,790	136,468	154,664	332,073	286,584
2018	918,888	160,805	169,994	317,016	271,072
2019	928,076	185,615	185,615	301,625	255,221
14	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	13,246	57,397	366,459	445,932
2011	883,033	26,491	70,643	335,553	450,347
2012	883,033	39,737	83,888	304,646	454,762
2013	883,033	52,982	97,134	273,740	459,177
2014	883,033	66,228	110,379	242,834	463,592
2015	891,863	89,186	124,861	209,588	468,228
2016	900,782	112,598	139,621	175,652	472,910
2017	909,790	136,468	154,664	141,017	477,640
2018	918,888	160,805	169,994	105,672	482,416
2019	928,076	185,615	185,615	69,606	487,240
15	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	432,367	375,262
2006	832,102	0	16,642	445,174	370,285
2007	848,744	0	25,462	458,322	364,960
2008	865,718	0	34,629	471,817	359,273
2009	883,033	0	44,152	485,668	353,213
2010	883,033	13,246	57,397	490,083	322,307
2011	883,033	26,491	70,643	494,498	291,401
2012	883,033	39,737	83,888	498,914	260,495
2013	883,033	52,982	97,134	503,329	229,589
2014	883,033	66,228	110,379	507,744	198,682
2015	891,863	89,186	124,861	512,821	164,995
2016	900,782	112,598	139,621	517,950	130,613
2017	909,790	136,468	154,664	523,129	95,528
2018	918,888	160,805	169,994	528,360	59,728
2019	928,076	185,615	185,615	533,644	23,202

16	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	13,246	57,397	366,459	445,932
2011	883,033	26,491	70,643	335,553	450,347
2012	883,033	39,737	83,888	304,646	454,762
2013	883,033	52,982	97,134	273,740	459,177
2014	883,033	66,228	110,379	242,834	463,592
2015	891,863	89,186	124,861	245,262	432,554
2016	900,782	112,598	139,621	247,715	400,848
2017	909,790	136,468	154,664	250,192	368,465
2018	918,888	160,805	169,994	252,694	335,394
2019	928,076	185,615	185,615	255,221	301,625

17	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	424,209	383,419
2006	832,102	0	16,642	428,532	386,927
2007	848,744	0	25,462	432,859	390,422
2008	865,718	0	34,629	437,188	393,902
2009	883,033	0	44,152	441,516	397,365
2010	883,033	17,661	52,982	428,271	384,119
2011	883,033	35,321	61,812	415,025	370,874
2012	883,033	52,982	70,643	401,780	357,628
2013	883,033	70,643	79,473	388,534	344,383
2014	883,033	88,303	88,303	375,289	331,137
2015	891,863	115,942	89,186	365,664	321,071
2016	900,782	144,125	90,078	355,809	310,770
2017	909,790	172,860	90,979	345,720	300,231
2018	918,888	202,155	91,889	335,394	289,450
2019	928,076	232,019	92,808	324,827	278,423

18	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	17,661	52,982	366,459	445,932
2011	883,033	35,321	61,812	335,553	450,347
2012	883,033	52,982	70,643	304,646	454,762
2013	883,033	70,643	79,473	273,740	459,177
2014	883,033	88,303	88,303	242,834	463,592
2015	891,863	115,942	89,186	214,047	472,688
2016	900,782	144,125	90,078	184,660	481,918
2017	909,790	172,860	90,979	154,664	491,286
2018	918,888	202,155	91,889	124,050	500,794
2019	928,076	232,019	92,808	92,808	510,442

19	*Vehicle Units*	*Fuel Cells Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	432,367	375,262
2006	832,102	0	16,642	445,174	370,285
2007	848,744	0	25,462	458,322	364,960
2008	865,718	0	34,629	471,817	359,273
2009	883,033	0	44,152	485,668	353,213
2010	883,033	17,661	52,982	490,083	322,307
2011	883,033	35,321	61,812	494,498	291,401
2012	883,033	52,982	70,643	498,914	260,495
2013	883,033	70,643	79,473	503,329	229,589
2014	883,033	88,303	88,303	507,744	198,682
2015	891,863	115,942	89,186	517,281	169,454
2016	900,782	144,125	90,078	526,957	139,621
2017	909,790	172,860	90,979	536,776	109,175
2018	918,888	202,155	91,889	546,738	78,105
2019	928,076	232,019	92,808	556,846	46,404
20	*Vehicle Units*	*Fuel Cells Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	17,661	52,982	366,459	445,932
2011	883,033	35,321	61,812	335,553	450,347
2012	883,033	52,982	70,643	304,646	454,762
2013	883,033	70,643	79,473	273,740	459,177
2014	883,033	88,303	88,303	242,834	463,592
2015	891,863	115,942	89,186	249,722	437,013
2016	900,782	144,125	90,078	256,723	409,856
2017	909,790	172,860	90,979	263,839	382,112
2018	918,888	202,155	91,889	271,072	353,772
2019	928,076	232,019	92,808	278,423	324,827
21	*Vehicle Units*	*Fuel Cells Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	424,209	383,419
2006	832,102	0	16,642	428,532	386,927
2007	848,744	0	25,462	432,859	390,422
2008	865,718	0	34,629	437,188	393,902
2009	883,033	0	44,152	441,516	397,365
2010	883,033	0	61,812	432,686	388,534
2011	883,033	0	79,473	423,856	379,704
2012	883,033	0	97,134	415,025	370,874
2013	883,033	0	114,794	406,195	362,043
2014	883,033	0	132,455	397,365	353,213
2015	891,863	0	160,535	387,961	343,367
2016	900,782	0	189,164	378,328	333,289
2017	909,790	0	218,350	368,465	322,975
2018	918,888	0	248,100	358,366	312,422
2019	928,076	0	278,423	348,029	301,625

22	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	0	61,812	370,874	450,347
2011	883,033	0	79,473	344,383	459,177
2012	883,033	0	97,134	317,892	468,007
2013	883,033	0	114,794	291,401	476,838
2014	883,033	0	132,455	264,910	485,668
2015	891,863	0	160,535	236,344	494,984
2016	900,782	0	189,164	207,180	504,438
2017	909,790	0	218,350	177,409	514,031
2018	918,888	0	248,100	147,022	523,766
2019	928,076	0	278,423	116,010	533,644
23	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	432,367	375,262
2006	832,102	0	16,642	445,174	370,285
2007	848,744	0	25,462	458,322	364,960
2008	865,718	0	34,629	471,817	359,273
2009	883,033	0	44,152	485,668	353,213
2010	883,033	0	61,812	494,498	326,722
2011	883,033	0	79,473	503,329	300,231
2012	883,033	0	97,134	512,159	273,740
2013	883,033	0	114,794	520,989	247,249
2014	883,033	0	132,455	529,820	220,758
2015	891,863	0	160,535	539,577	191,751
2016	900,782	0	189,164	549,477	162,141
2017	909,790	0	218,350	559,521	131,920
2018	918,888	0	248,100	569,710	101,078
2019	928,076	0	278,423	580,048	69,606
24	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	0	61,812	370,874	450,347
2011	883,033	0	79,473	344,383	459,177
2012	883,033	0	97,134	317,892	468,007
2013	883,033	0	114,794	291,401	476,838
2014	883,033	0	132,455	264,910	485,668
2015	891,863	0	160,535	272,018	459,310
2016	900,782	0	189,164	279,242	432,375
2017	909,790	0	218,350	286,584	404,856
2018	918,888	0	248,100	294,044	376,744
2019	928,076	0	278,423	301,625	348,029

25	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	428,288	387,498
2006	832,102	0	0	436,853	395,248
2007	848,744	0	0	445,590	403,153
2008	865,718	0	0	454,502	411,216
2009	883,033	0	0	463,592	419,441
2010	883,033	17,661	0	454,762	410,610
2011	883,033	35,321	0	445,932	401,780
2012	883,033	52,982	0	437,101	392,950
2013	883,033	70,643	0	428,271	384,119
2014	883,033	88,303	0	419,441	375,289
2015	891,863	124,861	0	405,798	361,205
2016	900,782	162,141	0	391,840	346,801
2017	909,790	200,154	0	377,563	332,073
2018	918,888	238,911	0	362,961	317,016
2019	928,076	278,423	0	348,029	301,625
26	*Vehicle Units*	*Fuel Cells Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	420,130	395,656
2006	832,102	0	0	420,211	411,890
2007	848,744	0	0	420,128	428,616
2008	865,718	0	0	419,873	445,845
2009	883,033	0	0	419,441	463,592
2010	883,033	17,661	0	392,950	472,423
2011	883,033	35,321	0	366,459	481,253
2012	883,033	52,982	0	339,968	490,083
2013	883,033	70,643	0	313,477	498,914
2014	883,033	88,303	0	286,986	507,744
2015	891,863	124,861	0	254,181	512,821
2016	900,782	162,141	0	220,692	517,950
2017	909,790	200,154	0	186,507	523,129
2018	918,888	238,911	0	151,616	528,360
2019	928,076	278,423	0	116,010	533,644
27	*Vehicle Units*	*Fuel Cells Units*	*Hybrid Units*	*Petrol Units*	*Diesel Units*
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	436,445	379,340
2006	832,102	0	0	453,495	378,606
2007	848,744	0	0	471,053	377,691
2008	865,718	0	0	489,131	376,588
2009	883,033	0	0	507,744	375,289
2010	883,033	17,661	0	516,574	348,798
2011	883,033	35,321	0	525,405	322,307
2012	883,033	52,982	0	534,235	295,816
2013	883,033	70,643	0	543,065	269,325
2014	883,033	88,303	0	551,896	242,834
2015	891,863	124,861	0	557,414	209,588
2016	900,782	162,141	0	562,989	175,652
2017	909,790	200,154	0	568,619	141,017
2018	918,888	238,911	0	574,305	105,672
2019	928,076	278,423	0	580,048	69,606

