Overcoming the Barriers to Sustainable Motorsport

Innovation Report

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Abstract

The aim of this Engineering Doctorate was to identify and develop strategies and technologies to overcome the barriers to sustainable motorsport. A top-down approach was taken beginning with an industry-wide strategy and ending with the development of individual sustainable technologies.

After identifying a set of target guidelines for the industry to follow, the economic, social and environmental barriers to the future sustainability of motorsport were identified. These barriers were addressed through the creation of an industry-wide regulatory strategy followed by an innovative company-focussed technology development process; High Performance Sustainability (HPS). The HPS process was used to develop Eco One, a revolutionary racing car featuring environmentally sustainable technology which generated significant public engagement and facilitated evaluation of the HPS process. This technology demonstrator was used to make iterative improvements to the HPS process, resulting in HPS2, a second generation process with greater focus on performance and the development of sustainable technology.

This novel process was used to research and develop individual environmentally-sustainable technologies; natural fibre reinforced composites and the use of high performance biodiesel. Firstly lignin, a natural, renewable, waste material was added to hemp/epoxy composites as an innovative compatibiliser with a resulting improvement in mechanical properties.

Secondly, engine parameters were modified for the use of biodiesel made from soybean oil, resulting in torque equal to diesel fuel but with a lower in-cylinder pressure. The impact of these technologies is the opportunity to use renewable materials for high performance applications, potentially competing with existing motorsport technology.

The innovations presented in this Engineering Doctorate led to recognised expertise in sustainable motorsport within WMG, and in turn resulted in sustainable motorsport projects including WorldFirst, in which a Formula 3 car was developed featuring natural fibre composites, high performance biodiesel and recycled carbon fibre components. The impacts of this work are the establishment of industrial projects with race teams and constructors, conference attendances and peer-reviewed publications, and dissemination of research through the development of academic courses and extensive media coverage.

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Contents

List of Figures

List of Tables

Glossary of Terms

ABS	Assisted Braking System
B50	A fuel blend consisting of 50% biodiesel, 50% diesel
B100	A fuel consisting of 100% biodiesel
BBC	British Broadcasting Corporation
BRSCC	British Racing and Sports Car Club
BTCC	British Touring Car Championship
BTDC	Before Top Dead Centre
CFRP	Carbon Fibre Reinforced Polymer
CN	Cetane Number
CNSL	Cashew Nut Shell Liquid
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ELV	End of Life Vehicle
EngD	Engineering Doctorate
F1	Formula 1
F3	Formula 3
FAME	Fatty Acid Methyl Esters
FIA	Federation Internationale de l'Automobile
FOTA	Formula One Teams Association
IFSS	Interfacial Shear Stress
IP	Intellectual Property
IRL	Indy Racing League
HPS	High Performance Sustainability
HPS2	Second Generation High Performance Sustainability

KEPI	Key Environmental Performance Indicator
KERS	Kinetic Energy Recovery System
LLP	Limited Liability Partnership
MSA	Motor Sports Association
NFRC	Natural Fibre Reinforced Composite
NO_x	Nitrogen Oxides
NPD	New Product Development
PET	Polyethylene Terephthalate
PU	Polyurethane
R&D	Research and Development
SOI	Start of Injection
TBL	Triple Bottom Line
TDC	Top Dead Centre
UCO	Used Cooking Oil
UK	United Kingdom
UTS	Ultimate Tensile Strength
VARTM	Vacuum Assisted Resin Transfer Moulding
WEEE	Waste Electrical and Electronic Equipment
WMG	The University department where the author was based, formerly Warwick Manufacturing Group
WTCC	World Touring Car Championship

1 Introduction

The aim of this Engineering Doctorate was to identify and develop strategies and technologies to overcome the barriers to sustainable motorsport. This was achieved by completing the following objectives:

- Identify the benefits of, and barriers to, sustainability in the motorsport industry
- Develop necessary tools and techniques to overcome these barriers
- Introduce innovative sustainable materials using these tools and techniques
- Optimise tools, techniques and materials through technology demonstrator projects

The structure and objectives of this Engineering Doctorate research programme were intended to follow the hierarchical structure of motorsport, and the scope of the research was therefore varied from the development of strategies that would influence the whole industry down to research into individual sustainable technologies.

The initial objective was the development of a strategy by which the motorsport industry as a whole could attain economic, social and environmental sustainability. Once this strategy was developed novel processes were developed to aid the introduction of sustainable materials and technologies into motorsport at a company or team level. This stage of the research programme also involved the manufacture of technology demonstrators to validate these processes.

The final stage was to demonstrate the use of the strategy and processes developed in the first two stages by conducting motorsport-themed research and development into individual technology areas. Rigorous scientific research was carried out on sustainable alternatives to existing composite and fuel technologies, and the effectiveness of these materials was proven through their application in motorsport demonstrator projects.

1.1 Structure of the Engineering Doctorate Research Programme

This Innovation Report represents the culmination of work in this research programme. Its structure is intended to intuitively guide the reader through the research carried out in the programme; highlighting key innovations and referring back to the objectives set out in the initial stages of research. The structure of the research undertaken is shown in Figure 1.1; asterisks denote instances of innovation or contribution to knowledge within the research. The dotted lines denote that the work undertaken was as part of a research team. This figure demonstrates that each aspect of the research was advanced from a process level down to the development of individual materials and technologies, which were validated through inclusion in functional, motorsport-related technology demonstrator projects.

This Innovation Report follows the same structure as the research programme; initially examining the validation of the research concept through reviewing the literature and the analysis of an industry consultation. These were used to identify the needs and requirements of the motorsport industry. These needs were addressed through the introduction of a Sustainability Strategy for Motorsport which addressed the challenges of introducing new regulations, and suggested a novel methodology for addressing the economic, social and environmental sustainability of motorsport. From a broad strategy which gives a holistic approach to the sustainability of motorsport, the focus then switched to the introduction of new materials and products at a company level with the development of the first generation High Performance Sustainability (HPS) process.

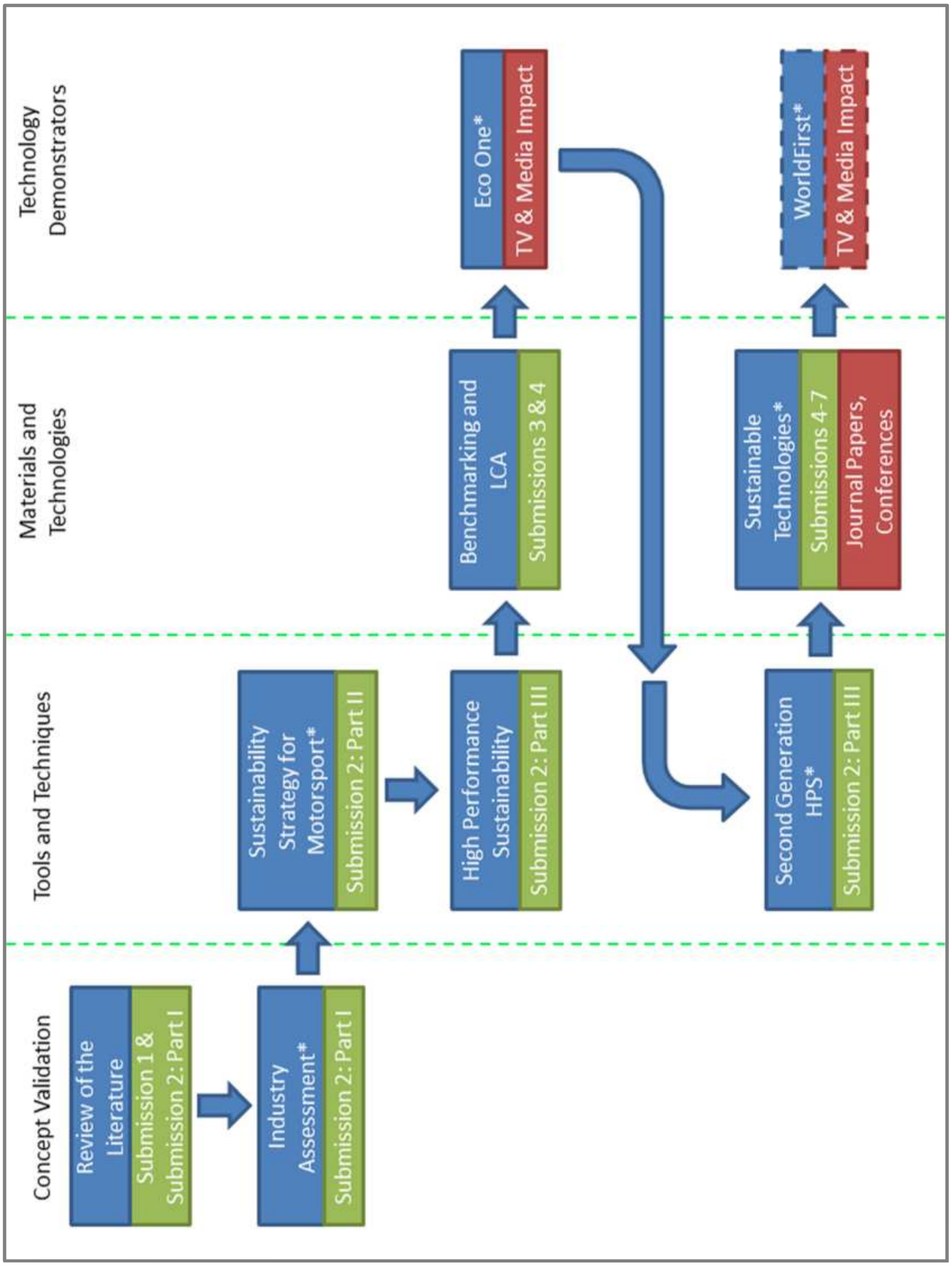

Figure 1.1: Structure of the Research Programme

This first generation process was used to select suitable sustainable materials for the replacement of those currently in use; this involved assessment of both their environmental impacts and mechanical properties. Eco One, a technology demonstrator project consisting of a single-seater racing car featuring sustainable materials in many aspects of its construction is presented as a method of evaluating the success of the first generation HPS process.

Lessons learned in the manufacture of Eco One were utilised in the development of the second generation sustainable product development process, HPS2. Novel sustainable technologies developed using this process are then presented; hemp/epoxy/lignin hybrid natural fibre reinforced composites (NFRCs), and an investigation of the use of biodiesel in a high performance engine. The development of these technologies provides validation of the second generation HPS process. The application of this research to the motorsport industry and the impact of the key research innovations are then presented, and conclusions relating to the completion of the initial aims and objectives are drawn. A Gantt chart representing the timing of the events in the research programme is shown in Figure 1.2.

The research programme summarised in this Innovation Report resulted in WMG having recognised expertise in sustainable motorsport, with the result that research in this field has continued beyond the scope of the Engineering Doctorate. Industrial collaborations on the WorldFirst project led to WMG being invited to supply sustainable body panels and consultancy for the Lola-Drayson Racing all-electric racecar (Drayson Racing, 2011), a project designed to showcase the rapid development of sustainable technologies in motorsport.

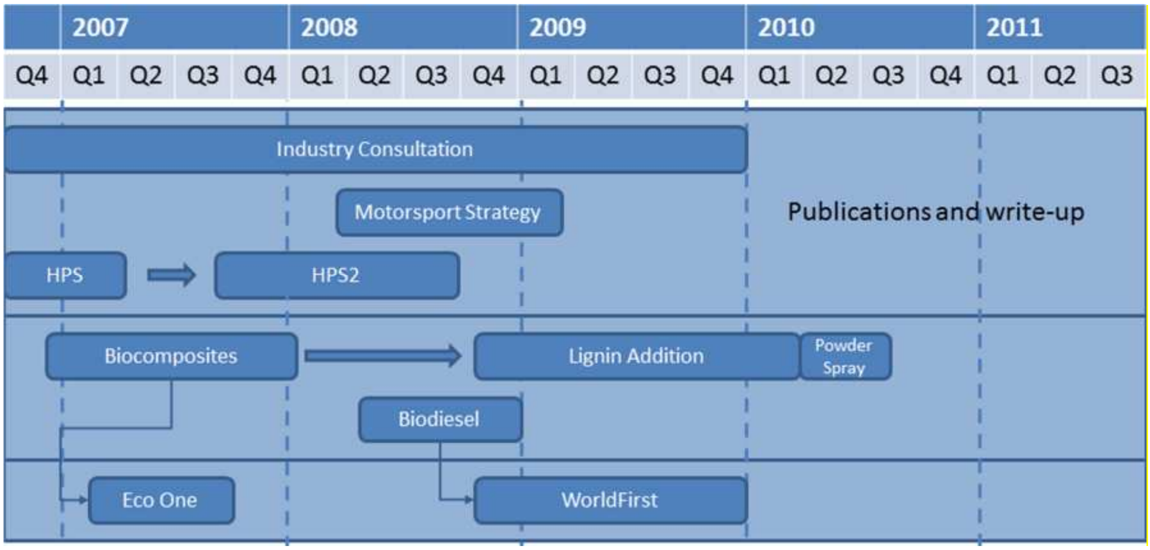

Figure 1.2: Project Timeline

1.2 A Guide to the Structure of the Portfolio

This Engineering Doctorate (EngD) portfolio consists of seven submissions comprising nine individual reports which cover different aspects of sustainability and the motorsport industry. In addition, the academic publications and other forms of dissemination are compiled in two further reports. This Innovation Report provides an extensive summary of the work completed; however the reader will be regularly directed to individual submissions for further detail where required. A brief synopsis of the contents of each submission follows.

