Environmental legislation as a driver of design

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ENVIRONMENTAL LEGISLATION AS A DRIVER OF DESIGN

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Abstract

Around the world there is an increasing tend to introduce regulations concerning the environmental impact of products. In the automotive industry legislation has concentrated on exhaust emissions. Initially on-highway applications were regulated, but now attention has spread to include off-highway vehicles. This paper examines the impact of legislation on diesel engine manufacturers. They have had to adapt dramatically their research, design and development processes in order to survive in the current fast paced competitive environment.

Keywords: environmental legislation, design planning

1 Introduction

The environmental impact of products and industrial practices has become a major design issue over the past few decades. There is an increased awareness of mankind's impact upon the Earth. Through a combination of public pressure and an increasing trend for individual governments (e.g. the USA and Japan) and inter-governmental bodies (e.g. the United Nations and the European Union) to legislate, companies are being forced to consider the full environmental impact effect of their products. These issues have been grouped together under the banner of Design For Environment (DFE), which is a branch of Design For X [1, 2].

One of the key environmental design steps is to carry out a lifecycle assessment. Along with the recycling of materials, reuse of products and remanufacture are key issues. Many guidelines have been published and can be thought of as subsets of DFE: e.g. design for energy efficiency, design for disassembly and design to minimise material usage [3].

In many industries legislation has had a much greater impact than merely to make firms consider how to dispose of their products in an environmentally responsible manner. The introduction of laws has caused fundamental changes to businesses and markets, especially to the product development process. Although a great deal of literature has been published on techniques for DFE and the environmental impact of various products, little is known of that describes how the introduction of legislation has affected the planning of product design and development. The purpose of this paper is to address this issue by highlighting how environmental regulations have caused radical changes in one particular industry – 'off-highway' diesel engine manufacture.

2 Background

Up until the late 1980s there was very little technological change in the diesel engine market [4]. Advances were made in materials and manufacturing techniques, but no radical step changes occurred. As an example of this, engines designed in the 1960s were still being made and sold, with a few minor modifications, 25 years later. The marketplace was characterised by stable product lines that met consistent customer demand. There were many independent manufacturers and companies launched new or upgraded engines when they saw fit. Since the introduction of laws governing exhaust emissions there has been a huge amount of change within the industry. There is now a massive amount of regulation in force that engine manufacturers must be aware of. This section briefly covers the key legislative points.

2.1 Exhaust emissions legislation

The first example of legislation to regulate engine exhaust emissions was introduced in California in 1959. This effort was aimed at hydrocarbon and carbon monoxide emissions from gasoline powered passenger cars. Since then laws have been introduced by many different regulatory bodies in a number of countries [5].

Each piece of legislation usually specifies limit values for various exhaust elements and the test procedures that are to be used to characterise the engine's emissions performance. Emissions test cycles consist of a series of speed and load conditions at which the engine is operated and the exhaust analysed. Test cycles are often defined to emulate the actual operating duty of the engine for the particular application class to which it would typically be applied [6]. The exhaust elements that are typically regulated for are: *Particulate Matter* (PM), *Nitrogen Oxides* (NO_x) – comprising of NO and NO_2, but no other oxides of nitrogen, *Hydrocarbons* (HC), *Carbon Monoxide* (CO) and *smoke*.

2.2 Categories of legislation

Regulations controlling exhaust emissions are generally specific to application class rather than to engine type. This is due to the different sorts of internal combustion engine on offer (e.g. spark ignition - SI, compression ignition - CI) and the variety of roles in they are used. The legislation can be split into two main categories: on-highway and off-highway. To date the trend has been to introduce laws first to on-highway applications and then, several years later, implement them in the off-highway sector.

Since the early 1960s, the US Environmental Protection Agency (EPA), European Union (EU) and Japan have lead the way in introducing emission control legislation for on-highway motor vehicles. Where laws governing vehicle emissions exist in other countries they tends to adopt US, European or Japanese standards and test methods.

Off highway engine applications (also termed off-road) – can be split into five categories: Non Road Mobile Machinery (NRMM), Marine, Locomotive, Stationary and Mining Engines. Of these, by far the most important category is the first, NRMM, which covers the majority of applications and engines. The term NRMM covers a wide range of vehicles, for example agricultural tractors, materials handling and construction equipment.