28	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	0	420,130	395,656
2006	832,102	0	0	420,211	411,890
2007	848,744	0	0	420,128	428,616
2008	865,718	0	0	419,873	445,845
2009	883,033	0	0	419,441	463,592
2010	883,033	17,661	0	392,950	472,423
2011	883,033	35,321	0	366,459	481,253
2012	883,033	52,982	0	339,968	490,083
2013	883,033	70,643	0	313,477	498,914
2014	883,033	88,303	0	286,986	507,744
2015	891,863	124,861	0	289,856	477,147
2016	900,782	162,141	0	292,754	445,887
2017	909,790	200,154	0	295,682	413,954
2018	918,888	238,911	0	298,638	381,338
2019	928,076	278,423	0	301,625	348,029

29	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790		0	419,890	379,900
2005	815,786		8,158	424,209	383,419
2006	832,102		16,642	428,532	386,927
2007	848,744		25,462	432,859	390,422
2008	865,718		34,629	437,188	393,902
2009	883,033		44,152	441,516	397,365
2010	883,033	13,246	57,397	428,271	384,119
2011	883,033	26,491	70,643	415,025	370,874
2012	883,033	39,737	83,888	401,780	357,628
2013	883,033	52,982	97,134	388,534	344,383
2014	883,033	66,228	110,379	375,289	331,137
2015	891,863	93,646	129,320	356,745	312,152
2016	900,782	121,606	148,629	337,793	292,754
2017	909,790	150,115	168,311	318,426	272,937
2018	918,888	179,183	188,372	298,638	252,694
2019	928,076	208,817	208,817	278,423	232,019

30	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	13,246	57,397	366,459	445,932
2011	883,033	26,491	70,643	335,553	450,347
2012	883,033	39,737	83,888	304,646	454,762
2013	883,033	52,982	97,134	273,740	459,177
2014	883,033	66,228	110,379	242,834	463,592
2015	891,863	93,646	129,320	205,129	463,769
2016	900,782	121,606	148,629	166,645	463,903
2017	909,790	150,115	168,311	127,371	463,993
2018	918,888	179,183	188,372	87,294	464,038
2019	928,076	208,817	208,817	46,404	464,038

31	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	432,367	375,262
2006	832,102	0	16,642	445,174	370,285
2007	848,744	0	25,462	458,322	364,960
2008	865,718	0	34,629	471,817	359,273
2009	883,033	0	44,152	485,668	353,213
2010	883,033	13,246	57,397	490,083	322,307
2011	883,033	26,491	70,643	494,498	291,401
2012	883,033	39,737	83,888	498,914	260,495
2013	883,033	52,982	97,134	503,329	229,589
2014	883,033	66,228	110,379	507,744	198,682
2015	891,863	93,646	129,320	508,362	160,535
2016	900,782	121,606	148,629	508,942	121,606
2017	909,790	150,115	168,311	509,482	81,881
2018	918,888	179,183	188,372	509,983	41,350
2019	928,076	208,817	208,817	510,442	0
32	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	13,246	57,397	366,459	445,932
2011	883,033	26,491	70,643	335,553	450,347
2012	883,033	39,737	83,888	304,646	454,762
2013	883,033	52,982	97,134	273,740	459,177
2014	883,033	66,228	110,379	242,834	463,592
2015	891,863	93,646	129,320	240,803	428,094
2016	900,782	121,606	148,629	238,707	391,840
2017	909,790	150,115	168,311	236,545	354,818
2018	918,888	179,183	188,372	234,316	317,016
2019	928,076	208,817	208,817	232,019	278,423
33	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	424,209	383,419
2006	832,102	0	16,642	428,532	386,927
2007	848,744	0	25,462	432,859	390,422
2008	865,718	0	34,629	437,188	393,902
2009	883,033	0	44,152	441,516	397,365
2010	883,033	13,246	57,397	428,271	384,119
2011	883,033	26,491	70,643	415,025	370,874
2012	883,033	39,737	83,888	401,780	357,628
2013	883,033	52,982	97,134	388,534	344,383
2014	883,033	66,228	110,379	375,289	331,137
2015	891,863	107,024	115,942	356,745	312,152
2016	900,782	148,629	121,606	337,793	292,754
2017	909,790	191,056	127,371	318,426	272,937
2018	918,888	234,316	133,239	298,638	252,694
2019	928,076	278,423	139,211	278,423	232,019

34	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	13,246	57,397	366,459	445,932
2011	883,033	26,491	70,643	335,553	450,347
2012	883,033	39,737	83,888	304,646	454,762
2013	883,033	52,982	97,134	273,740	459,177
2014	883,033	66,228	110,379	242,834	463,592
2015	891,863	107,024	115,942	205,129	463,769
2016	900,782	148,629	121,606	166,645	463,903
2017	909,790	191,056	127,371	127,371	463,993
2018	918,888	234,316	133,239	87,294	464,038
2019	928,076	278,423	139,211	46,404	464,038

35	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	432,367	375,262
2006	832,102	0	16,642	445,174	370,285
2007	848,744	0	25,462	458,322	364,960
2008	865,718	0	34,629	471,817	359,273
2009	883,033	0	44,152	485,668	353,213
2010	883,033	13,246	57,397	490,083	322,307
2011	883,033	26,491	70,643	494,498	291,401
2012	883,033	39,737	83,888	498,914	260,495
2013	883,033	52,982	97,134	503,329	229,589
2014	883,033	66,228	110,379	507,744	198,682
2015	891,863	107,024	115,942	508,362	160,535
2016	900,782	148,629	121,606	508,942	121,606
2017	909,790	191,056	127,371	509,482	81,881
2018	918,888	234,316	133,239	509,983	41,350
2019	928,076	278,423	139,211	510,442	0

36	Vehicle Units	Fuel Cells Units	Hybrid Units	Petrol Units	Diesel Units
2004	799,790	0	0	419,890	379,900
2005	815,786	0	8,158	416,051	391,577
2006	832,102	0	16,642	411,890	403,569
2007	848,744	0	25,462	407,397	415,884
2008	865,718	0	34,629	402,559	428,531
2009	883,033	0	44,152	397,365	441,516
2010	883,033	13,246	57,397	366,459	445,932
2011	883,033	26,491	70,643	335,553	450,347
2012	883,033	39,737	83,888	304,646	454,762
2013	883,033	52,982	97,134	273,740	459,177
2014	883,033	66,228	110,379	242,834	463,592
2015	891,863	107,024	115,942	240,803	428,094
2016	900,782	148,629	121,606	238,707	391,840
2017	909,790	191,056	127,371	236,545	354,818
2018	918,888	234,316	133,239	234,316	317,016
2019	928,076	278,423	139,211	232,019	278,423

APPENDIX I

PREDICTED DEMAND FOR PROPULSION SYSTEM CONFIGURATIONS

This appendix refines predictions made in Appendix H in that it estimates the future demand for three primary configurations of petrol engine and three primary configurations of diesel engine. To make these estimates the predicted demands for petrol and diesel engines are tabulated in Appendix H and apportioned to the six-engine configurations on the basis that their current ratio of demand is maintained over the next 15 years. The likelihood that this simplifying assumption will hold true is discussed in section 6.1.1 of this thesis.

1	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	348,927	79,360	14,149	304,169	69,180
2006	832,102	0	0	0	355,906	80,947	14,432	310,252	70,564
2007	848,744	0	0	0	363,024	82,566	14,721	316,457	71,975
2008	865,718	0	0	0	370,284	84,218	15,015	322,786	73,415
2009	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2010	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2011	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2012	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2013	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2014	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2015	891,863	0	0	0	381,467	86,761	15,469	332,534	75,632
2016	900,782	0	0	0	385,282	87,629	15,624	335,860	76,388
2017	909,790	0	0	0	389,134	88,505	15,780	339,218	77,152
2018	918,888	0	0	0	393,026	89,390	15,938	342,610	77,924
2019	928,076	0	0	0	396,956	90,284	16,097	346,037	78,703
Count				15	0	0	15	0	0

2	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	342,281	77,849	14,447	310,572	70,637
2006	832,102	0	0	0	342,348	77,864	15,040	323,315	73,535
2007	848,744	0	0	0	342,280	77,848	15,651	336,444	76,521
2008	865,718	0	0	0	342,072	77,801	16,280	349,968	79,597
2009	883,033	0	0	0	341,720	77,721	16,928	363,899	82,765
2010	883,033	0	0	0	327,331	74,448	17,573	377,762	85,918
2011	883,033	0	0	0	312,943	71,176	18,218	391,625	89,071
2012	883,033	0	0	0	298,555	67,904	18,863	405,487	92,224
2013	883,033	0	0	0	284,167	64,631	19,507	419,350	95,377
2014	883,033	0	0	0	269,779	61,359	20,152	433,213	98,530
2015	891,863	0	0	0	257,944	58,667	21,005	451,547	102,700
2016	900,782	0	0	0	245,846	55,915	21,873	470,203	106,943
2017	909,790	0	0	0	233,481	53,103	22,756	489,188	111,261
2018	918,888	0	0	0	220,843	50,229	23,655	508,506	115,655
2019	928,076	0	0	0	207,929	47,292	24,569	528,161	120,125
Count				15	0	10	15	0	0

3	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	355,574	80,872	13,851	297,765	67,724
2006	832,102	0	0	0	369,464	84,031	13,825	297,189	67,593
2007	848,744	0	0	0	383,768	87,285	13,791	296,470	67,429
2008	865,718	0	0	0	398,497	90,634	13,751	295,604	67,232
2009	883,033	0	0	0	413,661	94,083	13,704	294,585	67,001
2010	883,033	0	0	0	428,049	97,356	13,059	280,722	63,848
2011	883,033	0	0	0	442,437	100,628	12,414	266,859	60,695
2012	883,033	0	0	0	456,825	103,901	11,769	252,996	57,542
2013	883,033	0	0	0	471,213	107,173	11,124	239,134	54,389
2014	883,033	0	0	0	485,602	110,446	10,479	225,271	51,236
2015	891,863	0	0	0	504,990	114,855	9,933	213,522	48,564
2016	900,782	0	0	0	524,717	119,342	9,374	201,516	45,833
2017	909,790	0	0	0	544,788	123,907	8,803	189,248	43,043
2018	918,888	0	0	0	565,209	128,551	8,220	176,715	40,192
2019	928,076	0	0	0	585,983	133,276	7,625	163,912	37,280
Count				15	0	0	15	0	5