Submission 1: An Introduction provides a review of the motivation for the adoption of sustainability, including environmental technologies currently available to related industries such as automotive. The hypothesis that sustainability is an opportunity for motorsport to regain relevance to society, (therefore increasing its audience, sponsorship revenues and ultimately financial stability) is introduced.

Submission 2 is presented in three parts; it identifies the motivation for the adoption of sustainability in motorsport, the barriers to its adoption and tools and techniques to facilitate overcoming these barriers. *Part I - Assessing the Sustainability of Motorsport in its Current Form* identifies the strengths, weaknesses, opportunities and threats facing the motorsport industry, and relates these to the triple bottom line of sustainability. This information is used to develop a set of guidelines towards the future sustainability of the industry. *Part II - Identifying and Mitigating the Barriers to Sustainable Motorsport* assesses the barriers to sustainability within the motorsport industry through the analysis of primary and secondary data. The analysis is then used to develop a regulation-focussed, holistic strategy for addressing the 'triple bottom line' of economic, social and environmental sustainability. The strategy is intended to guide the whole industry through a top-down, regulation-based approach and is therefore intended for use by regulators and governing bodies. *Part III – Development of Sustainable Technologies for Motorsport* follows on from the holistic strategy developed in *Part II* by introducing a process for the development of sustainable technologies. The High Performance Sustainability (HPS) process is evaluated through application in a racing car featuring environmentally sustainable technologies and then evolved into a second generation (HPS2) process with focus on increased performance of sustainable technologies.

Submission 3: The Use of Fibre Reinforced Composites in Motorsport gives an introduction and overview of one of the potential areas that could be the subject of sustainable development using the tools and techniques devised as part of this engineering doctorate. The various uses of composites in different forms of motorsport from club racing through to Formula 1 are discussed, and an environmental impact assessment of synthetic fibre reinforced composites is carried out.

Submissions 4 to 6 demonstrate how the High Performance Sustainability process can be used to develop different motorsport technologies from composites to fuels. *Submission 4: Developing Natural Fibre Reinforced Composites for Motorsport* outlines the development of natural fibre reinforced composites to make them more suitable for the challenging motorsport environment. The innovative addition of a low cost, renewable and biodegradable compatibiliser to these composites is shown to result in an improvement in mechanical properties, allowing them to be used for a wider range of applications.

Submission 5: Lignin/Epoxy Powder Coating Resins and Powder Sprayed Natural Fibre Composites presents a feasibility study carried out by the author on the possibility of using lignin as an additive to epoxy powder coating resins. This work was then extended to attempt the use of powder coating as a rapid manufacturing process for NFRCs. Potential applications for lignin/epoxy powder coating resins and powder coated NFRCs are also identified.

Submission 6: First Generation Biodiesel as a Motorsport Fuel is an experimental report regarding the testing and development of an engine operating on biodiesel manufactured from a range of natural fats. It includes the use of in-cylinder pressure transducers to measure the variation in start of injection timing and ignition delay in diesel and biodiesel fuels, and the use of this data to tune an engine suitable for motorsport.

Submission 7: A Cost Analysis of Natural Fibre Reinforced Composites is presented as an extension to *Submission 4* and details the financial implications of developing a Formula 3 wing mirror from autoclaved carbon fibre, injection moulded Polyamide 6,6 and a vacuum assisted resin transfer moulded (VARTM) hemp/epoxy composite filled with lignin.

In addition to the seven submissions, the peer-reviewed academic outputs from the author's work are compiled in *Publications*.

Other dissemination activities, including television footage and press cuttings resulting from the Engineering Doctorate research are included in a submission entitled *Disseminating the Innovation*.

1.3 Summary of the Innovations

The work carried out during the Engineering Doctorate research programme resulted in contributions to knowledge and innovation. These are listed, along with their location within the Innovation Report for ease of location, and are also signified by asterisks in Figure 1.1.

- Application of the Triple Bottom Line of sustainability to motorsport (Chapter 3)
- Development of a strategy for the implementation of economic, social and environmental sustainability of the motorsport industry (Chapter 4)
- Project management and manufacture of the world's first environmentally friendly racing car, Eco One (Chapter 5 and Appendix A1)
- The addition of untreated Kraft lignin to hemp/epoxy composites as an environmentally sustainable compatibiliser (Chapter 6)
- Invention of a manufacturing process for hemp/epoxy composites based on powder coating (Chapter 6)
- Novel approach to the use of biodiesel as a high-performance fuel for motorsport (Chapter 7)

In addition to the individual contributions listed above, the whole concept of the research programme is innovative; application of sustainable development to motorsport has not previously been attempted, and has been proven through the research presented in this Innovation Report to have a positive impact.

2 Motorsport and Sustainability

Motorsport is an industry worth approximately £5 billion to the UK economy, and employs 40,000 staff, 25,000 of whom are engineers (UKTI, 2007). It also reinvests more than 30% of its revenues into research and development (R&D), compared to 2% of reinvestment by the wider engineering industry (UKTI, 2007). Motorsport is therefore a significant contributor to the UK economy and its future should be secured in order to maintain the UK's capability in this innovative, niche market. Motorsport thrives on the sponsorship revenues it generates through its entertainment value to the general public, attracting a diverse global audience. Public engagement is therefore a key activity for motorsport as a whole and individual teams looking to increase investment from sponsors.

'Green' issues and environmental sustainability are a popular topic for discussion in the mainstream media, and governmental pressure to consider the impact of everyday activities have led to a greater awareness of energy consumption and reducing the amount of waste generated. Environmental legislation has also had an impact on a wide range of industries, from automotive to electronics, and this is set to increase as the price of fossil fuels continues to rise and increasingly stringent emissions and energy targets some into force.

Motorsport, as an extroverted user of fossil fuels for racing, is in danger of losing the interest and support of the public and therefore its main source of income; sponsorship. The hypothesis behind this research programme was that by adopting environmental sustainability, motorsport would engage with a wider audience therefore securing long-term sponsorship and ensuring a successful future for one of the most successful niche engineering industries in the UK.

2.1 The UK Motorsport Industry

Motorsport is an activity involving complex interrelationships with a number of different stakeholders and industries. The relationship between these activities and the relevant stakeholders is shown in Figure 2.1. As well as being a popular type of competitive sport with many different forms, classes and championships, it is also responsible for one of the most successful niche engineering industries in the world and a global multi-million pound media activity.

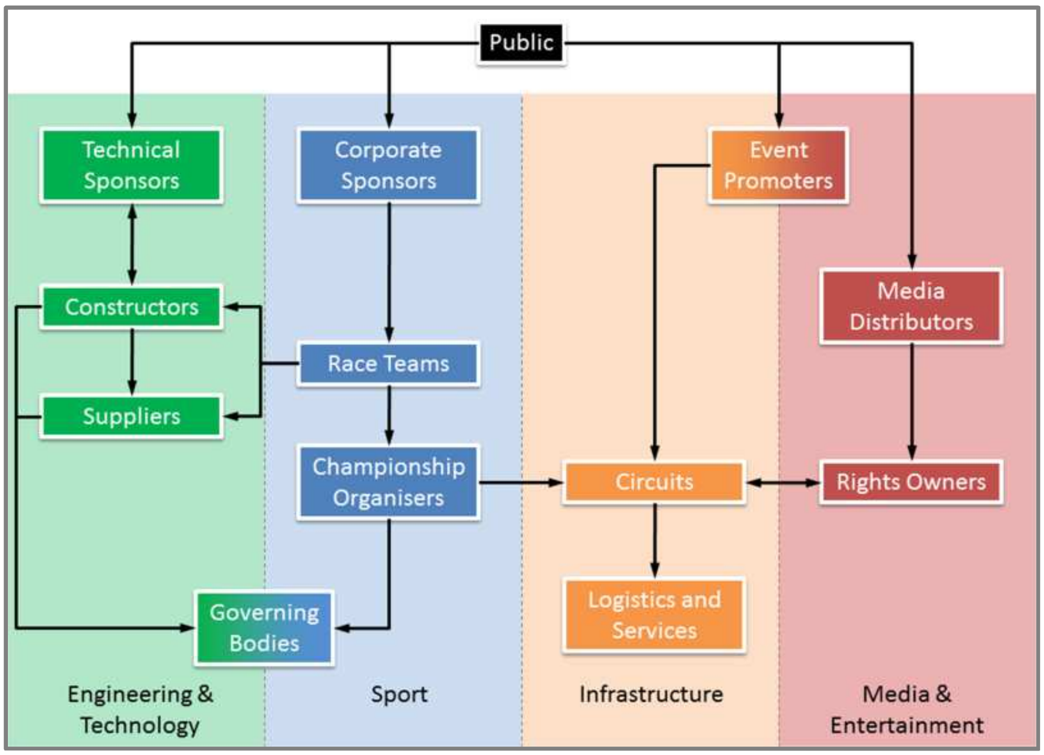

Figure 2.1: Motorsport Activities and Stakeholders

The public plays a key role in this complex range of activities; all of the functions of motorsport are dependent on the interest and ultimately the financial investment of the public, whether it takes the form of television subscriptions, tickets to motorsport events or the purchase of goods or services provided by the companies that sponsor motorsport.

Sponsorship of motorsport is lucrative due to the brand awareness that a widely televised activity creates, and has also been found to have a positive impact on brand loyalty, particularly if public engagement (customer involvement) is encouraged (Sirgy *et* al, 2008). The profile of motorsport fans also makes them attractive to advertisers; a 2006 study found that 91% of F1 fans were male, 26% held management jobs and 53% were aged between 16 and 34, a profile which advertisers find particularly attractive but hard to reach (Edgecliffe-Johnson, 2008).

Motorsport sponsorship influences consumer behaviour to such an extent that a study published in The Lancet showed that boys of 12 and 13 years of age who watched motorsport on television were significantly more likely to start smoking due to tobacco sponsorship of popular teams (Charlton *et al*, 1997). Such has been the success of motorsport sponsorship, particularly Formula 1, that the majority of motorsport funding (approximately 300 million Euros per team) is generated through this means (Symonds, 2008).

In order for companies to benefit from a sponsorship arrangement they need to be assured of targeting a large audience, and for the association with motorsport to reflect positively on their corporate image. Satisfying the changing needs of sponsors is therefore of key importance to the motorsport industry.

2.1.1 Regulation of Motorsport

An example regulatory structure is shown in Figure 2.2, and represents the different levels of governance which affect individual teams and suppliers in the British Touring Car Championship (BTCC). The BTCC is a national championship, and therefore is directly regulated by the UK Motor Sports Association (MSA). However, guidelines for global motorsport activities are set out by the FIA; the MSA regulations are therefore derived from these. The

MSA uses the FIA guidelines to help set regulations for individual championships within the UK such as British Formula 3 (F3). The teams competing in these championships build their cars to meet these regulations by sourcing components from suppliers. The direction and focus of motorsport research and development (R&D) is therefore defined by the regulations imposed by motorsport's governing bodies.