2.3 Non Road Mobile Machinery legislation

Regulation to control the exhaust emissions from Non-Road Mobile Machinery was developed by the USA and the European Commission in collaboration with Japan. This resulted in regulations for NRMM emissions, which are standardised with respect to the major provisions such as test cycles and limit values. Two waves of regulation were defined in the first phase of developing emissions controls. These are known as Tier 1 and Tier 2 in EPA terminology or Stage 1 and Stage 2 by the EU. The introduction dates were phased relative to engine power categories (the highest power output being regulated first). Table 1, which shows the introduction dates for Tier 2 and estimated data for Tier 3.

Industry associations were involved in the consultative process and ensured that the regulators were aware of the importance of world-wide harmonisation. The International Standards Organisation (ISO) also played an important role by developing a standard for emissions testing non-road engines (ISO 8178) [7], which forms the basis for testing procedures included in the legislation. The process of compiling regulations for Tier 3 is currently underway. A fourth stage of regulation is expected in the next decade.

Table 1. Introduction dates and emissions levels for Tier 2 and Tier 3 (? = estimates – discussions ongoing)

Power Band kW	**Tier 2**			**Tier 3**		
	Date	NO_X & HC g/kW hr	PM g/kW hr	Date	NO_X & HC g/kW hr	PM g/kW hr
< 8	2005	7.5	0.8	2009?	5.0?	0.3?
8 – 19	2005	7.5	0.8	2009?	5.0?	0.3?
19 – 37	2004	7.5	0.6	2008?	4.7?	0.17?
37 – 75	2004	7.5	0.4	2008	4.7	0.13?
75 – 130	2003	6.6	0.3	2007	4.0	0.13?
130 – 225	2003	6.6	0.2	2006	4.0	0.13?

Achievement of what is effectively a world-wide standard for the first two phases of NRMM emissions control provides significant benefits for engine and equipment manufacturers. Such an EU-US- Japanese alignment does not exist with on-highway vehicle regulations. This is due in part to historic reasons, but also the different nature of the vehicles traditionally used on-highway in the EU and US allied to the volumes of product supplied into each territory has meant that the imperative for standardised legislation has not been so pressing. In the case of NRMM, the regulators recognised the needs for harmonised laws: often the same non-road machine models are offered in the EU, US, Japan and other territories. The cost of engineering and providing specific machines for individual territories, especially considering the diversity and relatively low volumes, would place a large cost burden on industry and consumers.

It is important to note that both the EU and US regulations refer directly to the engine and not the whole machine. Therefore, the legislation regulates the supply of engines by the engine manufacturer. It is the responsibility of the engine manufacturer to ensure that when an engine is provided to a customer, it complies with all the requirements of the relevant regulations.

While the US and EU legislation for non-road diesel engine emissions is effectively harmonised with respect to test cycles, limit values and measurement, there are significant differences in some provisions within the respective regulations. In the USA emissions control started on 1st January 1996 [8] whereas in Europe it started 3 years later [9]. Initially in Europe, there were some exceptions, the most important of which concerned agricultural tractor engines. Exhaust emission control for such engines has since been introduced [10]. There are also differences with certification. In Europe a government appointed body must witness certification whereas in the USA self-certification is allowed. Although the USA does not witness type approval they put great emphasis on production compliance through audit of engine emissions and build procedures. The US EPA regulations also include details on tamper proofing. It is mandatory that engine settings (e.g. those on the fuel injection pump) cannot be easily changed by the operator. In Europe there are no such requirements although most manufacturers do take steps in this area. The concept of deterioration factors is also present in US legislation to verify that engine emissions will not increase beyond the limits at the end of the engines useful life. These do not exist in Europe.

Countries other than the USA and those in the EU intend to base their legislation on that of the USA or EU. This will prevent there being a proliferation of test procedures around the world. However most countries are still concentrating upon on-highway legislation before regulating NRMM. For example in South America there are presently no off-highway emissions control laws, but increasingly stringent on-highway regulations.

3 Case study details

The analysis presented in this paper draws primarily on a detailed case study, which was undertaken with Perkins Engines Company Limited in 2002, to understand the critical issues that affect the design process. Perkins' is a leading European based diesel engine manufacturer whose business is the design and manufacture of diesel engines covering the power output range 4kW – 1940kW (5.5– 2,600 bhp).