4	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	342,281	77,849	14,447	310,572	70,637
2006	832,102	0	0	0	342,348	77,864	15,040	323,315	73,535
2007	848,744	0	0	0	342,280	77,848	15,651	336,444	76,521
2008	865,718	0	0	0	342,072	77,801	16,280	349,968	79,597
2009	883,033	0	0	0	341,720	77,721	16,928	363,899	82,765
2010	883,033	0	0	0	327,331	74,448	17,573	377,762	85,918
2011	883,033	0	0	0	312,943	71,176	18,218	391,625	89,071
2012	883,033	0	0	0	298,555	67,904	18,863	405,487	92,224
2013	883,033	0	0	0	284,167	64,631	19,507	419,350	95,377
2014	883,033	0	0	0	269,779	61,359	20,152	433,213	98,530
2015	891,863	0	0	0	287,008	65,277	19,702	423,544	96,331
2016	900,782	0	0	0	304,556	69,268	19,242	413,638	94,078
2017	909,790	0	0	0	322,426	73,333	18,770	403,491	91,770
2018	918,888	0	0	0	340,622	77,471	18,286	393,100	89,407
2019	928,076	0	0	0	359,151	81,686	17,791	382,461	86,987
Count				15	0	8	15	0	0
5	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	345,604	78,604	14,000	300,967	68,452
2006	832,102	0	16,642	0	349,127	79,406	14,128	303,720	69,078
2007	848,744	0	25,462	0	352,652	80,207	14,256	306,464	69,702
2008	865,718	0	34,629	0	356,178	81,009	14,383	309,195	70,324
2009	883,033	0	44,152	0	359,705	81,812	14,510	311,913	70,942
2010	883,033	0	61,812	0	352,511	80,175	14,187	304,982	69,365
2011	883,033	0	79,473	0	345,317	78,539	13,865	298,051	67,789
2012	883,033	0	97,134	0	338,123	76,903	13,542	291,119	66,212
2013	883,033	0	114,794	0	330,928	75,267	13,220	284,188	64,636
2014	883,033	0	132,455	0	323,734	73,630	12,897	277,256	63,059
2015	891,863	0	151,617	0	319,706	72,714	12,701	273,028	62,098
2016	900,782	0	171,149	0	315,564	71,772	12,499	268,688	61,111
2017	909,790	0	191,056	0	311,308	70,804	12,292	264,233	60,097
2018	918,888	0	211,344	0	306,934	69,809	12,079	259,663	59,058
2019	928,076	0	232,019	0	302,443	68,788	11,861	254,974	57,992
Count				15	0	6	15	0	0
6	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	0	61,812	0	302,152	68,722	16,444	353,502	80,401
2011	883,033	0	79,473	0	280,570	63,813	16,767	360,433	81,977
2012	883,033	0	97,134	0	258,987	58,904	17,089	367,365	83,554
2013	883,033	0	114,794	0	237,405	53,996	17,412	374,296	85,130
2014	883,033	0	132,455	0	215,823	49,087	17,734	381,227	86,707
2015	891,863	0	151,617	0	196,183	44,620	18,237	392,040	89,166
2016	900,782	0	171,149	0	176,129	40,059	18,748	403,032	91,666
2017	909,790	0	191,056	0	155,654	35,402	19,268	414,203	94,207
2018	918,888	0	211,344	0	134,752	30,648	19,796	425,558	96,789
2019	928,076	0	232,019	0	113,416	25,795	20,333	437,099	99,414
Count				15	2	12	15	0	0

7	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	352,250	80,116	13,703	294,563	66,996
2006	832,102	0	16,642	0	362,685	82,489	13,521	290,657	66,107
2007	848,744	0	25,462	0	373,396	84,925	13,326	286,477	65,157
2008	865,718	0	34,629	0	384,390	87,426	13,119	282,013	64,141
2009	883,033	0	44,152	0	395,675	89,993	12,897	277,256	63,059
2010	883,033	0	61,812	0	402,869	91,629	11,930	256,462	58,330
2011	883,033	0	79,473	0	410,064	93,265	10,963	235,668	53,600
2012	883,033	0	97,134	0	417,258	94,901	9,996	214,874	48,871
2013	883,033	0	114,794	0	424,452	96,538	9,028	194,079	44,142
2014	883,033	0	132,455	0	431,646	98,174	8,061	173,285	39,412
2015	891,863	0	151,617	0	443,228	100,808	7,165	154,016	35,029
2016	900,782	0	171,149	0	454,999	103,485	6,249	134,344	30,555
2017	909,790	0	191,056	0	466,961	106,206	5,315	114,263	25,988
2018	918,888	0	211,344	0	479,117	108,971	4,362	93,767	21,326
2019	928,076	0	232,019	0	491,469	111,780	3,389	72,850	16,569
Count				15	0	0	15	3	8

8	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	0	61,812	0	302,152	68,722	16,444	353,502	80,401
2011	883,033	0	79,473	0	280,570	63,813	16,767	360,433	81,977
2012	883,033	0	97,134	0	258,987	58,904	17,089	367,365	83,554
2013	883,033	0	114,794	0	237,405	53,996	17,412	374,296	85,130
2014	883,033	0	132,455	0	215,823	49,087	17,734	381,227	86,707
2015	891,863	0	151,617	0	225,247	51,230	16,934	364,038	82,797
2016	900,782	0	171,149	0	234,838	53,412	16,117	346,466	78,800
2017	909,790	0	191,056	0	244,599	55,632	15,281	328,506	74,716
2018	918,888	0	211,344	0	254,531	57,891	14,428	310,153	70,541
2019	928,076	0	232,019	0	264,637	60,189	13,555	291,399	66,276
Count				15	0	12	15	0	0

9	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	348,927	79,360	14,149	304,169	69,180
2006	832,102	0	0	0	355,906	80,947	14,432	310,252	70,564
2007	848,744	0	0	0	363,024	82,566	14,721	316,457	71,975
2008	865,718	0	0	0	370,284	84,218	15,015	322,786	73,415
2009	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2010	883,033	17,661	0	0	370,496	84,266	14,993	322,310	73,307
2011	883,033	35,321	0	0	363,302	82,630	14,671	315,379	71,730
2012	883,033	52,982	0	0	356,108	80,993	14,348	308,448	70,154
2013	883,033	70,643	0	0	348,914	79,357	14,026	301,516	68,577
2014	883,033	88,303	0	0	341,720	77,721	13,704	294,585	67,001
2015	891,863	115,942	0	0	334,238	76,019	13,352	287,030	65,282
2016	900,782	144,125	0	0	326,572	74,276	12,992	279,294	63,523
2017	909,790	172,860	0	0	318,720	72,490	12,624	271,375	61,722
2018	918,888	202,155	0	0	310,678	70,661	12,247	263,269	59,878
2019	928,076	232,019	0	0	302,443	68,788	11,861	254,974	57,992
Count				15	0	4	15	0	0

10	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	342,281	77,849	14,447	310,572	70,637
2006	832,102	0	0	0	342,348	77,864	15,040	323,315	73,535
2007	848,744	0	0	0	342,280	77,848	15,651	336,444	76,521
2008	865,718	0	0	0	342,072	77,801	16,280	349,968	79,597
2009	883,033	0	0	0	341,720	77,721	16,928	363,899	82,765
2010	883,033	17,661	0	0	320,137	72,812	17,250	370,830	84,342
2011	883,033	35,321	0	0	298,555	67,904	17,573	377,762	85,918
2012	883,033	52,982	0	0	276,973	62,995	17,895	384,693	87,495
2013	883,033	70,643	0	0	255,390	58,086	18,218	391,625	89,071
2014	883,033	88,303	0	0	233,808	53,178	18,540	398,556	90,648
2015	891,863	115,942	0	0	210,715	47,925	18,888	406,042	92,350
2016	900,782	144,125	0	0	187,137	42,563	19,242	413,638	94,078
2017	909,790	172,860	0	0	163,066	37,088	19,600	421,345	95,831
2018	918,888	202,155	0	0	138,495	31,499	19,964	429,165	97,610
2019	928,076	232,019	0	0	113,416	25,795	20,333	437,099	99,414
Count				15	2	10	15	0	0

11	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	355,574	80,872	13,851	297,765	67,724
2006	832,102	0	0	0	369,464	84,031	13,825	297,189	67,593
2007	848,744	0	0	0	383,768	87,285	13,791	296,470	67,429
2008	865,718	0	0	0	398,497	90,634	13,751	295,604	67,232
2009	883,033	0	0	0	413,661	94,083	13,704	294,585	67,001
2010	883,033	17,661	0	0	420,855	95,720	12,736	273,791	62,271
2011	883,033	35,321	0	0	428,049	97,356	11,769	252,996	57,542
2012	883,033	52,982	0	0	435,243	98,992	10,802	232,202	52,812
2013	883,033	70,643	0	0	442,437	100,628	9,834	211,408	48,083
2014	883,033	88,303	0	0	449,631	102,264	8,867	190,614	43,353
2015	891,863	115,942	0	0	457,760	104,113	7,816	168,017	38,214
2016	900,782	144,125	0	0	466,007	105,989	6,743	144,950	32,968
2017	909,790	172,860	0	0	474,373	107,892	5,648	121,404	27,612
2018	918,888	202,155	0	0	482,860	109,822	4,530	97,373	22,147
2019	928,076	232,019	0	0	491,469	111,780	3,389	72,850	16,569
Count				15	0	0	15	3	7