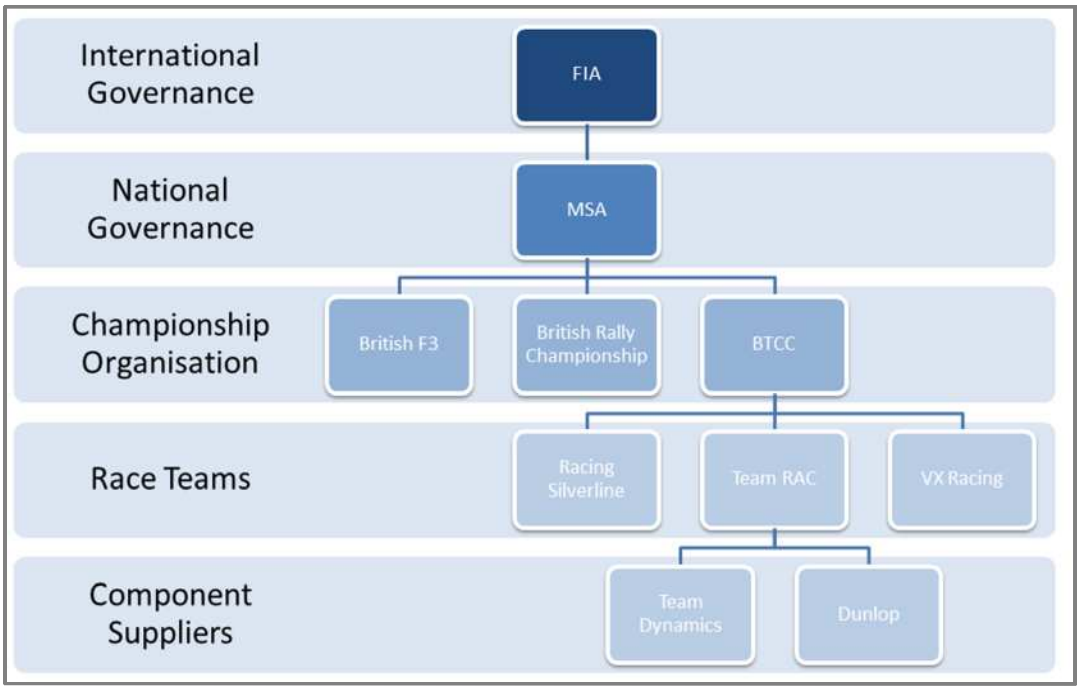

Figure 2.2: Regulatory Structure of the British Touring Car Championship (BTCC)

Unlike the design and development of most consumer products which are subject to safety regulations and standards but mostly driven by the market, motorsport products are designed to meet a strict performance and safety specification. Regulations define the majority of features of the product; development is therefore focussed on achieving the best possible performance from the narrow window of possibilities that remain within the rules. Teams design right up to the edge of these boundaries, and even occasionally cross it, in order to achieve the best possible performance.

Despite having no direct link with the engineering activities of motorsport, regulations set out by the regulatory bodies effectively control the components and technologies developed by the motorsport industry through changing the requirements of the competing teams. The teams are forced to meet the regulations if they wish to compete, and therefore so must the components and technologies which they use.

Because of this need to respond to regulatory changes, the motorsport industry is capable of developing innovative technologies incredibly rapidly. Teams have to not only develop their own technological solutions, but also imitate those of their competitors in order to remain competitive (Jenkins, 2010). The financial and human resources of motorsport have led to the development and wider adoption of technologies such as disc brakes (Lawrence, 1991), active suspension, carbon fibre monocoques and aerodynamic downforce (Wright, 2001). In essence, motorsport is accustomed to managing change in order to maintain competitive advantage, and implementing these changes in a shorter time period than many other industries (Jenkins, 2010).

2.2 Sustainability

'Sustainability' is a widely-used term, and one which has a multitude of definitions. This can make it difficult for companies to define a sustainability strategy, as decisions are often misguided by confusion over what they are actually trying to achieve.

A widely respected definition of sustainability, and one which was used throughout this EngD research programme, comes from the Brundtland Report (Brundtland, 1987). This introduced the notion that sustainability is:

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

In order to satisfy this definition, it is necessary to consider the "Triple Bottom Line" (TBL); consideration for economic, social and environmental sustainability (Elkington, 1997). The logic behind the triple bottom line concept is that without consideration for all these three aspects, no product, business or material will be able to continue to succeed indefinitely.

Environmental sustainability has been the subject of much recent government legislation which has had an impact on many industries. The End of Life Vehicle (ELV) directive requires automotive manufacturers to take physical and financial responsibility for their products when they reach the end of their useful life, effectively forcing them to make use of recyclable materials in the manufacture of new vehicles. From 2015 onwards manufacturers will have to carry out at least 95% reuse and recovery by an average weight per vehicle and year (UK Government, 2005).

The Waste Electrical and Electronic Equipment (WEEE) directive requires manufacturers of electrical goods to take back any of their end of life products from consumers at end of life, free of charge (UK Government, 2007).

Both of these directives have forced industries to address their material choices due to their increased responsibility when their products reach end of life. The industries affected deal in high volume manufacturing (millions of products annually) therefore the impact of the sustainability of these goods is significant. Motorsport on the other hand is a low-volume niche industry which could be expected to escape such legislation. However other niche industries such as yachts (Europa, 2011) are coming under scrutiny and the risk of government legislation on the environmental performance of motorsport is high.

2.2.1 The Business Context of Sustainability

Despite the challenges of adopting environmental and social sustainability within a business, there is much evidence in the literature that this approach has been taken across a range of industries. Elkington (1998) first introduced the concept of the Triple Bottom Line (TBL) to provide an assessment framework for sustainability within businesses. The goal of the TBL is for a company's financial interests to coincide with the interests of external stakeholders (Savitz & Weber, 2006).

Environmental sustainability can be a time-consuming and costly consideration when developing new products (Handfield *et al*, 2001) and research has also been published which indicates the potential for trade-offs between environmental performance and the needs of the customer (Walley & Whitehead, 1994). However there is conflicting evidence that environmental initiatives in fact present an opportunity; companies can gain a competitive advantage through environmental improvement (Miles & Munilla, 1993; Porter & van der Linde, 1995) and critically for motorsport, also improve their corporate image (Kolk, 2000). Developing socially and environmentally responsible products and processes is an opportunity for economic success; it also avoids the risk of generating negative public perception through the decision not to adopt sustainability.

3 Validating the Concept of Sustainable Motorsport

Although the TBL has been applied in businesses spanning several industries, the motorsport industry's unique characteristics mean that its route to sustainability should be carefully considered. The opening phase of this research programme was to analyse the sustainability of the existing motorsport industry and thereby establish the need for further research in this area. In this chapter a motorsport-specific TBL is presented which refines the generic definitions from the literature to be applicable to the unique motorsport environment. The application of an existing process to a new industry is a contribution to innovation.

This chapter represents research from *Submission 1*, *Submission 2 part I* and *Submission 2: part II,* which is collated and summarised for clarity. It consists of an assessment of motorsport's current sustainability followed by guidelines for future sustainable development and identification of the barriers preventing this from being achieved. These three components are presented for each aspect of the TBL. For full details of this research and the methodologies used, the reader is directed to the respective submissions within the Engineering Doctorate Portfolio.

3.1 Sustainability in Current Motorsport

Despite a lack of evidence of sustainable development within motorsport in general, there is evidence that a limited number of championships, teams and competitors are making attempts to address this. Some of these are competitions purely focussed on efficiency and environmental considerations such as the Shell Eco-marathon in which teams compete to travel the furthest distance possible around a race track using only one litre of gasoline (Shell, 2011). This encourages the development of innovative design solutions to efficiency, and is arguably more relevant to the public than mainstream motorsport due to its potential similarity to automotive applications and focus on fuel efficiency. However, the lack of on-track competitive action and minimal media coverage mean that this type of racing lacks the marketing potential of mainstream motorsport. This kind of event therefore addresses environmental sustainability by seeking alternatives to fossil fuels for transport applications, and is also relevant to society by developing efficiency improvements which may be applicable to the automotive industry, but generates limited sponsorship or media coverage.

The next type of event is that which mandates the use of some form of environmental sustainability on competitors. An example of this is the TTXGP and associated events instigated by entrepreneur Azhar Hussain (TTXGP, 2010). The initial concept of the TTXGP was to compete in the famous Isle of Man Tourist Trophy motorcycle races using electric motorcycles. The event maintains the excitement of competitive racing, and the performance of the electric motorcycles is impressive enough to interest spectators, although not comparable to those powered by more traditional internal combustion engines. The initial event was successful, and similar events are now being launched around the world under the same brand. The TTXGP maintains the entertainment value of competitive motorsport, thus maintaining a better level of public engagement than the Shell eco-marathon, while still addressing environmental sustainability by seeking to develop electric vehicle technology.

Although events of this type are growing in popularity, they are still in the early stages of development and therefore have limited support or resources for technological development. Current regulations are restrictive of new or unknown technology therefore series such as those described above are not regulated by the world's motorsport governing bodies. They require their own sets of rules which results in vehicles being designed specifically to compete in one event, limiting the opportunity for companies such as chassis constructors or engine manufacturers to become involved at a commercial scale. This limits their economic sustainability at the current time.

The final group are competitors in traditional motorsport who introduce ‘green’ materials and technologies without them being stipulated in the regulations. Examples of this include the Drayson Racing team, who took part in the 2008 American Le Mans Series using second-generation E85 bioethanol fuel (Drayson Racing, 2008), and the OakTec team, who have competed in UK rallying since 2004 in hybrid vehicles (Oaktec, 2010). The endeavours of individuals and teams to introduce sustainable fuels, drivetrains or materials are driven by a number of different factors such as individual desire, attempting to appeal to a new audience and access to different types of sponsors.

These activities make limited attempts at achieving environmental sustainability, changing the power source or some materials on their vehicle but not taking a holistic approach to addressing its environmental impact. They do however benefit from the economic and social aspects of traditional motorsport, gaining media coverage and the potential to attract sponsors.

Interest in sustainable motorsport is not limited to those directly involved; an FIA Institute seminar on sustainable motorsports (on 16th November 2010) was attended by delegates from major automotive manufacturers including Audi, BMW, Ferrari, Ford, McLaren, Nissan, Porsche, Renault and Volkswagen (FIA Institute, 2011). This is evidence that there is a market for sustainability in the motorsport industry.

3.2 Motorsport's Triple Bottom Line

"We should never forget we are not just racing for ourselves; somebody has to be interested in what we are doing, has to go to the grandstand and watch the races on TV (Television) and if we miss these people and go in the wrong direction then we are wasting all the money that is invested in motorsport." (Baretzky, 2011)

The above quote is from Dr Ulrich Baretzky, Head of Engine Technology at Audi Sport, speaking at a Motorsport Industry Association conference in January 2011. It is reproduced here because it neatly sums up the challenge facing motorsport at the start of the 21^{st} Century; how to remain relevant in the face of increasing concern for the environment and sustainability?

Dr. Baretzky's statement includes reference to the three pillars of the triple bottom line, which are yet to be defined in the context of motorsport. The meaning of each pillar was analysed and applied to a motorsport context in *Submission 2: Part I*, and can be summarised as follows:

- Economic Sustainability

The existence of secure, long-term sources of funding for motorsport activities, either through corporate sponsorship as is currently the case, or by identifying new sources of income.

- Social Sustainability

Remaining relevant to, and generating benefit for society. Carry out motorsport activities which positively (or at least do not negatively) affect the stakeholders involved, including the fans, teams and the general public.

- Environmental Sustainability

Create minimal environmental impact through motorsport activities either now or in future. This should include consideration of materials, fuels, manufacturing processes and end of life disposal of waste.

The TBL has previously not been applied to the motorsport industry; the work presented here therefore provides a contribution to the innovation of the research programme.

3.2.1 Methodologies

Assessment of each of these three aspects, suggested guidelines for their achievement in future and the barriers to this achievement were completed. A strengths, weaknesses, opportunities and threats (SWOT) analysis was used to evaluate evidence from the literature on the current state of the motorsport industry. Barriers to sustainable motorsport were identified through collection and analysis of primary and secondary data. Primary data was gathered from influential members of the motorsport industry through semi-structured interviews. Details of the interviewees are given below in Table 3.1; quotes from these interviews are interspersed within this chapter to support the findings. A limitation of this section of the work is the relatively small sample of interviewees. People working at director level in motorsport companies are under significant time pressures, and therefore are not easily convinced to take part in interviews. Those interviewed were however in decision-making positions within their companies, and influential within the wider motorsport industry. A secondary limitation to the data gathered in semi-structured interviews is the lack of evidence gathered from two important groups; consumers and regulatory bodies. Evidence from secondary data collection was used to represent the consumer; reports published by companies such as Mintel allow access to significantly more accurate data than it would have been possible to gather within the scope of the Engineering Doctorate. Although a consultant to a regulatory body was interviewed, further interviews with members of the FIA would have added further rigour to this aspect of the research. Primary and secondary data collection methodologies and the full analysis of the data are discussed in detail in *Submission 2: Part II – Identifying and Mitigating the Barriers to Sustainable Motorsport*.

Table 3.1: Details of Interviewees

Name	Position	Company	Business Type
Interviewee 1	Managing Director	Williams Hybrid Power	Supplier
Interviewee 2	Managing Director	Potenza Technologies	Consultancy
	Technical Director	Westfield Sportscars	Constructor
Interviewee 3	Technical Director	Flybrid Systems LLP	Supplier
Interviewee 4	Team Owner	Michael Crawford Motorsports	Race Team
Interviewee 5	Technical Advisor	British Touring Car Championship	Consultant

Analysis of strengths, weaknesses, opportunities and threats (SWOT) is a method of strategic planning in relation to a specific project or business venture (Westwood, 2006). The objective of SWOT analysis in this case was to analyse the potential integration of sustainability into the motorsport industry. Strengths and weaknesses of the current industry with respect to its sustainability were therefore identified. The external influences on the future of motorsport were identified based on opportunities and threats resulting from the adoption of sustainability. The detailed SWOT analysis can be found in *Submission 2: Part I - Assessing the Sustainability of Motorsport in its Current Form*; a summary of the pertinent points is shown in Table 3.2.