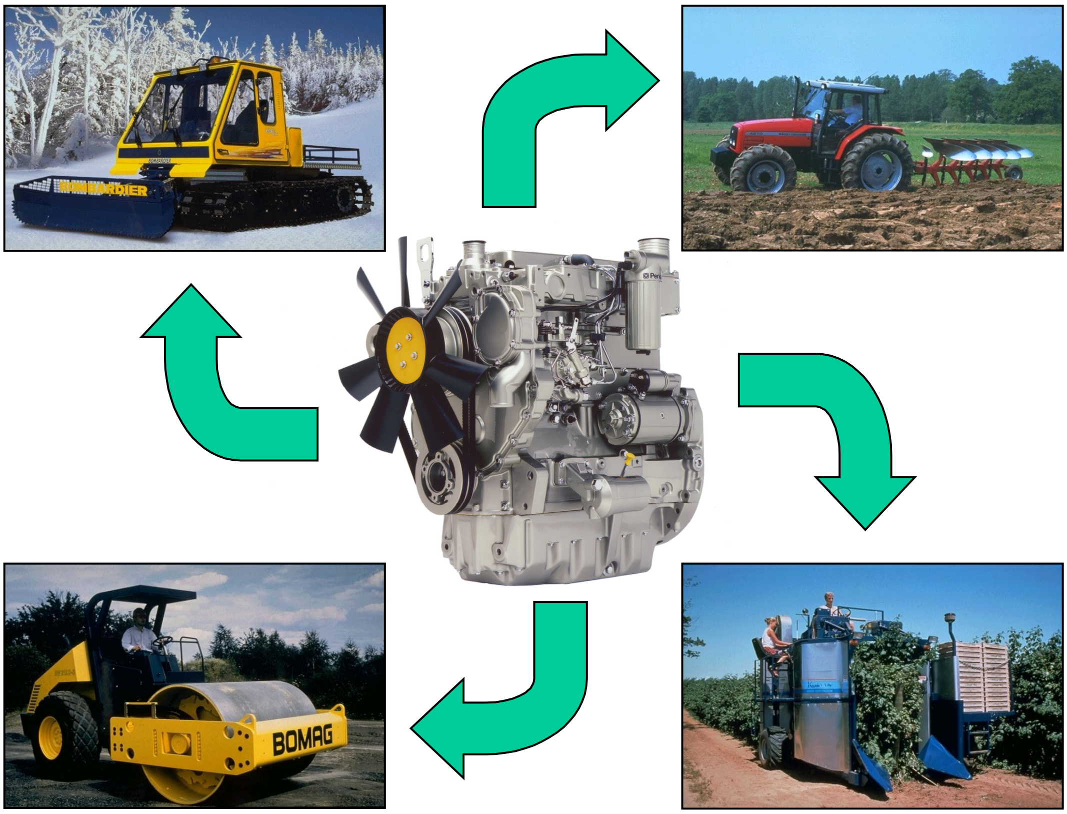

Figure 1. One engine can be used in many different NRMM applications

Perkins' engines power in excess of 5,000 applications for more than 1,000 customers. Most are Original Equipment Manufacturers (OEMs), which range from large concerns such as Caterpillar, Massey Fergusson and JCB that take delivery of thousands of engines, to small manufacturers of specialist equipment that produce well under 50 machines a year. This range is illustrated in Figure 1. Although many types of engines are produced, the main sales volume is provided by 4-cylinder engines of approximately 1 litre per cylinder capacity for the off-highway vehicle market.

3.1 Engineer interviews

As part of the study, 20 engineers were interviewed for between 45 minutes and 2 hours; the conversations were recorded and transcribed. The interviewees came from a wide range of roles and functions, which included project managers, strategic planners, manufacturing engineers, conceptual designers, detail designers and change process administrators.

During the interviews, repeated mention was made of how successive waves of environmental legislation had affected all aspects of the firm. Without exception, the interviewees described how the introduction of Tier 1 and Tier 2 emissions requirements had caused a huge change in the design and development process. In the past the research focus was on improving the torque curve, durability and fuel economy. Now, before any of those important issues can be addressed, a legal engine must be created. Many commented on the how the pace of development had increased dramatically over the past decade.

3.2 Engine programmes

Company data on several recent development projects was investigated and this reinforced the picture created from the interviews. Engines of approximately 1 litre per cylinder capacity that produce power between 40 kW – 180 kW (54 bhp – 240 bhp) were examined. These are produced in 3-, 4- and 6-cylinder types. When a new series is launched the 6-cylinder offering is released first followed by the 4- and 3- cylinder products as this fits the legislation introduction cycle.