12	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	342,281	77,849	14,447	310,572	70,637
2006	832,102	0	0	0	342,348	77,864	15,040	323,315	73,535
2007	848,744	0	0	0	342,280	77,848	15,651	336,444	76,521
2008	865,718	0	0	0	342,072	77,801	16,280	349,968	79,597
2009	883,033	0	0	0	341,720	77,721	16,928	363,899	82,765
2010	883,033	17,661	0	0	320,137	72,812	17,250	370,830	84,342
2011	883,033	35,321	0	0	298,555	67,904	17,573	377,762	85,918
2012	883,033	52,982	0	0	276,973	62,995	17,895	384,693	87,495
2013	883,033	70,643	0	0	255,390	58,086	18,218	391,625	89,071
2014	883,033	88,303	0	0	233,808	53,178	18,540	398,556	90,648
2015	891,863	115,942	0	0	239,779	54,536	17,586	378,039	85,981
2016	900,782	144,125	0	0	245,846	55,915	16,610	357,072	81,213
2017	909,790	172,860	0	0	252,011	57,318	15,614	335,647	76,340
2018	918,888	202,155	0	0	258,274	58,742	14,595	313,759	71,362
2019	928,076	232,019	0	0	264,637	60,189	13,555	291,399	66,276
Count				15	0	10	15	0	0

13	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	345,604	78,604	14,000	300,967	68,452
2006	832,102	0	16,642	0	349,127	79,406	14,128	303,720	69,078
2007	848,744	0	25,462	0	352,652	80,207	14,256	306,464	69,702
2008	865,718	0	34,629	0	356,178	81,009	14,383	309,195	70,324
2009	883,033	0	44,152	0	359,705	81,812	14,510	311,913	70,942
2010	883,033	13,246	57,397	0	348,914	79,357	14,026	301,516	68,577
2011	883,033	26,491	70,643	0	338,123	76,903	13,542	291,119	66,212
2012	883,033	39,737	83,888	0	327,331	74,448	13,059	280,722	63,848
2013	883,033	52,982	97,134	0	316,540	71,994	12,575	270,325	61,483
2014	883,033	66,228	110,379	0	305,749	69,540	12,091	259,928	59,118
2015	891,863	89,186	124,861	0	294,275	66,930	11,561	248,526	56,525
2016	900,782	112,598	139,621	0	282,540	64,261	11,019	236,869	53,874
2017	909,790	136,468	154,664	0	270,541	61,532	10,464	224,955	51,164
2018	918,888	160,805	169,994	0	258,274	58,742	9,898	212,779	48,395
2019	928,076	185,615	185,615	0	245,735	55,890	9,319	200,337	45,565
Count				15	0	8	15	0	2

14	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	13,246	57,397	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	26,491	70,643	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	39,737	83,888	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	52,982	97,134	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	66,228	110,379	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	89,186	124,861	0	170,752	38,836	17,097	367,538	83,593
2016	900,782	112,598	139,621	0	143,105	32,548	17,268	371,213	84,429
2017	909,790	136,468	154,664	0	114,887	26,130	17,441	374,925	85,273
2018	918,888	160,805	169,994	0	86,091	19,581	17,615	378,675	86,126
2019	928,076	185,615	185,615	0	56,708	12,898	17,791	382,461	86,987
Count				15	4	12	15	0	0

15	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	352,250	80,116	13,703	294,563	66,996
2006	832,102	0	16,642	0	362,685	82,489	13,521	290,657	66,107
2007	848,744	0	25,462	0	373,396	84,925	13,326	286,477	65,157
2008	865,718	0	34,629	0	384,390	87,426	13,119	282,013	64,141
2009	883,033	0	44,152	0	395,675	89,993	12,897	277,256	63,059
2010	883,033	13,246	57,397	0	399,272	90,811	11,769	252,996	57,542
2011	883,033	26,491	70,643	0	402,869	91,629	10,640	228,736	52,024
2012	883,033	39,737	83,888	0	406,466	92,447	9,512	204,477	46,506
2013	883,033	52,982	97,134	0	410,064	93,265	8,383	180,217	40,989
2014	883,033	66,228	110,379	0	413,661	94,083	7,255	155,957	35,471
2015	891,863	89,186	124,861	0	417,797	95,024	6,025	129,513	29,457
2016	900,782	112,598	139,621	0	421,975	95,974	4,769	102,526	23,318
2017	909,790	136,468	154,664	0	426,195	96,934	3,488	74,985	17,055
2018	918,888	160,805	169,994	0	430,457	97,903	2,181	46,884	10,663
2019	928,076	185,615	185,615	0	434,761	98,882	847	18,212	4,142
Count				15	0	0	15	4	8

16	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	13,246	57,397	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	26,491	70,643	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	39,737	83,888	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	52,982	97,134	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	66,228	110,379	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	89,186	124,861	0	199,816	45,446	15,795	339,535	77,224
2016	900,782	112,598	139,621	0	201,814	45,901	14,637	314,647	71,564
2017	909,790	136,468	154,664	0	203,832	46,360	13,454	289,228	65,782
2018	918,888	160,805	169,994	0	205,871	46,823	12,247	263,269	59,878
2019	928,076	185,615	185,615	0	207,929	47,292	11,014	236,762	53,849
Count				15	0	12	15	0	0

17	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	345,604	78,604	14,000	300,967	68,452
2006	832,102	0	16,642	0	349,127	79,406	14,128	303,720	69,078
2007	848,744	0	25,462	0	352,652	80,207	14,256	306,464	69,702
2008	865,718	0	34,629	0	356,178	81,009	14,383	309,195	70,324
2009	883,033	0	44,152	0	359,705	81,812	14,510	311,913	70,942
2010	883,033	17,661	52,982	0	348,914	79,357	14,026	301,516	68,577
2011	883,033	35,321	61,812	0	338,123	76,903	13,542	291,119	66,212
2012	883,033	52,982	70,643	0	327,331	74,448	13,059	280,722	63,848
2013	883,033	70,643	79,473	0	316,540	71,994	12,575	270,325	61,483
2014	883,033	88,303	88,303	0	305,749	69,540	12,091	259,928	59,118
2015	891,863	115,942	89,186	0	297,908	67,756	11,724	252,026	57,321
2016	900,782	144,125	90,078	0	289,879	65,930	11,348	243,940	55,482
2017	909,790	172,860	90,979	0	281,659	64,061	10,963	235,667	53,600
2018	918,888	202,155	91,889	0	273,247	62,147	10,569	227,205	51,676
2019	928,076	232,019	92,808	0	264,637	60,189	10,167	218,549	49,707
Count				15	0	8	15	0	1

18	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	17,661	52,982	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	35,321	61,812	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	52,982	70,643	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	70,643	79,473	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	88,303	88,303	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	115,942	89,186	0	174,385	39,662	17,260	371,038	84,389
2016	900,782	144,125	90,078	0	150,443	34,217	17,597	378,284	86,037
2017	909,790	172,860	90,979	0	126,005	28,659	17,939	385,638	87,710
2018	918,888	202,155	91,889	0	101,064	22,986	18,286	393,100	89,407
2019	928,076	232,019	92,808	0	75,611	17,197	18,639	400,674	91,130
Count				15	3	12	15	0	0

19	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	352,250	80,116	13,703	294,563	66,996
2006	832,102	0	16,642	0	362,685	82,489	13,521	290,657	66,107
2007	848,744	0	25,462	0	373,396	84,925	13,326	286,477	65,157
2008	865,718	0	34,629	0	384,390	87,426	13,119	282,013	64,141
2009	883,033	0	44,152	0	395,675	89,993	12,897	277,256	63,059
2010	883,033	17,661	52,982	0	399,272	90,811	11,769	252,996	57,542
2011	883,033	35,321	61,812	0	402,869	91,629	10,640	228,736	52,024
2012	883,033	52,982	70,643	0	406,466	92,447	9,512	204,477	46,506
2013	883,033	70,643	79,473	0	410,064	93,265	8,383	180,217	40,989
2014	883,033	88,303	88,303	0	413,661	94,083	7,255	155,957	35,471
2015	891,863	115,942	89,186	0	421,430	95,850	6,188	133,014	30,253
2016	900,782	144,125	90,078	0	429,314	97,643	5,098	109,596	24,927
2017	909,790	172,860	90,979	0	437,313	99,463	3,986	85,697	19,491
2018	918,888	202,155	91,889	0	445,429	101,309	2,852	61,309	13,944
2019	928,076	232,019	92,808	0	453,664	103,182	1,694	36,425	8,285
Count				15	0	0	15	4	8

20	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	17,661	52,982	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	35,321	61,812	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	52,982	70,643	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	70,643	79,473	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	88,303	88,303	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	115,942	89,186	0	203,449	46,273	15,957	343,035	78,020
2016	900,782	144,125	90,078	0	209,153	47,570	14,966	321,718	73,172
2017	909,790	172,860	90,979	0	214,951	48,888	13,953	299,940	68,219
2018	918,888	202,155	91,889	0	220,843	50,229	12,918	277,695	63,159
2019	928,076	232,019	92,808	0	226,832	51,591	11,861	254,974	57,992
Count				15	0	12	15	0	0

21	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	345,604	78,604	14,000	300,967	68,452
2006	832,102	0	16,642	0	349,127	79,406	14,128	303,720	69,078
2007	848,744	0	25,462	0	352,652	80,207	14,256	306,464	69,702
2008	865,718	0	34,629	0	356,178	81,009	14,383	309,195	70,324
2009	883,033	0	44,152	0	359,705	81,812	14,510	311,913	70,942
2010	883,033	0	61,812	0	352,511	80,175	14,187	304,982	69,365
2011	883,033	0	79,473	0	345,317	78,539	13,865	298,051	67,789
2012	883,033	0	97,134	0	338,123	76,903	13,542	291,119	66,212
2013	883,033	0	114,794	0	330,928	75,267	13,220	284,188	64,636
2014	883,033	0	132,455	0	323,734	73,630	12,897	277,256	63,059
2015	891,863	0	160,535	0	316,073	71,888	12,538	269,528	61,302
2016	900,782	0	189,164	0	308,225	70,103	12,170	261,617	59,502
2017	909,790	0	218,350	0	300,189	68,275	11,793	253,521	57,661
2018	918,888	0	248,100	0	291,962	66,404	11,408	245,237	55,777
2019	928,076	0	278,423	0	283,540	64,489	11,014	236,762	53,849
Count				15	0	6	15	0	0