Table 3.2: SWOT Analysis of the Motorsport Industry

STRENGTHS	WEAKNESSES
• Good technical resources • High level of investment in R&D • Strong media presence • Loyal following of fans • Ability to adapt to change	• Relevance to society falling • Innovation limited by regulations • Reliant on corporate sponsors • Protective of IP • Negative environmental image
OPPORTUNITIES	**THREATS**
• Develop sustainable technologies • Introduce new regulations • Commercialise IP • Use motorsport as a tool for public engagement	• Environmental legislation • TV viewing figures lower than 2008 • Reduction in sponsorship revenues • Become unfashionable

Assessment of the existing motorsport industry highlighted, in the opinion of the author, three main motivations for the adoption of sustainability in motorsport:

- Developing sustainable technologies could help make motorsport more relevant to society

Environmental sustainability is a popular topic of discussion among the media, governments and the general public. By adopting sustainability, motorsport could regain societal relevance and in turn larger viewing audiences. With greater interest in motorsport, the support of existing sponsors would be secured.

- Addressing sustainability is an opportunity for motorsport to attract new sponsors from different sectors

The renewable energy sector is growing rapidly, and many other companies offering environmentally-linked services are emerging. These represent an opportunity for motorsport to attract new sources of funding.

- Motorsport is an ideal platform to rapidly develop sustainable materials and technologies

The industry has large financial and technical resources and some of the most innovative engineers in the world at its disposal. There is great potential for motorsport to increase the speed of development of sustainable materials and technologies.

The TBL of motorsport and SWOT analysis were used to develop a set of guidelines for the motorsport industry to follow in order to achieve sustainability, full details of which can be found in *Submission 2: Part I - Assessing the Sustainability of Motorsport in its Current Form.* Each element of the SWOT analysis (Table 3.2) was assessed against the TBL to interpret its impact on the future economic, social and environmental sustainability of motorsport.

From analysis of the primary and secondary data, the following key points were identified:

- Any change in motorsport should be driven by regulation
- Public engagement is an important part of motorsport's activities
- Cost is a driver for material selection due to the pressures of securing sponsorship
- Motorsport companies have little expertise in environmental sustainability
- There are no sustainability tools or techniques specific to motorsport

The results from assessment of motorsport's sustainability, SWOT analysis and data from semi-structured interviews follow. The results have been collated into categories representing the three pillars of the TBL.

3.2.2 Economic Sustainability

"…(if we)…go in the wrong direction then we are wasting all the money that is invested in motorsport."

It is estimated that the research required to reduce the lap time of a Formula One car by 0.03 seconds costs in the region of one million Euros (Symonds, 2008). This level of spending has arisen due to the level of technological maturity reached by the majority of motorsport products. The basic concept of technology maturity is that every technology has a lifecycle. New technologies are faced with difficulties and barriers which have to be overcome therefore the rate of development is slow. As a technology becomes better understood, controlled, and diffused, the rate of technological improvement increases (Sahal, 1981). When a technology reaches maturity, the rate of performance increase slows due to the additional time and effort required. The cost and difficulty of advancing this technology is higher than one lower in maturity. This theory is represented by the curve shown in Figure 3.1.

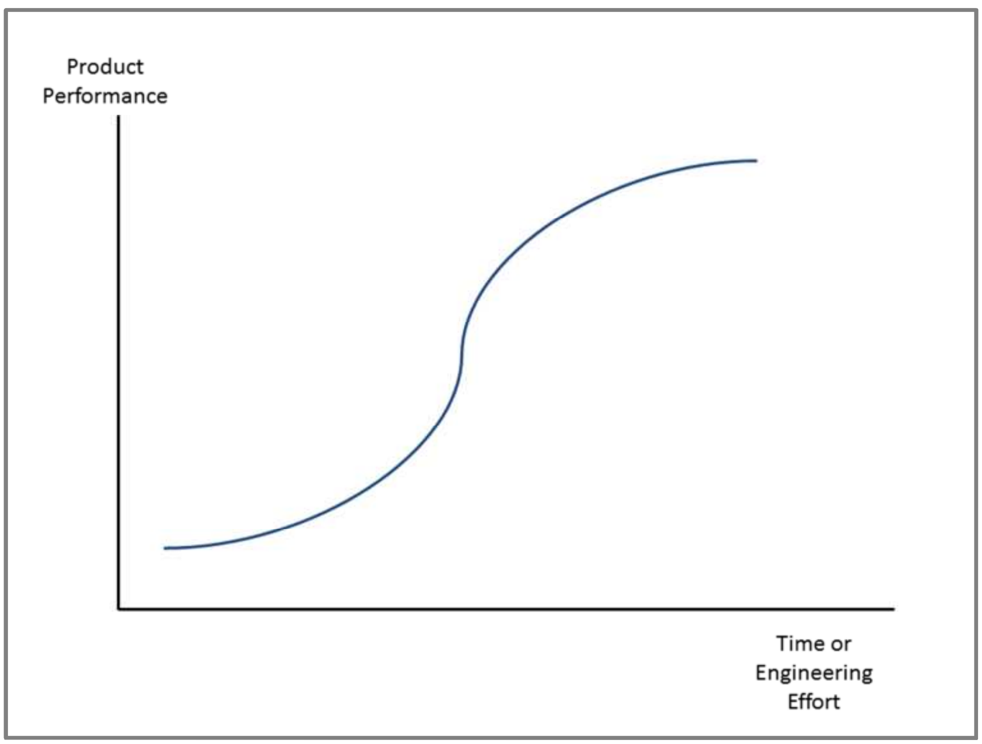

Figure 3.1: Technology S-Curve (adapted from Christensen, 1992)

A racing car can be considered to be a mature product; it retains most of the basic elements from year to year and normally undergoes iterative development rather than step changes in design. It is this high level of spending and difficulty in making advancements in motorsport that make teams protective of their technology; under the current regulatory framework implementation of a novel technology developed for the race track on a publicly available road vehicle would rapidly lose the team in question any competitive advantage gained through R&D, as any other team could carry out reverse engineering to obtain it. Restrictive regulations mean that the development of new technology is limited to iterative progress, and therefore the cost required to advance these technologies is high.

The huge financial resources which motorsport requires in order to maintain this level of technology development has one main source; corporate sponsorship. Motorsport sponsorship exists due to the relationships between three main entities; motorsport, its sponsors and the consumer. These relationships are represented by the diagram shown in Figure 3.2. The figure shows the cyclical value stream that exists between these three groups, with the counter-rotating arrows representing the two-way interactions which occur between each pair of groups. The relationships between each pair of entities are mutually beneficial, but also depend on the continuing existence of relationships with the third entity. The transfer of value in motorsport is cyclical therefore the removal or diminishing of any of the relationships in this triumvirate would result in the cycle ending.

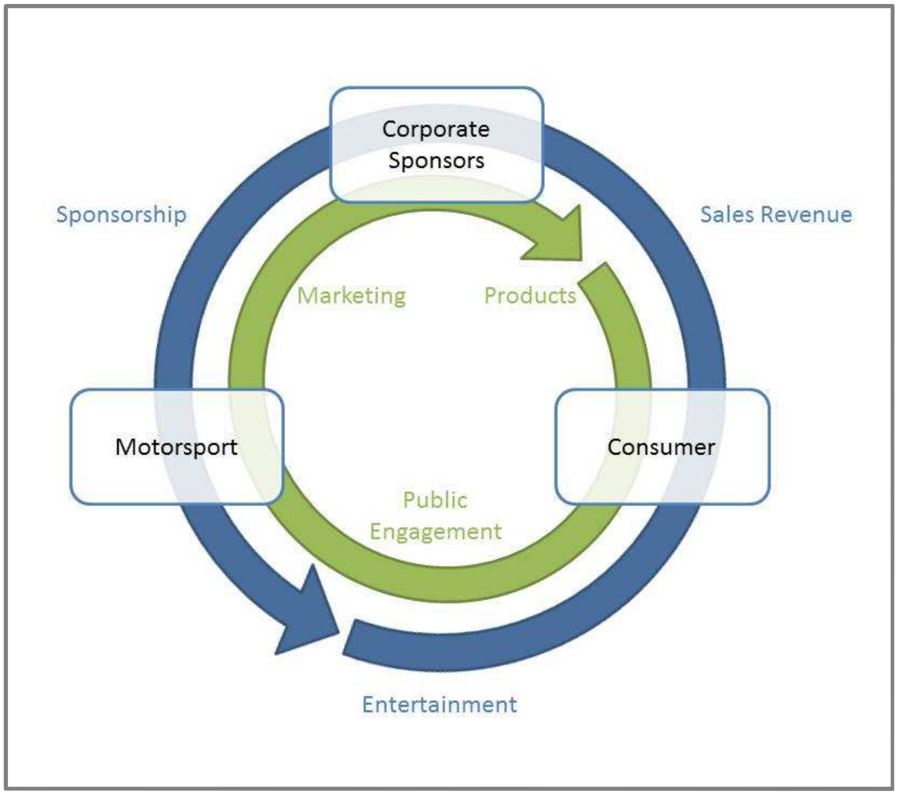

Figure 3.2: Relationships Between Motorsport, Sponsors and the Consumer

An example is the relationship between motorsport and its corporate sponsors. Sponsors provide motorsport teams with funding which allow them to build competitive racing cars. In return, motorsport provides the sponsors with an opportunity to market their products or services to a large audience, increasing brand awareness and potentially generating a positive association with the brand if the team they sponsor wins a race. This mutually beneficial situation can only exist if the consumer is also part of the value stream. Without spectators, the marketing value of sponsorship is minimal, and therefore little income from sponsors is generated.

These spectators then generate a greater awareness of the sponsors by viewing their logos and branding on the cars they have sponsored, and may generate a positive association with a brand if, for example, the car that they sponsor wins a race. This then leads to increased revenue for the sponsoring companies through selling their products and services to the consumers. Motorsport provides an excellent marketing opportunity for companies, providing the positive link between the consumer and motorsport remains intact. This is achieved through public engagement; generating interest and enthusiasm for motorsport from consumers by providing entertainment and generating positive public perception of its activities.

3.2.2.1 Economic Guidelines

'Secure long-term sources of funding for motorsport activities'

Motorsport has access to good technical resources, has high levels of reinvestment into R&D to potentially fund innovation into new technology, and has an excellent record of managing changes in regulations. Although currently well-funded, motorsport relies on one major source of income; corporate sponsorship. The threat to motorsport if that income stream was reduced or removed is great therefore the industry should look to source alternative sources of funding. Motorsport's strengths in R&D could be used to develop new products and technologies, the IP of which could be protected and licensed (or sold) either to other teams or into other industries such as aerospace or automotive. Efforts should also go into appealing to a wider range of sponsors by increasing the appeal of motorsport into different sectors.

3.2.2.2 Barriers to Economic Sustainability

During semi-structured interviews it was reinforced that sponsorship is the major source of revenue for motorsport:

"…all that matters is getting money from sponsors, either by winning or clever marketing. The more money we have, the more we get to spend on racing!" **Interviewee 4**

Relying on one major source of income is a risk to the future economic success of the industry, and a need to generate new funding opportunities has been identified. This view has been supported by the Chairman of Prodrive, who stated that:

"Motorsport cannot continue to rely upon conventional sponsorship. It must develop new revenue streams" (Richards, 2003).

Motorsport has the opportunity to capitalise on the IP that it generates in order to reduce this reliance on sponsorship, but little of motorsport's IP is currently sold or licensed. Another reason for the lack of commercialisation of motorsport technology is a lack of motivation on the part of motorsport teams, who are focussed on winning rather than making a profit. As a result, it has been noted that:

"Few teams understand the full potential of the intellectual property they create" (Richards, 2003).

This undervaluation of IP by the motorsport industry is a key barrier to overcome in order for motorsport to capitalise on its research and development capabilities, and therefore reduce its reliance on corporate sponsors.

3.2.3 Social Sustainability

"…somebody has to be interested in what we are doing…"

In the 1930s the vehicles used for racing were very similar to the road cars of the time. As purpose built racing cars were introduced, the race track was used as a proving ground for automotive technologies. An example of this is the introduction of the first disc brakes to the

C-Type Jaguar racer in the 1950s; within a decade they were found on almost every production road car (Lawrence, 1991). By the 1990's however, the transfer of technologies from motorsport to automotive was minimal (Foxhall, 1991). This again confirms the hypothesis that motorsport is a maturing area of technology (see Figure 3.1); as the costs of developing technological advancements in motorsport increases, their relevance to other industries which produce lower value products decreases.