Several ranges were examined as shown in Table 2. The first engines of this type were the 4.236 / 6.354 family. In legislative terms, these were unregulated. After many years of production, a new, improved range, 1000 Series, was launched in the mid-1980s, which also was unregulated. This is sometimes termed 'Tier 0'. With the introduction of the first wave of environmental regulation in the late 1990s, 1000 Series was redesigned, which resulted in 'New' 1000 Series. The past year has seen the launch of a new range, 1100 Series, to meet the demands of Tier 2 legislation. Conceptual design activities are now well underway for the next generation of engines that will meet Tier 3 requirements, which will be launched later this decade.

Table 2. 1 litre per cylinder engine ranges

Range	Legislation Level	Year of Introduction
4.236 / 6.354 Family	N/A	c.1963
1000 Series	N/A ('Tier 0')	c.1985
New 1000 Series	Tier 1	1996 / 1997
1100 Series	Tier 2	2002 / 2003
Under Development	Tier 3	2006 / 2007

4 Impact of environmental legislation

The impact of emissions regulation can be examined under three headings: production life, research and development, and marketing and supply.

4.1 Production life

The most obvious effect has been to reduce dramatically the manufacturing life span of engines. Due to legislation making the product illegal a new engine must be launched. Figure 2 compares the length of time in production for four recent 4-cylinder engines. The 4.236 engine was manufactured for approximately 30 years, which is five times as long as the 1104 engine will be made.

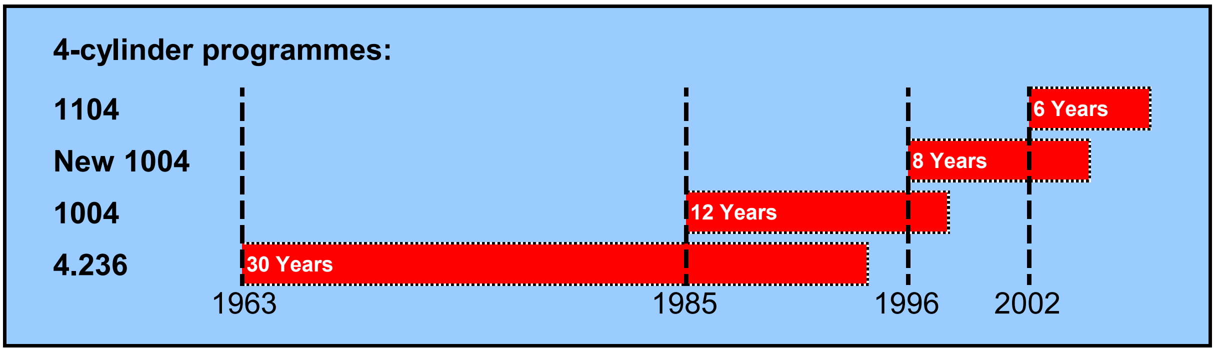

Figure 2. Comparison of recent 4-cylinder programmes

4.2 Research and Development

A critical result of the regulation is to synchronise the product development activities of all the major engine companies. Emissions compliant engines are launched within a few months of each other to meet the next round of regulation [11].

Before the introduction of environmental legislation, the development time for a single new engine was approximately seven years. The Tier 2 requirements will only be in place for five years before Tier 3 comes into effect. Thus, in order to avoid a situation where the design and development time is longer than the production period, the engine manufacturers have been forced to reduce their time to market. A whole engine series can now be created and launched within seven years.

Added to this reduction, the focus of research and development has been widened. As stated in section 3.1, designers in the past would concentrate upon improving the torque curve and engine durability. Now the design emphasis must be on meeting the emissions requirements; if they cannot be met, the company cannot sell engines. This is not to say that fuel economy, etc. are ignored, because making a compliant engine is not enough to ensure survival. As shall be discussed in section 4.3, factors such as reliability and product support are vital for sales.

With ever tightening emissions levels, a greater investment in research and development is needed. The amount of money invested in engine projects is growing with each successive generation of products. Figure 3 charts the annual spend and duration of recent 1 litre per cylinder engine development projects. The figures have been adjusted to take account of inflation and normalised for reasons of confidentiality. Tier 0 refers to the pre-legislation product, 1000 Series. Figure 3, clearly illustrates a number of key points.

- The peak annual spend on a project has risen dramatically. Estimates for the Tier 3 product show that the cost of the project at its height will be over 2.5 times that for Tier 0.
- The total amount spent on a project has significantly increased; the area under each curve shows this. Tier 1 cost approximately 60% more in real terms than Tier 0 and Tier 2 will be over 80% more expensive than Tier 1. The Tier 3 curve is a projection only, but it is expected that the peak annual spend will be greater than for Tier 2. However, engine

customers will be hoping to pay the same price for a Tier 3 product as they are spending currently on Tier 2.