22	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	0	61,812	0	302,152	68,722	16,444	353,502	80,401
2011	883,033	0	79,473	0	280,570	63,813	16,767	360,433	81,977
2012	883,033	0	97,134	0	258,987	58,904	17,089	367,365	83,554
2013	883,033	0	114,794	0	237,405	53,996	17,412	374,296	85,130
2014	883,033	0	132,455	0	215,823	49,087	17,734	381,227	86,707
2015	891,863	0	160,535	0	192,550	43,794	18,074	388,540	88,370
2016	900,782	0	189,164	0	168,790	38,390	18,419	395,961	90,058
2017	909,790	0	218,350	0	144,536	32,873	18,770	403,491	91,770
2018	918,888	0	248,100	0	119,779	27,243	19,125	411,133	93,508
2019	928,076	0	278,423	0	94,513	21,496	19,486	418,886	95,272
Count				15	3	12	15	0	0

23	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	352,250	80,116	13,703	294,563	66,996
2006	832,102	0	16,642	0	362,685	82,489	13,521	290,657	66,107
2007	848,744	0	25,462	0	373,396	84,925	13,326	286,477	65,157
2008	865,718	0	34,629	0	384,390	87,426	13,119	282,013	64,141
2009	883,033	0	44,152	0	395,675	89,993	12,897	277,256	63,059
2010	883,033	0	61,812	0	402,869	91,629	11,930	256,462	58,330
2011	883,033	0	79,473	0	410,064	93,265	10,963	235,668	53,600
2012	883,033	0	97,134	0	417,258	94,901	9,996	214,874	48,871
2013	883,033	0	114,794	0	424,452	96,538	9,028	194,079	44,142
2014	883,033	0	132,455	0	431,646	98,174	8,061	173,285	39,412
2015	891,863	0	160,535	0	439,595	99,982	7,002	150,516	34,233
2016	900,782	0	189,164	0	447,661	101,816	5,921	127,273	28,947
2017	909,790	0	218,350	0	455,843	103,677	4,817	103,551	23,552
2018	918,888	0	248,100	0	464,145	105,565	3,691	79,341	18,045
2019	928,076	0	278,423	0	472,567	107,481	2,542	54,637	12,427
Count				15	0	0	15	3	8

24	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	0	61,812	0	302,152	68,722	16,444	353,502	80,401
2011	883,033	0	79,473	0	280,570	63,813	16,767	360,433	81,977
2012	883,033	0	97,134	0	258,987	58,904	17,089	367,365	83,554
2013	883,033	0	114,794	0	237,405	53,996	17,412	374,296	85,130
2014	883,033	0	132,455	0	215,823	49,087	17,734	381,227	86,707
2015	891,863	0	160,535	0	221,614	50,404	16,772	360,537	82,001
2016	900,782	0	189,164	0	227,500	51,743	15,788	339,395	77,192
2017	909,790	0	218,350	0	233,481	53,103	14,783	317,794	72,279
2018	918,888	0	248,100	0	239,559	54,485	13,757	295,727	67,260
2019	928,076	0	278,423	0	245,735	55,890	12,708	273,187	62,134
Count				15	0	12	15	0	0

25	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	348,927	79,360	14,149	304,169	69,180
2006	832,102	0	0	0	355,906	80,947	14,432	310,252	70,564
2007	848,744	0	0	0	363,024	82,566	14,721	316,457	71,975
2008	865,718	0	0	0	370,284	84,218	15,015	322,786	73,415
2009	883,033	0	0	0	377,690	85,902	15,316	329,242	74,883
2010	883,033	17,661	0	0	370,496	84,266	14,993	322,310	73,307
2011	883,033	35,321	0	0	363,302	82,630	14,671	315,379	71,730
2012	883,033	52,982	0	0	356,108	80,993	14,348	308,448	70,154
2013	883,033	70,643	0	0	348,914	79,357	14,026	301,516	68,577
2014	883,033	88,303	0	0	341,720	77,721	13,704	294,585	67,001
2015	891,863	124,861	0	0	330,605	75,193	13,189	283,529	64,486
2016	900,782	162,141	0	0	319,233	72,607	12,663	272,223	61,915
2017	909,790	200,154	0	0	307,602	69,961	12,126	260,662	59,285
2018	918,888	238,911	0	0	295,705	67,255	11,576	248,843	56,597
2019	928,076	278,423	0	0	283,540	64,489	11,014	236,762	53,849
Count				15	0	4	15	0	0

26	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	342,281	77,849	14,447	310,572	70,637
2006	832,102	0	0	0	342,348	77,864	15,040	323,315	73,535
2007	848,744	0	0	0	342,280	77,848	15,651	336,444	76,521
2008	865,718	0	0	0	342,072	77,801	16,280	349,968	79,597
2009	883,033	0	0	0	341,720	77,721	16,928	363,899	82,765
2010	883,033	17,661	0	0	320,137	72,812	17,250	370,830	84,342
2011	883,033	35,321	0	0	298,555	67,904	17,573	377,762	85,918
2012	883,033	52,982	0	0	276,973	62,995	17,895	384,693	87,495
2013	883,033	70,643	0	0	255,390	58,086	18,218	391,625	89,071
2014	883,033	88,303	0	0	233,808	53,178	18,540	398,556	90,648
2015	891,863	124,861	0	0	207,082	47,099	18,725	402,541	91,554
2016	900,782	162,141	0	0	179,798	40,893	18,913	406,567	92,470
2017	909,790	200,154	0	0	151,948	34,559	19,102	410,633	93,395
2018	918,888	238,911	0	0	123,522	28,094	19,293	414,739	94,329
2019	928,076	278,423	0	0	94,513	21,496	19,486	418,886	95,272
Count				15	2	10	15	0	0

27	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	355,574	80,872	13,851	297,765	67,724
2006	832,102	0	0	0	369,464	84,031	13,825	297,189	67,593
2007	848,744	0	0	0	383,768	87,285	13,791	296,470	67,429
2008	865,718	0	0	0	398,497	90,634	13,751	295,604	67,232
2009	883,033	0	0	0	413,661	94,083	13,704	294,585	67,001
2010	883,033	17,661	0	0	420,855	95,720	12,736	273,791	62,271
2011	883,033	35,321	0	0	428,049	97,356	11,769	252,996	57,542
2012	883,033	52,982	0	0	435,243	98,992	10,802	232,202	52,812
2013	883,033	70,643	0	0	442,437	100,628	9,834	211,408	48,083
2014	883,033	88,303	0	0	449,631	102,264	8,867	190,614	43,353
2015	891,863	124,861	0	0	454,127	103,287	7,653	164,517	37,418
2016	900,782	162,141	0	0	458,669	104,320	6,414	137,879	31,359
2017	909,790	200,154	0	0	463,255	105,363	5,149	110,692	25,176
2018	918,888	238,911	0	0	467,888	106,417	3,859	82,948	18,866
2019	928,076	278,423	0	0	472,567	107,481	2,542	54,637	12,427
Count				15	0	0	15	3	7

28	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	0	0	342,281	77,849	14,447	310,572	70,637
2006	832,102	0	0	0	342,348	77,864	15,040	323,315	73,535
2007	848,744	0	0	0	342,280	77,848	15,651	336,444	76,521
2008	865,718	0	0	0	342,072	77,801	16,280	349,968	79,597
2009	883,033	0	0	0	341,720	77,721	16,928	363,899	82,765
2010	883,033	17,661	0	0	320,137	72,812	17,250	370,830	84,342
2011	883,033	35,321	0	0	298,555	67,904	17,573	377,762	85,918
2012	883,033	52,982	0	0	276,973	62,995	17,895	384,693	87,495
2013	883,033	70,643	0	0	255,390	58,086	18,218	391,625	89,071
2014	883,033	88,303	0	0	233,808	53,178	18,540	398,556	90,648
2015	891,863	124,861	0	0	236,146	53,709	17,423	374,539	85,185
2016	900,782	162,141	0	0	238,508	54,246	16,281	350,001	79,605
2017	909,790	200,154	0	0	240,893	54,789	15,115	324,935	73,904
2018	918,888	238,911	0	0	243,302	55,337	13,924	299,333	68,081
2019	928,076	278,423	0	0	245,735	55,890	12,708	273,187	62,134
Count				15	0	10	15	0	0

29	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	345,604	78,604	14,000	300,967	68,452
2006	832,102	0	16.642	0	349,127	79,406	14,128	303,720	69,078
2007	848,744	0	25,462	0	352,652	80,207	14,256	306,464	69,702
2008	865,718	0	34,629	0	356,178	81,009	14,383	309,195	70,324
2009	883,033	0	44,152	0	359,705	81,812	14,510	311,913	70,942
2010	883,033	13,246	57,397	0	348,914	79,357	14,026	301,516	68,577
2011	883,033	26,491	70,643	0	338,123	76,903	13,542	291,119	66,212
2012	883,033	39,737	83,888	0	327,331	74,448	13,059	280,722	63,848
2013	883,033	52,982	97,134	0	316,540	71,994	12,575	270,325	61,483
2014	883,033	66,228	110,379	0	305,749	69,540	12,091	259,928	59,118
2015	891,863	93,646	129,320	0	290,641	66,104	11,398	245,025	55,729
2016	900,782	121,606	148,629	0	275,201	62,592	10,690	229,799	52,266
2017	909,790	150,115	168,311	0	259,423	59,003	9,966	214,243	48,728
2018	918,888	179,183	188,372	0	243,302	55,337	9,227	198,353	45,114
2019	928,076	208,817	208,817	0	226,832	51,591	8,472	182,124	41,423
Count				15	0	8	15	0	3