Due to the type of materials and technologies used by the motorsport industry, it has more commonality with the aerospace and defence industries; the industry body for UK motorsport has been attempting to develop these relationships into a greater degree of technology transfer in recent years (MIA, 2010). The nature of these industries is that they are secretive with regards to the technologies that they use, therefore any technology outputs from motorsport are unseen by the public.

The Formula One administration states that:

"a modern Formula One car has almost as much in common with a jet fighter as it does with an ordinary road car" (Formula One, 2009a)

Little race-bred technology now filters down to the automotive industry, indeed in some cases automotive technology is more advanced than that used in racing. An example of this is ABS (assisted braking system); "most modern road cars can lay claim to having considerably cleverer retardation (than a Formula One car)" (Formula One, 2009b).

Henry and Pinch (2000) showed that the majority of investment in "Motorsport Valley" in the UK comes from a variety of medium sized British companies, not the major automotive manufacturers that might be expected. Because of this lack of collaboration with the automotive industry, motorsport technology rarely finds its way into the mass market, and therefore the public have little connection with it.

Motorsport, then, has extensive financial and technical resources at its disposal, but the products it develops have little relevance to the world outside of motorsport except in applications which are unseen by the public. Viewing figures for the 2006-2010 F1 seasons are shown in Figure 3.3. The factors behind viewer numbers for TV events are many and varied, but the overall decrease in viewing figures since 2007 gives an indication that audience interest in F1, and motorsport in general, may be waning.

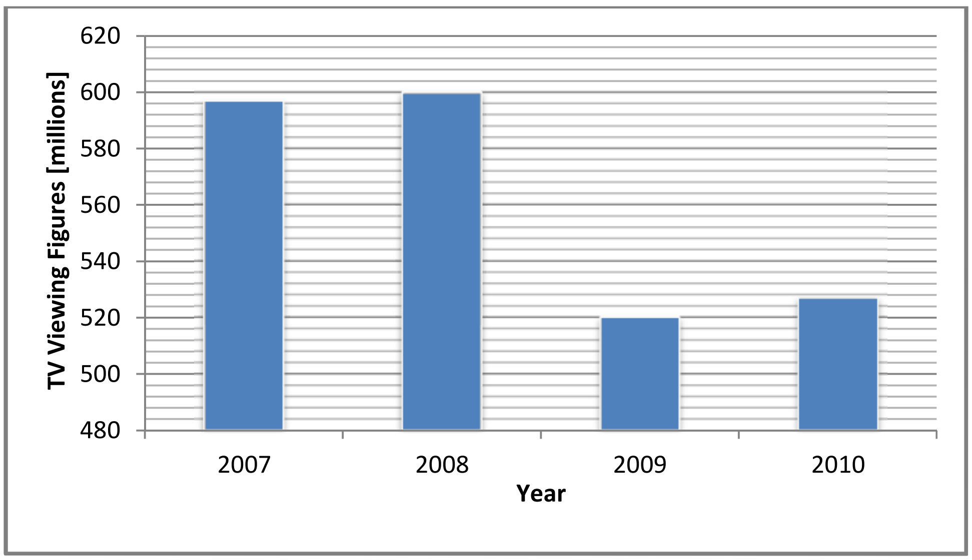

Figure 3.3: 2007-2010 TV Viewing Figures for F1
Data from: (McCullagh, 2009; Sylt, 2010; Formula One, 2011a)

Data from surveys of UK adults carried out for a Mintel marketing report in 2009 also showed that the number of people who said they had an interest in motorsport and those holding racing licenses fell by 1.7% and 5% respectively between 2003-2008 (Mintel, 2009). In combination with the decline in TV viewing figures for F1 shown in Figure 3.3, there is strong evidence to suggest that public interest in motorsport is waning.

3.2.3.1 Social Guidelines

'Remaining relevant to and generating benefit for society'

The widespread media engagement enjoyed by motorsport in combination with its technical resources results in a unique opportunity for public engagement. The author's hypothesis is that the regulations of motorsport should develop in line with the needs of society, and greater connection between the consumer and the motorsport industry should be encouraged in order to reach a wider audience. Using motorsport as a tool for public engagement could help to mitigate the threats facing the motorsport industry; becoming irrelevant and unfashionable. Although these may not appear severe in isolation, losing the interest of the public would ultimately lead to the breakdown of the relationship shown in Figure 3.2, with no influx of sponsorship revenues and little public interest.

3.2.3.2 Barriers to Social Sustainability

Social sustainability involves remaining relevant to society by engaging with the public and generating benefit for stakeholders, which in motorsport includes the consumer. The Formula One Teams Association (FOTA) have previously announced that improving public engagement was an intention of F1:

"[F1 intends to]…dramatically improve engagement with the public" Luca di Montezemolo, FOTA Chairman, (BBC, 2009).

However, too much of this focus is on the entertainment value of motorsport which helps to generate media coverage and attract sponsors. Motorsport is interested in maintaining a 'green' image rather than addressing the key issues of sustainability:

"…there's not a lot of consideration for sustainability. The teams need to have **Interviewee 5**

a green image, and all of them try to do so, but the main thing is putting on a good show."

This focus on entertainment is due to the key part that the public plays in ensuring the success of motorsport; the consumer has been identified by several sources as motorsport's most important stakeholder:

"…we all share one common goal: to work together to improve F1 by ensuring its stability, sustainability, substance and show for the benefit of our most important stakeholder, namely the consumer." Luca di Montezemolo, Chairman of FOTA, (BBC, 2009).

"We should never forget we are not just racing for ourselves; somebody has to be interested in what we are doing, has to go to the grandstand and watch the races on TV (Television) and if we miss these people and go in the wrong direction then we are wasting all the money that is invested in motorsport." Ulrich Baretzky, Head of Engine Technology, Audi Sport (Baretzky, 2011).

Ulrich Baretzky highlighted that maintaining the level of public engagement that motorsport currently enjoys gives motorsport its purpose. The danger of 'missing' people by taking motorsport in the wrong direction was also a point raised by Interviewee 1:

"The danger is that if we don't change with the times then in ten years Formula 1 will look like historic racing, it won't be cutting edge…" **Interviewee 1**

Motorsport should therefore adapt to the changing environment in which it operates, remaining relevant by engaging the public and addressing the current trends in society.

The motorsport industry has identified the importance of the consumer as a stakeholder, but is currently attempting to engage the public by providing entertainment, with little thought for further ways in which it can be of benefit to society. Lack of effective public engagement or societal relevance is therefore a barrier to social sustainability in motorsport.

3.2.4 Environmental Sustainability

"…we are not just racing for ourselves…"

The environmental impact of many industries is now coming under scrutiny, and government legislation to place more responsibility on producers of goods is increasing. There is a high likelihood that other activities such as motorsport will be subject to such sanctions in future, so contingency plans should be put in place in the event that the sustainability of motorsport comes under the same scrutiny.

Motorsport teams use exotic materials to give their cars a competitive edge, but some of the materials used to achieve these performance gains are energy intensive, non-recyclable, manufactured from crude oil derivatives and difficult to dispose of at end of life (*Submission 3: The Use of Fibre Reinforced Composites in Motorsport*). An example of this is carbon fibre, which has an embodied energy of up to 286MJ/kg and is difficult to recycle (Suzuki & Takahashi, 2005).

Due to the rapidity with which design upgrades and new components are introduced, a racing car typically has a life expectancy of less than a year, and often the lifecycle of components is significantly less than that due to upgraded parts being introduced. Many components are therefore one-offs which result in waste which is disposed of in landfill because it is not easily recyclable.

The use of sustainable materials and technologies in mainstream motorsport is currently an unusual and irregular occurrence. The regulators of motorsport have however identified that sustainability is an issue that matters to the public resulting in the adoption of technologies such as kinetic energy recovery systems (KERS) to Formula 1 (Formula One, 2011b) and hybrids to Sports Prototype racing (Leggett, 2011). Different strategies have also been implemented in an attempt to reduce fossil fuel usage, such as the banning of refuelling during pitstops in F1, and the switch from gasoline to Ethanol in series such as IndyCar in the USA (IndyCar Series, 2008). However at the same time as F1 was limiting the use of fuel, a new tyre supplier was introduced with the intention of making tyres wear out more quickly to make the racing more exciting (Formula One, 2011c). These changes give an indication that the regulatory bodies of motorsport have identified that sustainability is an issue that they need to address, although there is little evidence of a clear strategy to enable them to achieve this. A lack of sustainability strategy has contributed to companies leaving motorsport; fear that motorsport had become irrelevant in a world striving for sustainability and efficiency was one of the reasons for the Honda motor company withdrawing from Formula One (Lim, 2008).

3.2.4.1 Environmental Guidelines

'Create minimal environmental impact through motorsport activities either now or in future'

Despite attempts to introduce new regulations encouraging 'green' technologies in recent years, motorsport is perceived as having a negative environmental impact, resulting as much from the logistics of moving people and equipment around the world by aeroplane as from burning fossil fuels, or using energy intensive materials such as carbon fibre.

In the author's opinion, motorsport should face these threats and deficiencies from the top down; new regulations which encourage the adoption of sustainable initiatives within different forms of motorsport would help drive innovative R&D into sustainable materials and technologies, improving motorsport's image in the eyes of the consumer as well as mitigating any risk posed by future environmental legislation.

3.2.4.2 Barriers to Environmental Sustainability

There is evidence that attitudes to environmental issues in motorsport are changing. Series' such as the Indy Racing League in the USA have adopted renewable fuels such as bioethanol.

"The IndyCar Series is proud to be fuelled by ethanol, a renewable energy fuel" Terry Angstadt, President of the Indy Racing League (IRL), (IndyCar, 2008)

The motivation for this move to biofuels is unlikely to have been purely driven by environmental concerns; Interviewee 5, a technical director for a governing body identified that teams are unwilling to adopt new technologies unless there is a financial benefit of doing so, or they are forced to by regulation:

"It's very much regulation driven. If it costs then they won't want to do it. If they're not told they have to do it then they won't do it at all." **Interviewee 5**

The business potential of adopting environmentally friendly technologies is beginning to be understood, with the result that technologies such as hybrid systems are being developed by motorsport companies:

"A few years ago anyone attempting a project like this [flywheel hybrid systems] was thought of as a "tree hugger", but not anymore. It's serious business." **Interviewee 3**

However, a problem still to be addressed is the comparative performance of environmentally-friendly materials and technologies. Material performance is of great importance to motorsport, allowing on-track performance to be exciting which attracts the public. This need for high-performance materials is true of race teams, but also their suppliers:

"Fitness for purpose is the only concern for us…we're a low volume supplier and it just has to work." **Interviewee 1**

The use of ethanol can actually give a performance advantage as it has a higher octane number than gasoline (Al-Hasan, 2003), but this is not true of the majority of environmentally-friendly alternatives, and more than just fuel will have to be considered for motorsport to become environmentally sustainable. Materials such as glass and carbon fibre reinforced composites have excellent specific mechanical properties and replacing them will not be straightforward. The main environmental barrier to sustainable motorsport is therefore the current inferior performance of environmentally sustainable materials.

3.3 Eight Guidelines for the Development of Sustainable Motorsport

A set of eight points for motorsport to follow in order to achieve a secure and sustainable future (Figure 3.4) were developed, the full details of which can be found in *Submission 2: Part I – Assessing the Sustainability of Motorsport in its Current Form*. They address the three aspects of sustainability; economic, social and environmental, and identify specific activities which would lead to achieving sustainability in these three areas. The guidelines were developed into a diagrammatical framework (Figure 3.4) which groups each point by the aspect of sustainability that it addresses. By following each of the guidelines motorsport companies, teams and regulators can begin to formulate a sustainability strategy and hence improve their triple bottom line. They are intended to be used as an aid to decision-making when considering new material or process options, and can then be used as a checklist at regular intervals to ensure that sustainability targets are being met.