- Projects now significantly overlap. There was almost a four year gap between the completion of the Tier 0 project and the start of design work for Tier 1. Preliminary work for the Tier 3 product commenced before the peak cost for Tier 2. This trend is expected to continue with the introduction of Tier 4 later this decade.

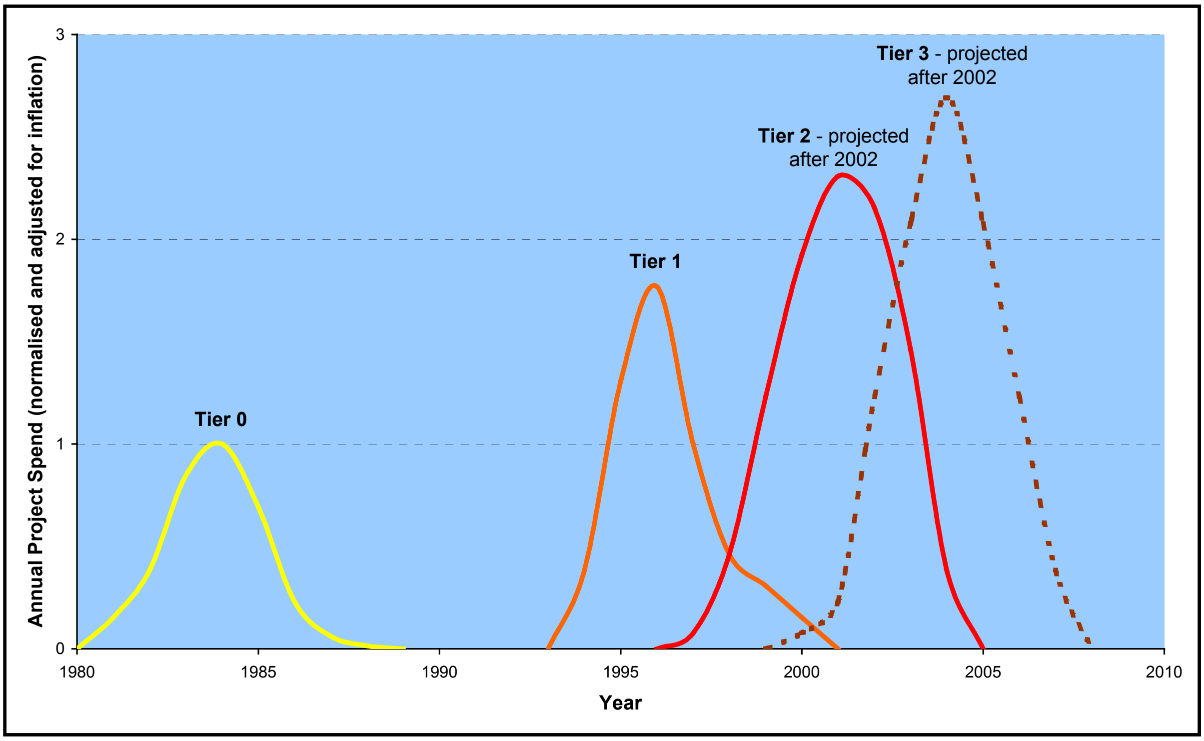

Figure 3. Annual spend of recent and future 1 litre per cylinder engine development projects

One of the reasons why project costs are rising is that the complexity of the product is increasing notably. Most of the 'easy' options were implemented to meet the requirements of Tier 1. The techniques used included improved inlet and exhaust ports, higher pressure fuel injection equipment and better piston-to-bore fit. Tier 2 has seen the nuances of combustion examined even more closely. This has resulted in an increase in the amount of electronics present within the engine: the 1100 Series engines contain complex engine control modules (ECM). Combined with improved fuel injection, this gives much greater control over combustion and thus reduced emissions. In product terms, legislation has seen manufacturing and build quality rise. The design of each part is being optimised much more closely – there is very little 'slack' within the product [12].

Along with greater spend per project, the introduction of environmental legislation has lead to an increased spend on capital costs to support R&D. The ever tightening regulations mean that more time must be spent running developmental engines and rig testing components. At Perkins a new suite of state-of-the-art test cells was recently opened to facilitate, amongst other things, more accurate analysis of emissions.