30	*Vehicle Units*	*FC Units*	*Hybrid Units*	*Petrol I3*	*Petrol I4*	*Petrol V6*	*Diesel I3*	*Diesel I4*	*Diesel V6*
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	13,246	57,397	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	26,491	70,643	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	39,737	83,888	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	52,982	97,134	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	66,228	110,379	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	93,646	129,320	0	167,119	38,010	16,934	364,038	82,797
2016	900,782	121,606	148,629	0	135,766	30,879	16,939	364,143	82,821
2017	909,790	150,115	168,311	0	103,769	23,601	16,943	364,213	82,837
2018	918,888	179,183	188,372	0	71,119	16,175	16,944	364,249	82,845
2019	928,076	208,817	208,817	0	37,805	8,598	16,944	364,249	82,845
Count				15	4	12	15	0	0

31	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	352,250	80,116	13,703	294,563	66,996
2006	832,102	0	16,642	0	362,685	82,489	13,521	290,657	66,107
2007	848,744	0	25,462	0	373,396	84,925	13,326	286,477	65,157
2008	865,718	0	34,629	0	384,390	87,426	13,119	282,013	64,141
2009	883,033	0	44,152	0	395,675	89,993	12,897	277,256	63,059
2010	883,033	13,246	57,397	0	399,272	90,811	11,769	252,996	57,542
2011	883,033	26,491	70,643	0	402,869	91,629	10,640	228,736	52,024
2012	883,033	39,737	83,888	0	406,466	92,447	9,512	204,477	46,506
2013	883,033	52,982	97,134	0	410,064	93,265	8,383	180,217	40,989
2014	883,033	66,228	110,379	0	413,661	94,083	7,255	155,957	35,471
2015	891,863	93,646	129,320	0	414,164	94,198	5,862	126,013	28,660
2016	900,782	121,606	148,629	0	414,636	94,305	4,440	95,455	21,710
2017	909,790	150,115	168,311	0	415,077	94,405	2,990	64,273	14,618
2018	918,888	179,183	188,372	0	415,484	94,498	1,510	32,458	7,382
2019	928,076	208,817	208,817	0	415,859	94,583	0	0	0
Count				15	0	0	15	4	8

32	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	13,246	57,397	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	26,491	70,643	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	39,737	83,888	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	52,982	97,134	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	66,228	110,379	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	93,646	129,320	0	196,183	44,620	15,632	336,035	76,428
2016	900,782	121,606	148,629	0	194,476	44,232	14,308	307,577	69,955
2017	909,790	150,115	168,311	0	192,714	43,831	12,956	278,516	63,346
2018	918,888	179,183	188,372	0	190,898	43,418	11,576	248,843	56,597
2019	928,076	208,817	208,817	0	189,027	42,992	10,167	218,549	49,707
Count				15	0	12	15	0	1

33	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	345,604	78,604	14,000	300,967	68,452
2006	832,102	0	16,642	0	349,127	79,406	14,128	303,720	69,078
2007	848,744	0	25,462	0	352,652	80,207	14,256	306,464	69,702
2008	865,718	0	34,629	0	356,178	81,009	14,383	309,195	70,324
2009	883,033	0	44,152	0	359,705	81,812	14,510	311,913	70,942
2010	883,033	13,246	57,397	0	348,914	79,357	14,026	301,516	68,577
2011	883,033	26,491	70,643	0	338,123	76,903	13,542	291,119	66,212
2012	883,033	39,737	83,888	0	327,331	74,448	13,059	280,722	63,848
2013	883,033	52,982	97,134	0	316,540	71,994	12,575	270,325	61,483
2014	883,033	66,228	110,379	0	305,749	69,540	12,091	259,928	59,118
2015	891,863	107,024	115,942	0	290,641	66,104	11,398	245,025	55,729
2016	900,782	148,629	121,606	0	275,201	62,592	10,690	229,799	52,266
2017	909,790	191,056	127,371	0	259,423	59,003	9,966	214,243	48,728
2018	918,888	234,316	133,239	0	243,302	55,337	9,227	198,353	45,114
2019	928,076	278,423	139,211	0	226,832	51,591	8,472	182,124	41,423
Count				15	0	8	15	0	3

34	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	13,246	57,397	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	26,491	70,643	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	39,737	83,888	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	52,982	97,134	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	66,228	110,379	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	107,024	115,942	0	167,119	38,010	16,934	364,038	82,797
2016	900,782	148,629	121,606	0	135,766	30,879	16,939	364,143	82,821
2017	909,790	191,056	127,371	0	103,769	23,601	16,943	364,213	82,837
2018	918,888	234,316	133,239	0	71,119	16,175	16,944	364,249	82,845
2019	928,076	278,423	139,211	0	37,805	8,598	16,944	364,249	82,845
Count				15	4	12	15	0	0

35	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	352,250	80,116	13,703	294,563	66,996
2006	832,102	0	16,642	0	362,685	82,489	13,521	290,657	66,107
2007	848,744	0	25,462	0	373,396	84,925	13,326	286,477	65,157
2008	865,718	0	34,629	0	384,390	87,426	13,119	282,013	64,141
2009	883,033	0	44,152	0	395,675	89,993	12,897	277,256	63,059
2010	883,033	13,246	57,397	0	399,272	90,811	11,769	252,996	57,542
2011	883,033	26,491	70,643	0	402,869	91,629	10,640	228,736	52,024
2012	883,033	39,737	83,888	0	406,466	92,447	9,512	204,477	46,506
2013	883,033	52,982	97,134	0	410,064	93,265	8,383	180,217	40,989
2014	883,033	66,228	110,379	0	413,661	94,083	7,255	155,957	35,471
2015	891,863	107,024	115,942	0	414,164	94,198	5,862	126,013	28,660
2016	900,782	148,629	121,606	0	414,636	94,305	4,440	95,455	21,710
2017	909,790	191,056	127,371	0	415,077	94,405	2,990	64,273	14,618
2018	918,888	234,316	133,239	0	415,484	94,498	1,510	32,458	7,382
2019	928,076	278,423	139,211	0	415,859	94,583	0	0	0
Count				15	0	0	15	4	8

36	Vehicle Units	FC Units	Hybrid Units	Petrol I3	Petrol I4	Petrol V6	Diesel I3	Diesel I4	Diesel V6
2004	799,790	0	0	0	342,086	77,804	13,872	298,204	67,824
2005	815,786	0	8,158	0	338,958	77,093	14,298	307,370	69,909
2006	832,102	0	16,642	0	335,568	76,322	14,736	316,784	72,049
2007	848,744	0	25,462	0	331,908	75,489	15,186	326,450	74,248
2008	865,718	0	34,629	0	327,966	74,593	15,648	336,377	76,506
2009	883,033	0	44,152	0	323,734	73,630	16,122	346,570	78,824
2010	883,033	13,246	57,397	0	298,555	67,904	16,283	350,036	79,612
2011	883,033	26,491	70,643	0	273,376	62,177	16,444	353,502	80,401
2012	883,033	39,737	83,888	0	248,196	56,450	16,605	356,967	81,189
2013	883,033	52,982	97,134	0	223,017	50,723	16,767	360,433	81,977
2014	883,033	66,228	110,379	0	197,838	44,996	16,928	363,899	82,765
2015	891,863	107,024	115,942	0	196,183	44,620	15,632	336,035	76,428
2016	900,782	148,629	121,606	0	194,476	44,232	14,308	307,577	69,955
2017	909,790	191,056	127,371	0	192,714	43,831	12,956	278,516	63,346
2018	918,888	234,316	133,239	0	190,898	43,418	11,576	248,843	56,597
2019	928,076	278,423	139,211	0	189,027	42,992	10,167	218,549	49,707
Count				15	0	12	16	0	1

APPENDIX J

INVESTMENT MODEL

Table J.1 Estimated initial investment requirements for I4-Petrol engines DTL based systems and "equivalent" investments in Q'@gile based systems.

Scenario	Maximum Demand	Required DTL Capacity	Required Q'@gile Cells	Required Gantry Robots	Q'@gile Total Investment	DTL initial Investment (CASE 3)	DTL initial Investment (CASE 2)	DTL initial Investment (CASE 1)
1	396,956	441,812	**36**	5	31,300,000	17,885,714	20,866,667	25,040,000
2	342,348	381,033	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
3	585,983	652,199	**53**	7	45,900,000	26,228,571	30,600,000	36,720,000
4	359,151	399,735	**33**	5	28,900,000	16,514,286	19,266,667	23,120,000
5	359,705	400,352	**33**	5	28,900,000	16,514,286	19,266,667	23,120,000
6	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
7	491,469	547,005	**45**	6	39,000,000	22,285,714	26,000,000	31,200,000
8	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
9	377,690	420,369	**34**	5	29,700,000	16,971,429	19,800,000	23,760,000
10	342,348	381,033	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
11	491,469	547,005	**45**	6	39,000,000	22,285,714	26,000,000	31,200,000
12	342,348	381,033	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
13	359,705	400,352	**33**	5	28,900,000	16,514,286	19,266,667	23,120,000
14	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
15	434,761	483,889	**39**	5	33,700,000	19,257,143	22,466,667	26,960,000
16	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
17	359,705	400,352	**33**	5	28,900,000	16,514,286	19,266,667	23,120,000
18	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
19	453,664	504,928	**41**	6	35,800,000	20,457,143	23,866,667	28,640,000
20	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
21	359,705	400,352	**33**	5	28,900,000	16,514,286	19,266,667	23,120,000
22	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
23	472,567	525,967	**43**	6	37,400,000	21,371,429	24,933,333	29,920,000
24	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
25	377,690	420,369	**34**	5	29,700,000	16,971,429	19,800,000	23,760,000
26	342,348	381,033	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
27	472,567	525,967	**43**	6	37,400,000	21,371,429	24,933,333	29,920,000
28	342,348	381,033	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
29	359,705	400,352	**33**	5	28,900,000	16,514,286	19,266,667	23,120,000
30	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
31	415,859	462,851	**38**	5	32,900,000	18,800,000	21,933,333	26,320,000
32	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
33	359,705	400,352	**33**	5	28,900,000	16,514,286	19,266,667	23,120,000
34	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000
35	415,859	462,851	**38**	5	32,900,000	18,800,000	21,933,333	26,320,000
36	342,086	380,742	**31**	4	26,800,000	15,314,286	17,866,667	21,440,000

Table J.2 Estimated initial investment requirements for I4-Diesel engines DTL based systems and "equivalent" investments in Q'@gile based systems.