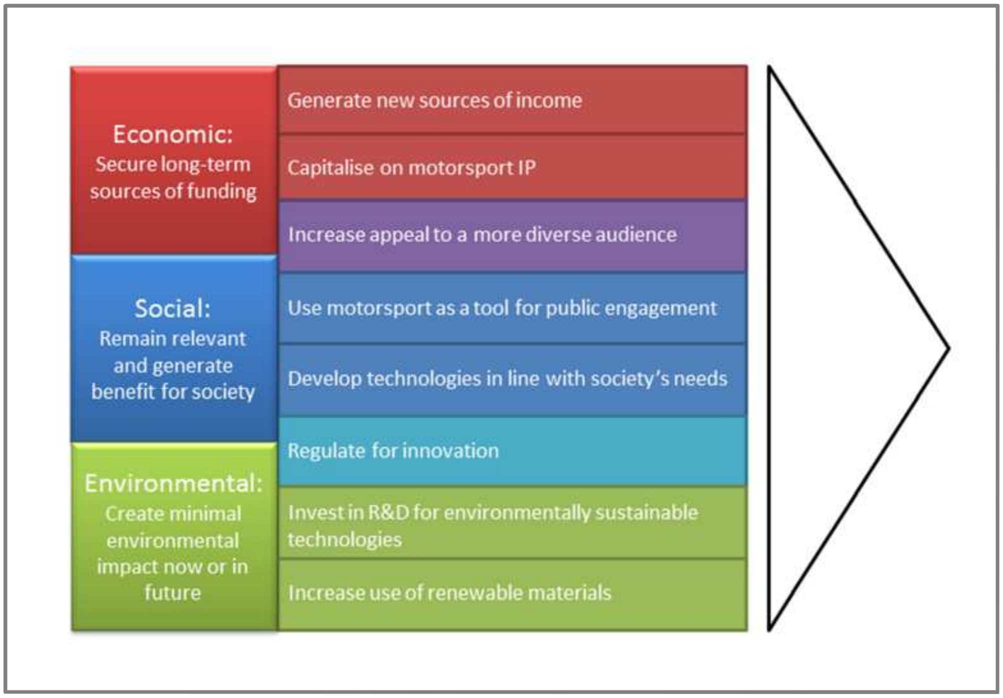

Figure 3.4: Guidelines for the Development of Sustainable Motorsport

The potential impact of this framework is to ensure that the motorsport industry can continue into the medium to long term. It addresses the three key elements of sustainability, and provides a set of guidelines for the motorsport industry to use which will allow them to move from their current state to a more sustainable future. These guidelines could be used as a checklist for the motorsport industry, in particular the governing bodies, to encourage sustainable development. As a decision making tool, it provides a framework on which to base choices for new regulations and the future strategy of the industry.

3.4 Summary

The three aspects of the Triple Bottom Line (TBL) were examined with specific application to the motorsport industry, and then the sustainability of the current motorsport industry was assessed using these new definitions. The current economic sustainability of motorsport is limited due to the uncertainty in future sponsorship incomes. It is dependent on motorsport continuing to be an attractive target for corporate sponsors.

Social sustainability is reliant on public engagement and societal relevance; declining viewing figures and public interest in motorsport suggest that this is at risk in the long term unless changes are made.

Regulatory bodies have made attempts to integrate environmentally sound technologies into motorsport, but with limited success; production of racing cars still involves the use of energy intensive and unsustainable materials and fuels.

The strengths of the motorsport industry are its substantial technical and financial resources, ability to rapidly develop innovative products and technologies, and generate media exposure. These are balanced by a reliance on a single source of funding which is dependent on continued public interest, and a recent decline in TV viewing figures and public participation in motorsport.

Motorsport obtains the majority of its funding through corporate sponsorship, therefore satisfying the needs of sponsors is critical to its economic sustainability. In real terms, this means engaging with a large audience in order to increase awareness of the sponsor’s brands and products, and to create a positive public image with which the sponsor can be associated. In order to achieve this, motorsport must be relevant to people and hence engage the public.

Access to a broader audience, and by association new sponsors, could be generated by making motorsport more relevant to society. This could be achieved by increasing the level of technology transfer from motorsport to other industries by licensing and commercialisation of motorsport intellectual property. This would also generate another income stream for the industry and reduce the reliance on corporate sponsorship.

The environment is a popular topic of discussion in the mainstream media, but also in governmental legislation, and across many industries. The development, use and then commercialisation of environmentally sustainable motorsport technologies is therefore an opportunity for motorsport to become more relevant to society, generate more secure sponsorship revenues and develop new sustainable materials and technologies that could benefit the world outside of motorsport.

A set of guidelines for the adoption of sustainable motorsport was developed. This consists of eight points which the motorsport industry must address if it is to move towards a sustainable future. The potential impact of this framework is to ensure that the motorsport industry can continue into the medium to long term by maintaining secure sources of funding, regaining relevance to society and creating minimal environmental impact.

For economic sustainability, the barriers were identified as a reliance on corporate sponsorship and a lack of exploitation of the intellectual property developed by motorsport's R&D activities. Barriers to the development of social sustainability in motorsport were found to be a lack of effective public engagement and minimal societal relevance brought about by diminished levels of technology transfer out of motorsport. The main barrier to environmentally sustainable motorsport was identified as the inferior performance of sustainable alternatives compared to their synthetic counterparts.

The motorsport industry, from suppliers to regulatory bodies, have identified the need to address the issue of sustainability, but the lack of a cohesive strategy to allow it to do so, or tools and techniques to facilitate its implementation, were identified as barriers to the adoption of sustainable motorsport.

In Chapters 4 and 5 of this Innovation Report a novel strategy for the development of sustainability in motorsport and an innovative technology development tool for sustainable motorsport are presented which were developed to overcome these barriers.

4 A Novel Strategy for the Development of Sustainable Motorsport

In order to address the barriers to sustainable motorsport it was necessary to make changes to the current method of technology development. Changes were introduced to different stages of the existing process in order to address each aspect of the triple bottom line. Full details of this work can be found in *Submission 2: Part II – Identifying and Mitigating the Barriers to Sustainable Motorsport*; a summary of the work is presented here.

It is the author's suggestion that in order to achieve social and environmental sustainability in motorsport, regulations must encourage the development of environmentally-friendly technologies which have relevance outside of motorsport. The first action to achieve this is to create a more open regulatory system in order to allow a greater degree of innovation. In the proposed process the regulatory bodies would introduce new rules requiring additional use of sustainable technologies every season. These could range from demanding the use of a certain percentage of recycled material in the construction of the car to mandating the use of bioethanol or biodiesel fuel. This would encourage the rapid development of environmentally sustainable technology.

The main reason for the lack of exploitation of motorsport IP was identified as the technology maturity of existing motorsport technology in Section 3.3.2. The use of new, environmentally sustainable technologies which are in an immature state of development would result in step changes in performance for the same engineering effort and resource needed to make an incremental change in a mature technology (Figure 4.1).

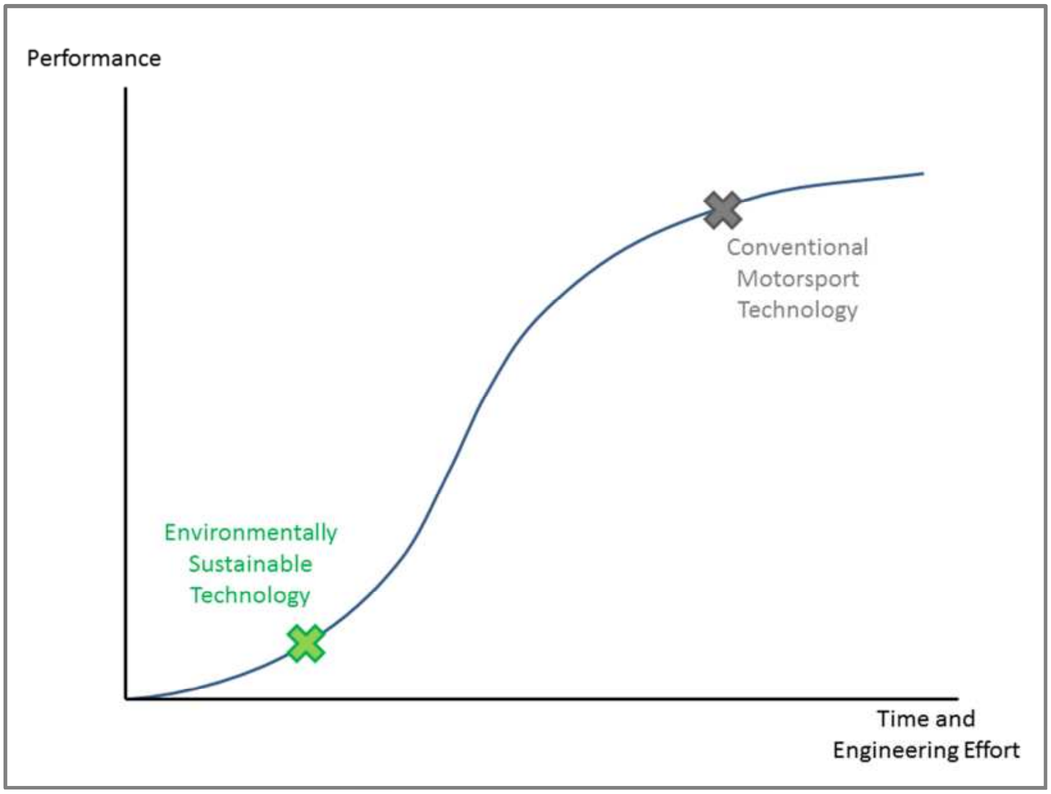

Figure 4.1: Technology Maturity of Environmentally Sustainable and Conventional Motorsport Technologies

In order to encourage the dissemination of technology outside of the motorsport industry and increase the relevance of motorsport to society, additional regulations would require any IP developed by the individual teams to be available to their competitors at cost, plus a fixed profit margin, after one season of use. This would guarantee the team that invented the technology a profit from their technology, but prevent them from intentionally charging a prohibitively high price. The exact profit margin would be set by regulation. Any competitive advantage to using this technology would only last for one season after which all the teams would have the opportunity to buy the technology. As well as reducing the performance gap between the front-running teams and those at the back of the grid, this would provide an additional income stream for the teams with the most successful R&D activities.

This process would encourage teams to license technology outside of motorsport to other industries. The current barrier to this is the reluctance to give away competitive advantage by revealing successful technologies, but in an environment of rapid technology development, by the time a competitor has the ability to copy a technology it is nearing obsolescence. The licensing and sale of motorsport IP and technology would generate income for the teams in addition to that provided by sponsors, reducing the industry's reliance on a single source of revenue and therefore increasing its economic sustainability.

Whereas the changes to the macro level of the process would have a holistic effect over the whole industry, the mid-level strategy is focussed on the actions and strategies for individual teams and companies working in motorsport. Any major changes to the sustainability of motorsport must come from regulation, but these changes must be implemented at a company or team level hence the need for further modifications of the process. Motorsport does not assign enough value to the IP which it generates, and is overly reliant on sponsorship for a source of income. Both of these barriers to the future economic sustainability of motorsport can be overcome through effective exploitation of the IP generated by the R&D activities within motorsport teams and companies.

The setting up of intellectual property capitalisation functions within teams would allow them to benefit financially from their technology development. These could come in the form of spin-out companies or departments within the teams whose role is to develop and market motorsport technologies. This would generate income, either through licensing or the direct sale of products to customers. This income could then be used to fund the exploitation of IP as well as providing the R&D activities within the teams with additional budget. Another benefit of this approach would be the potential for motorsport technology to be applied in other industries, increasing the visibility of the technology transfer out of motorsport and hence increasing the relevance of motorsport to society.

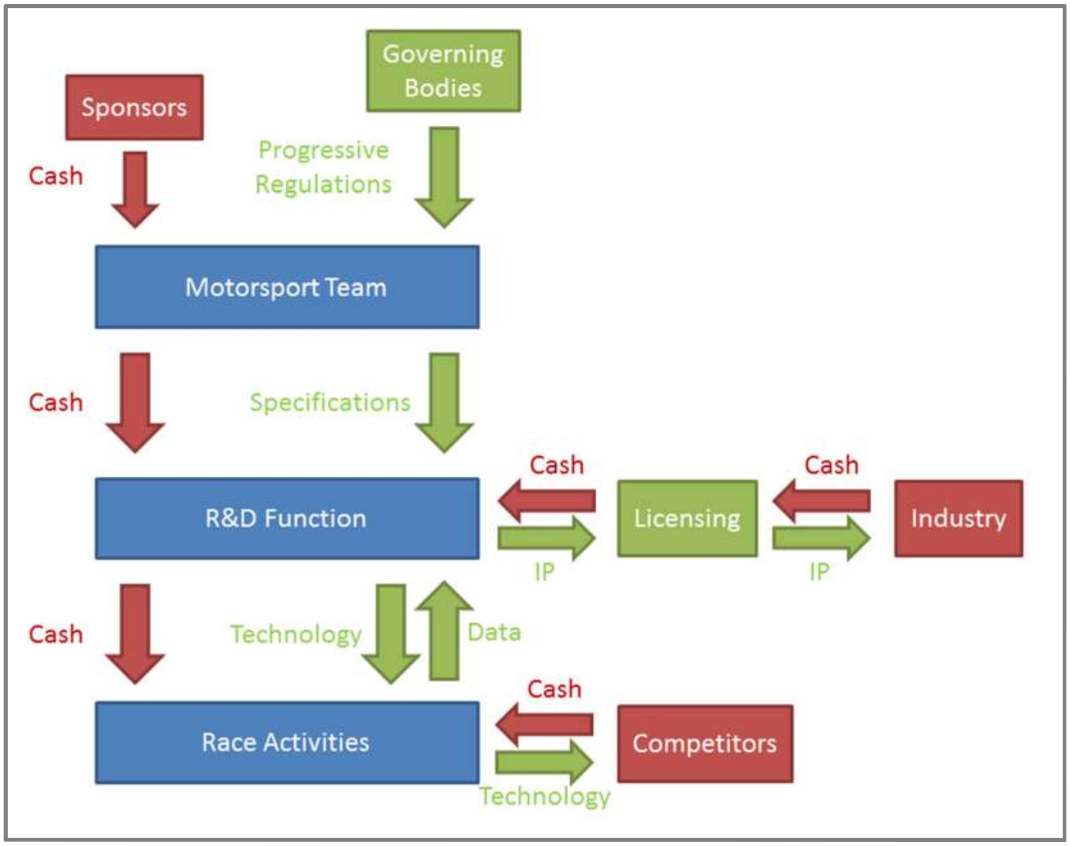

Figure 4.2: Strategy for the Development of Sustainable Motorsport

The Strategy for the Development of Sustainable Motorsport is shown in Figure 4.2. By developing environmentally sustainable technologies through regular, progressive changes to the regulations and licensing the IP generated through R&D, motorsport would become less reliant on corporate sponsorship, aid the rapid development of environmentally friendly technology and generate a greater level of technology transfer into other industries.