The dramatic increase in both project and capital costs has lead to most of the previously independent engine manufacturers becoming parts of larger industrial groupings. For example, Perkins is now part of Caterpillar Inc., USA. Organisational changes have also been witnessed. The focus is now on components and systems (e.g. fuel injection, electronics), with engineers gaining in-depth knowledge in particular fields.

4.3 Marketing and supply

The synchronisation of product development cycles and the need to clear the emissions 'hurdle' has turned diesel engines into commodity products. It is much harder for manufacturers to differentiate their product from that of their rivals as all engines must meet regulatory demands as a basic requirement. Gaining a significant technological advantage is difficult as the majority of design effort is aimed at making the engines emissions compliant.

Thus, the OEMs have much greater negotiating power than before. Customer relationships have become even more important than two decades ago. There is a clear need to create a strong, respected brand. With the 1100 Series, QFD techniques were used to identify systematically the critical needs of machine operators and OEMs around the world [13]. Focus groups held with leading customers coupled with independent research enabled four critical performance areas to be identified.

- **Productivity** – customers want a engine that maximises the efficiency of their machines. They also want to maximise the 'up-time' of their equipment. Therefore reliability and quality of the engine are also important.
- **Refinement** – aside from exhaust emissions that are covered by legislation, customers are concerned by subjective factors such as noise and smoke.
- **Cost of ownership** – low operating cost is becoming an increasingly more important issue. Fuel efficiency and service intervals are the key factors here.
- **Product support** – customers are taking a more holistic approach to engine choice. The quality of spare parts and after sales service is vital. Due to the large amounts of electronics now present, the vehicle operator can seldom make repairs in the field. Complicated diagnostic software has to be designed to assist mechanics analyse data from the ECM. Improved training is required for mechanics and after sales support staff.

One important issue that must be appreciated is that currently NRMM emission regulations only exist in western countries. Most diesel engine manufacturers export world wide or supply OEMs that do so. Customers in other areas of the globe do not want to operate a complex engine if they are not legally bound to. Legislation, when it is introduced, will take many years to match the severity of that in Europe or North America. The result is that manufacturers must be flexible enough to produce and support engines that meet a range of regulatory standards from Tier 0 through to Tier 3 and beyond.

5 Coping with legislation

The introduction of legislation has engendered more collaboration between engine manufacturers and OEMs to lobby governments over future legislation. Industry bodies, such as Euromot (the European Association of Internal Combustion Engine Manufacturers) are becoming more powerful and are closely involved in drawing up the next Tiers of emissions control. This 'pre-competitive' collaboration is very similar to that seen in the automotive industry in the late 1980s and early 1990s [14].

In terms of technology strategy there are also links to car and truck manufacturers. NRMM engine designers look to their on-highway counterparts for ideas and solutions to the next rounds of legislation because regulation impacts upon road vehicles before off-highway applications. For example, ECMs first appeared on car engines before transferring to off-highway diesels.

6 The future

The future will see even more stringent legislation being introduced. Discussions about Tier 4 will start soon and many expect further regulation beyond that. By 2010, the exhaust levels of pollutants will be only one percent of what they were from unregulated engines in the early 1980s [12]. In terms of technology strategy, there will be even more transfer from on-highway industries. For example, the concept of 'common rail' technology that revolutionised car diesels [15] is starting to be introduced to NRMM engines [11]. Improved materials and manufacturing techniques will further improve engine quality and help reduce weight and emissions.

Further into the future, NRMM emission regulations may become so severe that even advanced diesel engines cannot comply. The use of hybrid-electrical, fuel cell or gas technology may become widespread. Further discussion of these is outside the scope of this paper.

Other areas of engine design are starting to be legislated for. Perhaps the most notable is noise. Huge investment and research effort is being made into the field of noise, vibration and harshness (NVH). It is to be expected that even more aspects of engine design will be regulated in the future.

7 Conclusions

The introduction of environmental legislation has caused massive changes throughout the diesel engine industry. As this paper has shown, engine production lives have fallen; organisational and technological changes have occurred. The companies involved are now producing more complex products than ever before, within dramatically shorter time frames. Investment in research and development has risen significantly in order to meet the challenge laid down by regulators.

This series of events is similar to what was seen within the passenger car industry in the late 1980s and early 1990s [14]. As there, environmental regulation has now been accepted by diesel engine designers as being a standard part of the developmental landscape.

Although each successive wave of regulation looks exceptionally hard to meet, increased levels of innovation within the industry are ensuring that solutions are found. Diesel engine manufacturers have adapted and are now used to operating in a legislative environment.

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