Scenario	Maximum Demand	Required DTL Capacity	Required Q'@gile Cells	Required Gantry Robots	Q'@gile Total nvestment	DTL initial Investment (CASE 3)	DTL initial Investment (CASE 2)	DTL initial Investment (CASE 1)
1	346,037	385,139	32	4	27,600,000	15,771,429	18,400,000	22,080,000
2	528,161	587,843	48	6	41,400,000	23,657,143	27,600,000	33,120,000
3	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
4	433,213	482,166	39	5	33,700,000	19,257,143	22,466,667	26,960,000
5	311,913	347,159	28	4	24,400,000	13,942,857	16,266,667	19,520,000
6	437,099	486,491	40	5	34,500,000	19,714,286	23,000,000	27,600,000
7	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
8	381,227	424,306	35	5	30,500,000	17,428,571	20,333,333	24,400,000
9	329,242	366,446	30	4	26,000,000	14,857,143	17,333,333	20,800,000
10	437,099	486,491	40	5	34,500,000	19,714,286	23,000,000	27,600,000
11	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
12	398,556	443,593	36	5	31,300,000	17,885,714	20,866,667	25,040,000
13	311,913	347,159	28	4	24,400,000	13,942,857	16,266,667	19,520,000
14	382,461	425,679	35	5	30,500,000	17,428,571	20,333,333	24,400,000
15	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
16	363,899	405,020	33	5	28,900,000	16,514,286	19,266,667	23,120,000
17	311,913	347,159	28	4	24,400,000	13,942,857	16,266,667	19,520,000
18	400,674	445,950	36	5	31,300,000	17,885,714	20,866,667	25,040,000
19	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
20	363,899	405,020	33	5	28,900,000	16,514,286	19,266,667	23,120,000
21	311,913	347,159	28	4	24,400,000	13,942,857	16,266,667	19,520,000
22	418,886	466,220	38	5	32,900,000	18,800,000	21,933,333	26,320,000
23	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
24	381,227	424,306	35	5	30,500,000	17,428,571	20,333,333	24,400,000
25	329,242	366,446	30	4	26,000,000	14,857,143	17,333,333	20,800,000
26	418,886	466,220	38	5	32,900,000	18,800,000	21,933,333	26,320,000
27	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
28	398,556	443,593	36	5	31,300,000	17,885,714	20,866,667	25,040,000
29	311,913	347,159	28	4	24,400,000	13,942,857	16,266,667	19,520,000
30	364,249	405,409	33	5	28,900,000	16,514,286	19,266,667	23,120,000
31	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
32	363,899	405,020	33	5	28,900,000	16,514,286	19,266,667	23,120,000
33	311,913	347,159	28	4	24,400,000	13,942,857	16,266,667	19,520,000
34	364,249	405,409	33	5	28,900,000	16,514,286	19,266,667	23,120,000
35	298,204	331,901	27	4	23,600,000	13,485,714	15,733,333	18,880,000
36	363,899	405,020	33	5	28,900,000	16,514,286	19,266,667	23,120,000

Table J.3 Estimated initial investment requirements for V6-Petrol engines DTL based systems and "equivalent" investments in Q'@gile based systems.

Scenario	Maximum Demand	Required DTL Capacity	Required Q'@gile Cells	Required Gantry Robots	Q'@gile Total Investment	DTL initial Investment (Case 3)	DTL initial Investment (Case 2)	DTL initial Investment (Case 1)
1	90,284	100,486	17	3	15,100,000	8,628,571	10,066,667	12,080,000
2	77,864	86,663	14	2	12,200,000	6,971,429	8,133,333	9,760,000
3	133,276	148,336	24	3	20,700,000	11,828,571	13,800,000	16,560,000
4	81,686	90,917	15	2	13,000,000	7,428,571	8,666,667	10,400,000
5	81,812	91,057	15	2	13,000,000	7,428,571	8,666,667	10,400,000
6	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
7	111,780	124,411	21	3	18,300,000	10,457,143	12,200,000	14,640,000
8	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
9	85,902	95,609	16	2	13,800,000	7,885,714	9,200,000	11,040,000
10	77,864	86,663	14	2	12,200,000	6,971,429	8,133,333	9,760,000
11	111,780	124,411	21	3	18,300,000	10,457,143	12,200,000	14,640,000
12	77,864	86,663	14	2	12,200,000	6,971,429	8,133,333	9,760,000
13	81,812	91,057	15	2	13,000,000	7,428,571	8,666,667	10,400,000
14	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
15	98,882	110,056	18	3	15,900,000	9,085,714	10,600,000	12,720,000
16	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
17	81,812	91,057	15	2	13,000,000	7,428,571	8,666,667	10,400,000
18	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
19	103,182	114,842	19	3	16,700,000	9,542,857	11,133,333	13,360,000
20	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
21	81,812	91,057	15	2	13,000,000	7,428,571	8,666,667	10,400,000
22	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
23	107,481	119,626	20	3	17,500,000	10,000,000	11,666,667	14,000,000
24	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
25	85,902	95,609	16	2	13,800,000	7,885,714	9,200,000	11,040,000
26	77,864	86,663	14	2	12,200,000	6,971,429	8,133,333	9,760,000
27	107,481	119,626	20	3	17,500,000	10,000,000	11,666,667	14,000,000
28	77,864	86,663	14	2	12,200,000	6,971,429	8,133,333	9,760,000
29	81,812	91,057	15	2	13,000,000	7,428,571	8,666,667	10,400,000
30	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
31	94,583	105,271	17	3	15,100,000	8,628,571	10,066,667	12,080,000
32	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
33	81,812	91,057	15	2	13,000,000	7,428,571	8,666,667	10,400,000
34	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000
35	94,583	105,271	17	3	15,100,000	8,628,571	10,066,667	12,080,000
36	77,804	86,596	14	2	12,200,000	6,971,429	8,133,333	9,760,000

Table J.4 Estimated initial investment requirements for V6-Diesel engines DTL based systems and "equivalent" investments in Q'@gile based systems.

Scenario	Maximum Demand	Required DTL Capacity	Required Q'@gile Cells	Required Gantry Robots	Q'@gile Total Investment	DTL initial Investment (Case 3)	DTL initial Investment (Case 2)	DTL initial Investment (Case 1)
1	78,703	87,596	15	2	13,000,000	7,428,571	8,666,667	10,400,000
2	120,125	133,699	22	3	19,100,000	10,914,286	12,733,333	15,280,000
3	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
4	98,530	109,664	18	3	15,900,000	9,085,714	10,600,000	12,720,000
5	70,942	78,958	13	2	11,400,000	6,514,286	7,600,000	9,120,000
6	99,414	110,648	18	3	15,900,000	9,085,714	10,600,000	12,720,000
7	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
8	86,707	96,505	16	2	13,800,000	7,885,714	9,200,000	11,040,000
9	74,883	83,345	14	2	12,200,000	6,971,429	8,133,333	9,760,000
10	99,414	110,648	18	3	15,900,000	9,085,714	10,600,000	12,720,000
11	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
12	90,648	100,891	17	3	15,100,000	8,628,571	10,066,667	12,080,000
13	70,942	78,958	13	2	11,400,000	6,514,286	7,600,000	9,120,000
14	86,987	96,817	16	2	13,800,000	7,885,714	9,200,000	11,040,000
15	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
16	82,765	92,117	15	2	13,000,000	7,428,571	8,666,667	10,400,000
17	70,942	78,958	13	2	11,400,000	6,514,286	7,600,000	9,120,000
18	91,130	101,428	17	3	15,100,000	8,628,571	10,066,667	12,080,000
19	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
20	82,765	92,117	15	2	13,000,000	7,428,571	8,666,667	10,400,000
21	70,942	78,958	13	2	11,400,000	6,514,286	7,600,000	9,120,000
22	95,272	106,038	18	3	15,900,000	9,085,714	10,600,000	12,720,000
23	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
24	86,707	96,505	16	2	13,800,000	7,885,714	9,200,000	11,040,000
25	74,883	83,345	14	2	12,200,000	6,971,429	8,133,333	9,760,000
26	95,272	106,038	18	3	15,900,000	9,085,714	10,600,000	12,720,000
27	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
28	90,648	100,891	17	3	15,100,000	8,628,571	10,066,667	12,080,000
29	70,942	78,958	13	2	11,400,000	6,514,286	7,600,000	9,120,000
30	82,845	92,206	15	2	13,000,000	7,428,571	8,666,667	10,400,000
31	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
32	82,765	92,117	15	2	13,000,000	7,428,571	8,666,667	10,400,000
33	70,942	78,958	13	2	11,400,000	6,514,286	7,600,000	9,120,000
34	82,845	92,206	15	2	13,000,000	7,428,571	8,666,667	10,400,000
35	67,824	75,488	13	2	11,400,000	6,514,286	7,600,000	9,120,000
36	82,765	92,117	15	2	13,000,000	7,428,571	8,666,667	10,400,000

Table J.5 NPV of DTL based systems for I4-petrol, I4-diesel, V6-Petrol and V6-Diesel engine blocks over the 36 scenarios.