4.1 Reflections on the Strategy for the Development of Sustainable Motorsport

The novel process introduced here is focussed on regular, directed changes to regulations in order to drive the uniquely rapid innovation of motorsport to develop sustainable technologies. This strategy has the potential to impact on the sustainability of motorsport by improving its performance in three key areas; public engagement, financial security and environmental impact.

4.1.1 Public Engagement

Through the implementation of this strategy, motorsport technologies would be licensed and sold for use outside of motorsport, and the public would come into contact with motorsport-derived technology in their everyday lives. This would bring them closer to a sport which has become increasingly irrelevant over the years, because what the spectator viewed on track could one day feature in the technology they own. People would be incentivised to view motorsport as not just a form of entertainment, but as a snapshot of the technologies that would feature in their lives in the future. This could also lead to a return of car manufacturers to motorsport, as the licensing of motorsport IP could lead to the availability of environmentally sustainable technologies relevant to the automotive industry. Manufacturers could secure preferential access to IP generated by motorsport in return for sponsorship, or by funding their own motorsport team.

4.1.2 Financial Security

For the teams this strategy is potentially lucrative – in the past no IP was protected or sold because teams were too busy making the car faster. By patenting and licensing these technologies, either through a central organisation or through individual spinoff companies, revenue could be generated. These revenues could be used to fund motorsport R&D, and also reduce the reliance on corporate sponsorship. Conversely, adoption of a strategy which commands a larger viewing audience through improved public engagement has the potential to increase sponsorship revenues by appealing to a wider range of businesses.

4.1.3 Environmental Impact

This strategy would also help to improve the environmental sustainability of motorsport by fast-tracking environmentally-friendly technologies using the huge resources of motorsport R&D. Because these technologies would be fed out into the mass market, the impact that these technologies would have would be significantly greater than the improvement to motorsport's sustainability alone. This concept could even be extended off the track; teams could be forced to minimise their carbon footprint by using sustainable transport to events, or generate their own electricity.

4.2 Summary

A review of the motorsport industry showed that in order to achieve environmental sustainability, motorsport must adopt a holistic approach to the introduction of novel materials, manufacturing processes and technologies, implementing them on many aspects of the car rather than addressing one issue at a time. A barrier to progress in this field is the inferior performance of many environmentally sustainable materials compared to the materials currently in use. Significant development of these materials is needed in order to develop a better understanding of their potential, and therefore allowing their use with minimal decrease in performance.

A novel Strategy for the Development of Sustainable Motorsport was introduced which addresses each of the barriers to sustainability. Through regular changes to the regulations which enforce the use of environmentally sustainable technologies, the R&D capabilities of motorsport can be directed towards developing 'green' technologies which are in an early stage of maturity but more relevant than those currently used.

In order to exploit the additional IP generated through the development of novel technology, motorsport teams and companies should attempt to generate income from this by setting up intellectual property capitalisation functions. These could take the form of spin-out companies or a sub-team within their existing structure, whose role would be the licensing of motorsport-derived technology to other companies from a range of industries. This would allow a reduction in motorsport's reliance on corporate sponsorship, and also generate an increased level of technology transfer and hence improving engagement with the public.

By developing environmentally sustainable technologies through regular, progressive changes to the regulations and licensing the IP generated through R&D, motorsport would become less reliant on corporate sponsorship, aid the rapid development of environmentally friendly technology and generate a greater level of technology transfer into other industries.

This chapter introduced a strategy for the development of sustainability in motorsport which addressed the top level of the industry, influencing decisions made by regulators and holistically attending to the barriers to sustainability. The next stage in the process was to identify tools and techniques for individual companies to use when attempting to follow the wider sustainability strategy set down by regulations.

5 An Innovative Technology Development Tool for Sustainable Motorsport

Most companies are now attempting to address the issue of sustainability but there is a lack of research into how these environmental initiatives can be integrated into the product development process of normal products, not just those designed to be environmentally friendly (Baumann *et al*, 2002; Ammenberg & Sundin, 2005).

Research has shown that new product development of environmentally-friendly products is more likely to be hampered by organisational barriers than the technical challenge of adopting novel materials or technologies (Lenox & Ehrenfield, 1997; Pujari, 2006). The motorsport industry is capable of overcoming technical barriers, as proven by decades of motorsport development; but the organisational challenge of introducing environmental considerations has yet to be faced.

A study by Olson *et al* (2001) found that high levels of cooperation between the research and development and marketing functions within an organisation resulted in the most successful projects; this conclusion has also been drawn by previous research (Song & Parry, 1993; Souder, 1988). Motorsport has strengths in both of these fields; its ability to develop new products and technologies quickly, and the marketing effort needed to generate the majority of its earnings through corporate sponsorship. Increased collaboration between these two functions through the marketing of new technologies developed through research should therefore be a target for motorsport.

A case study carried out by Johansson and Magnusson (2006) evaluated the potential benefits and challenges of integrating a ‘green sub-project’ within an existing project to help deliver environmental goals. The introduction of a sub-project generated better general awareness of environmental issues within the project, and enabled effective knowledge transfer to take place. They found, however, that there is a risk of confusion within other sub-projects over the ownership of responsibility for implementing green initiatives. Implementation of an approach such as this therefore requires effective communication between different elements of the project team, and sufficient authority for the green sub-project to ensure that environmental targets are being met. This could be a particular challenge for the motorsport industry, where engineers and researchers are typically focussed on the development of products which will improve on-track performance with little consideration of their environmental impact. Ensuring the 'buy-in' and cooperation of all parts of the team is an essential step in introducing a new process tool to motorsport.

Typically NPD is used by companies that are developing a product or service to sell to the consumer. It is therefore necessary to consider the customer requirements and design a product which the customer wants or needs, manufacture it well to ensure high quality, and market it in such a way that the company generates a good share of its chosen market. The customer then buys the product or pays for the service, and revenue is generated for the company. Sustainability is normally driven either by legislation or by consumer demand for more environmentally friendly products.

5.1 The High Performance Sustainability (HPS) Process

The development of a technology development process specific to sustainable motorsport is innovative; no evidence of the existence of a similar process exists within the literature or within the motorsport industry, as established in *Submission 2: Parts II* and *III*.

Elements of existing NPD taken from the literature were adapted and modified for a new application in developing sustainable materials and components for motorsport. Rather than being rigidly defined, the process developed here was intended to give greater flexibility allowing it to run concurrently with product development processes already in use by different companies.

The process was based on the Stage Gate process introduced by Cooper (1994) as a framework, but with new activities introduced at each stage and gate specifically applied to the development of environmentally sustainable technologies for motorsport. Full details of the process development can be found in *Submission 2: Part III*.

The process was required to facilitate the adoption of environmentally sustainable technologies to engage the public, but that remained competitive in performance terms; it was therefore named High Performance Sustainability (HPS). This formed the basis of the research strategy used for the Engineering Doctorate research programme.

A Stage-Gate style process was chosen as the framework for the first generation HPS process due to its proven success in a wide variety of industries, and the fact that it is a commonly used NPD process. This meant that the HPS process would be applicable to the widest possible range of processes in use by the motorsport industry. The activities at each stage and gate of the process are shown in Table 5.1.

Table 5.1: Activities at each Stage and Gate of the HPS Process

Stage/Gate	Activities
Gate 1	Establish key environmental performance indicators
Stage 1	Investigate and identify potential technologies
Gate 2	Select the most suitable technologies from those identified
Stage 2	Environmental impact assessment based on the KEPIs
Gate 3	Go to Testing
Stage 3	Test for mechanical performance
Gate 4	Decision made on whether performance is adequate
Stage 4	Go to production, manufacture components and put the technology into use

The first part of the HPS process represented by Gate 1 is to identify Key Environmental Performance Indicators (KEPIs); parameters which will define how decisions on the sustainability of materials will be made. These may be defined by regulation or set out by the team in order to fulfil a corporate environmental strategy. For example, KEPIs for a motorsport fuel might include CO_2 emissions from the tailpipe, fossil fuel content etc. For a composite material they could include ease of recyclability and embodied energy. The number of KEPIs is flexible, and can be defined by the user. The development of the concept of KEPIs and their application in developing sustainable technologies for motorsport represents the contribution to innovation of the HPS process.

In Stage 1, Research is undertaken into the potential technologies which could be implemented within the scope of the design brief. An example of this could be the powertrain for a racing car; potential technologies include hybrid drivetrains, biofuels used in internal combustion (IC) engines, hydrogen fuel cells and battery-powered electric motors (*Submission 1: An Introduction*).

At Gate 2 the available technologies are compared with relation to the KEPIs and other factors affecting the choice of technologies for motorsport such as cost (*Submission 2: Part II – Identifying and Mitigating the Barriers to Sustainable Motorsport*), and the most suitable technology is taken forward to the next stage.

The next step (Stage 2) is to assess the environmental impact of the selected technology with reference to the KEPIs. The complexity of this stage can vary depending on the time and resources available to the user, from a comparison based on simple "good, average, bad" categories of impact through to a full life cycle assessment of each material. However complex the chosen level of assessment is, consideration must be given to the full lifecycle of the technology, not just the raw materials used in its production. This should include identification of an appropriate course of action for the end of life treatment of the technology. The desired environmental impact targets for a given technology should be identified during the development of the KEPIs in Gate 1.

If the results of the Environmental Impact Assessment are favourable and the targets set in the KEPIs are met, then the chosen technology can be taken to the next stage in the process at Gate 3. If it fails the environmental impact assessment then the process is moved back to Gate 2, and another technology is selected.

Fitness for purpose was identified from primary and secondary data as a critical success factor for motorsport technologies (*Submission 2: Part II – Identifying and Mitigating the Barriers to Sustainable Motorsport*). The assessment of the physical performance of the technology was therefore identified as an essential part of the HPS process. Mechanical testing of all components or materials would take place at Stage 3, with the results being used to inform a decision of whether the technology is adequate for the purpose it is intended to be used for. If at Gate 4 the technology is proven to be unfit for purpose, then another is identified from Stage 1 and the process is repeated.

If the performance of the technology meets the performance requirements; in other words it is fit for purpose, then the technology moves on to the final stage of the HPS process. If the technology's performance is not adequate, then the process returns to Gate 2 and a different sustainable technology is selected for development from those identified in Stage 1.

In the launch stage of HPS the technology is put into production. The manufacturing method identified during Stage 2 of the process is implemented, and once the component has been produced it is used for its intended application.

These stages and gates combine to form the first generation HPS process, shown in Figure 5.1.