Case 3

Scenario	NPV DTL I4-Petrol	NPV DTL I4-Diesel	NPV DTL V6-Petrol	NPV DTL V6-Diesel
1	21,211,350	18,703,938	10,232,952	8,809,826
2	18,161,795	28,055,907	8,267,683	12,943,667
3	31,105,462	15,993,222	14,027,953	7,725,540
4	19,584,920	22,837,779	8,809,826	10,775,095
5	19,584,920	16,535,365	8,809,826	7,725,540
6	18,161,795	23,379,922	8,267,683	10,775,095
7	26,429,477	15,993,222	12,401,524	7,725,540
8	18,161,795	20,669,207	8,267,683	9,351,969
9	20,127,064	17,619,652	9,351,969	8,267,683
10	18,161,795	23,379,922	8,267,683	10,775,095
11	26,429,477	15,993,222	12,401,524	7,725,540
12	18,161,795	21,211,350	8,267,683	10,232,952
13	19,584,920	16,535,365	8,809,826	7,725,540
14	18,161,795	20,669,207	8,267,683	9,351,969
15	22,837,779	15,993,222	10,775,095	7,725,540
16	18,161,795	19,584,920	8,267,683	8,809,826
17	19,584,920	16,535,365	8,809,826	7,725,540
18	18,161,795	21,211,350	8,267,683	10,232,952
19	24,260,905	15,993,222	11,317,238	7,725,540
20	18,161,795	19,584,920	8,267,683	8,809,826
21	19,584,920	16,535,365	8,809,826	7,725,540
22	18,161,795	22,295,636	8,267,683	10,775,095
23	25,345,191	15,993,222	11,859,381	7,725,540
24	18,161,795	20,669,207	8,267,683	9,351,969
25	20,127,064	17,619,652	9,351,969	8,267,683
26	18,161,795	22,295,636	8,267,683	10,775,095
27	25,345,191	15,993,222	11,859,381	7,725,540
28	18,161,795	21,211,350	8,267,683	10,232,952
29	19,584,920	16,535,365	8,809,826	7,725,540
30	18,161,795	19,584,920	8,267,683	8,809,826
31	22,295,636	15,993,222	10,232,952	7,725,540
32	18,161,795	19,584,920	8,267,683	8,809,826
33	19,584,920	16,535,365	8,809,826	7,725,540
34	18,161,795	19,584,920	8,267,683	8,809,826
35	22,295,636	15,993,222	10,232,952	7,725,540
36	18,161,795	19,584,920	8,267,683	8,809,826

Case 2

Scenario	NPV DTL I4-Petrol	NPV DTL I4-Diesel	NPV DTL V6-Petrol	NPV DTL V6-Diesel
1	24,746,575	21,821,261	11,938,443	10,278,130
2	21,188,761	32,731,891	9,645,630	15,100,945
3	36,289,706	18,658,759	16,365,946	9,013,129
4	22,849,074	26,644,076	10,278,130	12,570,944
5	22,849,074	19,291,260	10,278,130	9,013,129
6	21,188,761	27,276,576	9,645,630	12,570,944
7	30,834,390	18,658,759	14,468,445	9,013,129
8	21,188,761	24,114,075	9,645,630	10,910,630
9	23,481,574	20,556,260	10,910,630	9,645,630
10	21,188,761	27,276,576	9,645,630	12,570,944
11	30,834,390	18,658,759	14,468,445	9,013,129
12	21,188,761	24,746,575	9,645,630	11,938,443
13	22,849,074	19,291,260	10,278,130	9,013,129
14	21,188,761	24,114,075	9,645,630	10,910,630
15	26,644,076	18,658,759	12,570,944	9,013,129
16	21,188,761	22,849,074	9,645,630	10,278,130
17	22,849,074	19,291,260	10,278,130	9,013,129
18	21,188,761	24,746,575	9,645,630	11,938,443
19	28,304,389	18,658,759	13,203,444	9,013,129
20	21,188,761	22,849,074	9,645,630	10,278,130
21	22,849,074	19,291,260	10,278,130	9,013,129
22	21,188,761	26,011,575	9,645,630	12,570,944
23	29,569,390	18,658,759	13,835,944	9,013,129
24	21,188,761	24,114,075	9,645,630	10,910,630
25	23,481,574	20,556,260	10,910,630	9,645,630
26	21,188,761	26,011,575	9,645,630	12,570,944
27	29,569,390	18,658,759	13,835,944	9,013,129
28	21,188,761	24,746,575	9,645,630	11,938,443
29	22,849,074	19,291,260	10,278,130	9,013,129
30	21,188,761	22,849,074	9,645,630	10,278,130
31	26,011,575	18,658,759	11,938,443	9,013,129
32	21,188,761	22,849,074	9,645,630	10,278,130
33	22,849,074	19,291,260	10,278,130	9,013,129
34	21,188,761	22,849,074	9,645,630	10,278,130
35	26,011,575	18,658,759	11,938,443	9,013,129
36	21,188,761	22,849,074	9,645,630	10,278,130

Case 1

Scenario	NPV DTL I4-Petrol	NPV DTL I4-Diesel	NPV DTL V6-Petrol	NPV DTL V6-Diesel
1	29,695,890	26,185,513	14,326,132	12,333,756
2	25,426,513	39,278,270	11,574,756	18,121,134
3	43,547,647	22,390,511	19,639,135	10,815,755
4	27,418,889	31,972,891	12,333,756	15,085,133
5	27,418,889	23,149,512	12,333,756	10,815,755
6	25,426,513	32,731,891	11,574,756	15,085,133
7	37,001,268	22,390,511	17,362,134	10,815,755
8	25,426,513	28,936,889	11,574,756	13,092,757
9	28,177,889	24,667,512	13,092,757	11,574,756
10	25,426,513	32,731,891	11,574,756	15,085,133
11	37,001,268	22,390,511	17,362,134	10,815,755
12	25,426,513	29,695,890	11,574,756	14,326,132
13	27,418,889	23,149,512	12,333,756	10,815,755
14	25,426,513	28,936,889	11,574,756	13,092,757
15	31,972,891	22,390,511	15,085,133	10,815,755
16	25,426,513	27,418,889	11,574,756	12,333,756
17	27,418,889	23,149,512	12,333,756	10,815,755
18	25,426,513	29,695,890	11,574,756	14,326,132
19	33,965,267	22,390,511	15,844,133	10,815,755
20	25,426,513	27,418,889	11,574,756	12,333,756
21	27,418,889	23,149,512	12,333,756	10,815,755
22	25,426,513	31,213,891	11,574,756	15,085,133
23	35,483,268	22,390,511	16,603,133	10,815,755
24	25,426,513	28,936,889	11,574,756	13,092,757
25	28,177,889	24,667,512	13,092,757	11,574,756
26	25,426,513	31,213,891	11,574,756	15,085,133
27	35,483,268	22,390,511	16,603,133	10,815,755
28	25,426,513	29,695,890	11,574,756	14,326,132
29	27,418,889	23,149,512	12,333,756	10,815,755
30	25,426,513	27,418,889	11,574,756	12,333,756
31	31,213,891	22,390,511	14,326,132	10,815,755
32	25,426,513	27,418,889	11,574,756	12,333,756
33	27,418,889	23,149,512	12,333,756	10,815,755
34	25,426,513	27,418,889	11,574,756	12,333,756
35	31,213,891	22,390,511	14,326,132	10,815,755
36	25,426,513	27,418,889	11,574,756	12,333,756

Table J.6 NPV of Q'@gile based systems for I4-petrol, I4-diesel, V6-Petrol and V6-Diesel engine blocks over the 36 scenarios.

Scenario	NPV Q'@gile I4-Petrol	NPV Q'@gile I4-Diesel	NPV Q'@gile V6-Petrol	NPV Q'@gile V6-Diesel
1	28,253,964	24,651,894	13,136,191	11,483,366
2	21,655,009	31,007,883	10,203,512	14,400,925
3	34,852,240	18,379,971	16,195,288	8,818,865
4	24,211,880	28,618,264	11,196,406	13,371,310
5	24,895,633	21,562,202	11,675,674	10,158,338
6	18,502,660	28,014,859	8,721,248	12,902,397
7	31,545,866	15,323,893	14,842,227	7,212,674
8	20,968,718	25,542,247	9,861,645	11,762,000
9	25,786,756	22,371,711	12,017,448	10,548,545
10	19,099,464	28,692,484	8,955,791	13,354,039
11	32,489,143	16,001,714	15,209,557	7,620,631
12	21,591,738	26,366,975	10,203,969	12,126,950
13	23,651,850	20,348,976	11,131,101	9,660,995
14	17,028,927	26,654,568	8,129,232	12,260,121
15	30,126,271	13,983,641	14,178,559	6,761,496
16	19,611,671	24,183,240	9,458,899	11,155,812
17	23,866,475	20,590,160	11,190,086	9,719,979
18	17,354,967	26,941,459	8,409,569	12,509,183
19	30,459,525	14,224,824	14,300,968	6,883,905
20	19,903,001	24,397,865	9,581,308	11,386,002
21	24,602,019	21,240,258	11,503,118	10,044,767
22	18,202,492	27,612,113	8,409,569	12,843,412
23	31,304,683	14,993,414	14,614,321	7,212,674
24	20,688,381	25,248,633	9,802,660	11,654,219
25	25,493,142	22,106,927	11,898,673	10,429,770
26	18,858,281	28,398,869	8,892,367	13,239,704
27	32,138,828	15,673,518	15,038,351	7,620,631
28	21,302,563	25,981,608	10,037,203	12,126,950
29	23,264,658	20,009,655	10,903,195	9,452,433
30	16,737,597	26,360,954	8,006,823	12,029,931
31	29,948,511	13,591,402	13,898,222	6,550,651
32	19,318,056	23,889,626	9,084,840	11,092,388
33	23,264,658	20,009,655	10,903,195	9,452,433
34	16,737,597	26,360,954	8,006,823	12,029,931
35	29,948,511	13,591,402	13,898,222	6,550,651
36	19,318,056	23,889,626	9,084,840	11,092,388