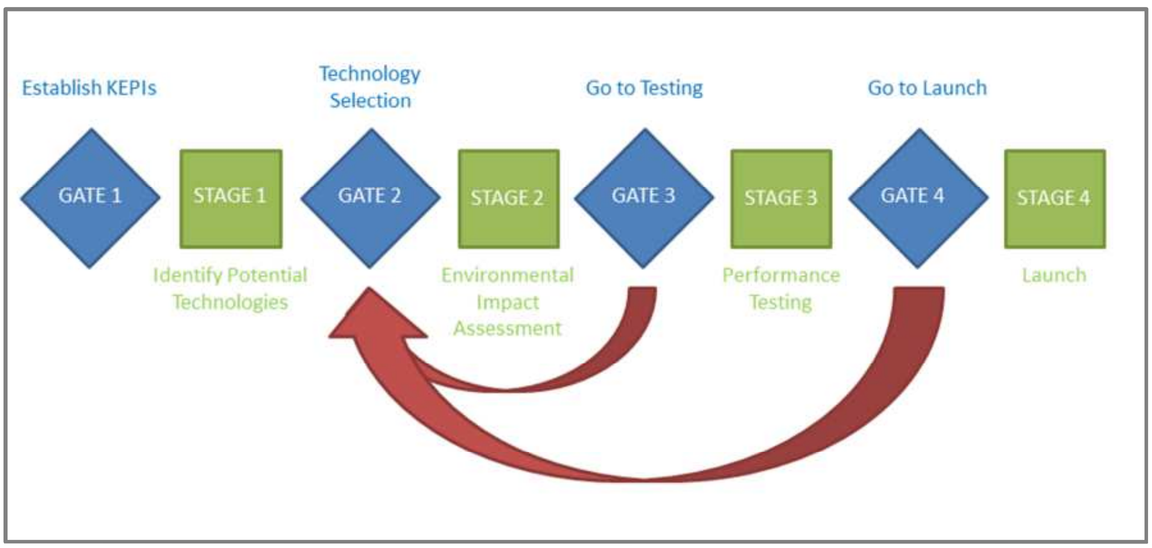

Figure 5.1: First Generation High Performance Sustainability Process

5.1.1 Developing Motorsport Technology with the HPS Process

Validation of the process was achieved through the manufacture of a motorsport technology demonstrator using HPS. Eco One, an environmentally friendly racing car, was based on a Formula Student car (Figure 5.2) previously built at WMG. The Formula Student car was analysed to identify potential environmentally considerate alternatives for the existing components. The available sustainable materials were identified and compared against the KEPIs to evaluate their environmental performance. The materials selected are shown in Table 5.2.

Table 5.2: Alternative Sustainable Materials Used in Eco One

Component	Original Material/Technology	Sustainable Alternative
Fuel	Gasoline-fuelled IC engine	E85-fuelled IC engine
Brake Pads	Aramid and heavy metal composite	Cashew Nut Shell Liquid (CNSL) and plant fibre hybrid composite
Tyres	Composite with carbon black	Composite with potato starch
Engine Lubricant	Mineral oil (petrochemical)	Plant oils
Bodywork	Carbon fibre/epoxy	Hemp fibre/epoxy

Further details of the selection and development of the technologies used in Eco One can be found in *Submission 2: Part III* and Appendix A1 at the end of this report.

In this stage the various components and technologies were manufactured or procured and then assembled onto Eco One. The finished car (Figure 5.3) was launched at the Eden Project in March 2007.

Figure 5.2: W5 Formula Student Car

Figure 5.3: Eco One

The media impact and public engagement generated by this innovative project was extensive, including national and international television appearances, newspaper and magazine articles and radio interviews; this reaffirmed the need for sustainable motorsport. Full details of this can be found in the *Dissemination of the Innovation* in the Engineering Doctorate portfolio. The development of Eco One provided valuable insights into the strengths and weaknesses of the HPS process.

5.1.2 Summary of the HPS Process

The 1st Gen HPS process was successfully used to create Eco One, a single seat racing car with hemp/epoxy bodywork, potato tyres, cashew nut shell brake pads, plant oil lubrication and bioethanol fuel (see Appendix A1 for details). The main advantages of the process were its flexibility and ease of implementation, allowing it to be applied to all components on the car.

The key disadvantage with this process as identified by the Eco One project is the potential for a detrimental effect on performance caused by the use of sustainable materials. The performance of the components was assessed to evaluate their adequacy, but in order to remain competitive in motorsport, the performance of sustainable technologies must be continuously developed. If adopting a sustainable material or technology results in loss of competitive advantage, or indeed a reduction in performance compared to a competitor then few motorsport teams would implement such a material by choice. In a paper published in 2003, Pujari and colleagues identified that environmentally-friendly products need to be effective in terms of their performance as well as their environmental performance if they are to succeed. They go on to state that:

"The most advanced environmental technologies will not contribute to the pursuit of sustainability unless they can wrestle market share away from conventional products" (Pujari *et al*, 2003).

A limitation of the HPS model is therefore that it placed too little focus on the mechanical performance of the materials selected; sustainability was the key consideration, and in some instances resulted in a loss in performance. HPS1 also relied on the existence of sustainable materials which could be utilised in a motorsport environment rather than on the development of new materials and technologies. This does not capitalise on the unique R&D capabilities of motorsport, and therefore should be modified.

5.2 Second Generation High Performance Sustainability Process

The second generation high performance sustainability process, or HPS2, utilises the same initial stages and gates as its predecessor, however significant changes were implemented after Gate 3 in order to overcome the limitations identified during the development of Eco One. The HPS2 process is described in detail in *Submission 2: Part III*.

5.3 Key Developments from the First Generation

The first generation HPS process assessed whether a sustainable technology's performance was *adequate* for use in a given application. In the HPS2 process, this is extended to deciding whether a material will be *competitive*. If the performance of the technology is not deemed to be competitive, then it is pushed back to the testing and development stage to improve performance. The introduction of this gate was intended to greater utilise the R&D capabilities of the motorsport industry to increase the rate of advancement of sustainable materials, rather than simply assessing whether existing materials were suitable for use.

Additional stages were added at the back end of HPS2 in order to greater reflect the continuous technology development that occurs in motorsport, and also to consider the end of life impacts of the novel technologies implemented using the process.

Once any changes to the manufacturing processes have been implemented, parts are manufactured and quality checked before installation on the motorsport vehicle.

A typical Stage-Gate process does not include the use of a product, because at launch any products developed are typically passed onto a customer and are beyond the control of the company which developed them. This stage was modified from the first generation process to emphasise the competitive nature of motorsport, and is intended to make sure any new materials and technologies are tested on-track and continuously developed.

After every race, the on-track performance of any component introduced using the HPS2 process is re-assessed to ensure that it is still competitive compared to its competitors. This applies not just to individual components, but how they affect the car as a whole.

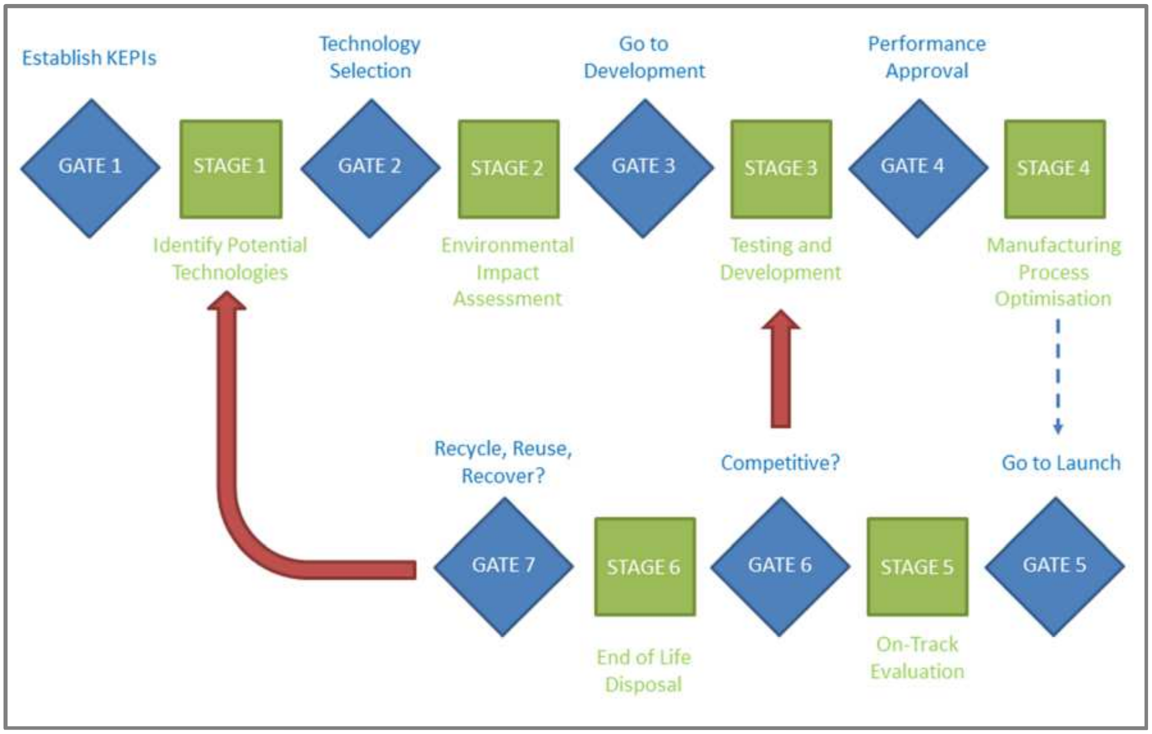

Figure 5.4: Second Generation High Performance Sustainability Process

The final stage is the appropriate disposal of end of life waste. End of life waste is a particular problem for motorsport due to the continuous development that occurs; parts regularly become obsolete as new iterations of components are introduced. End of life technology is broken down into constituent materials for treatment. Any materials, whole components or energy generated through incineration of materials should be evaluated to investigate the possibility that they can be fed back into Stage 1 of the HPS2 process in order to assess the potential of using end of life wastes as new sources of materials for development. Although volumes of recycled material are likely to be low, the potential to extend their useable life is advantageous in terms of environmental sustainability, and could also result in cost reductions.

5.4 Summary of the HPS2 Process

The second generation HPS process is shown in Figure 5.4. It addresses the deficiencies of the first generation by recognising the need for a balance between sustainability and on-track performance. The addition of developmental stages encourages the use of motorsport R&D for the advancement of relevant, sustainable materials and technologies, and the continuous reassessment of these materials in order to maintain competitiveness.

The addition of a stage and gate to consider the potential use of end of life materials as a resource encourages both producer responsibility and a reduction in the consumption of materials with high embodied energy such as carbon fibre, which are typically landfilled after use.

The second generation process (HPS2) was used to develop individual motorsport technologies to demonstrate the efficacy of the process and the potential impact of its use. To carry out in-depth research on all of these technologies would have been beyond the scope of the Engineering Doctorate, therefore two areas identified in *Submission 1: An Introduction*; composites and fuels, were selected as the subject of further research and development.

The development of a novel technology development process for sustainable motorsport was a valuable contribution to knowledge. In order to prove the innovation of this process, and its suitability for use in motorsport applications, it was used to develop individual sustainable technologies. In the next two chapters the development of these technologies using the HPS2 process is presented.

5.5 Impact of the Innovation

The creation of a technology development process for sustainable motorsport represented a step change in the approach taken towards introducing sustainability to motorsport. Rather than considering one element at a time, HPS2 allows the concurrent development of technologies which are environmentally sustainable as well as providing competitive performance. The HPS2 Process was used in the development of the WorldFirst F3 car, a technology demonstrator for sustainable motorsport technology which was a direct continuation of the Eco One Project previously described in this report. Project managed by Dr. James Meredith at WMG and with industrial partners including Lola Cars and BASF, WorldFirst combined innovative environmentally sustainable technologies with genuinely competitive on-track performance. The author was directly involved with the implementation of biodiesel fuel for this project which will be discussed in detail in Chapter 6 of this Innovation Report. A report published in Professional Motorsport World magazine on the technologies used in WorldFirst can be found in *Disseminating the Innovation* in the Engineering Doctorate portfolio.

An example of the success of the HPS2 process in developing sustainable technologies with competitive performance are the body panels such as the sidepods, damper hatch and engine cover. Much of the F3 car tub and body panels were constructed from carbon fibre reinforced composite. By following the HPS2 process and examining potential end of life treatment routes, recycled carbon fibre was identified as a potential source of material for motorsport, resulting in a reduction in cost and waste compared to virgin carbon fibre. The properties of recycled carbon fibre have been found to be within 85% of the properties of virgin carbon fibre when used as an impact absorbing structure, which has significant interest from the motorsport industry.

As a result of the technologies developed using HPS2, WMG has been named as a supplier of sustainable composite body panels for the Lola Drayson all-electric racecar (Drayson Racing Technologies, 2011a), a technology demonstrator project which will showcase the potential of sustainable technologies in motorsport. Lord Drayson formed the company in November 2007, after the launch of Eco One and during the Engineering Doctorate research programme, to "act as a racing laboratory to pioneer the development of green technologies in the challenging environment of motor racing" (Drayson Racing Technologies, 2011b). The concepts introduced and demonstrated by HPS2 are therefore being adopted by the motorsport industry.

6 Developing Innovative Sustainable Composites for Motorsport

Submission 3: The Use of Fibre Reinforced Composites in Motorsport demonstrated that the fibre reinforced composites used in motorsport can be advantageous in terms of mass reduction and a corresponding increase in performance, but that their cost and environmental impact are high compared to traditional engineering materials. When considering the environmental impact of their products, the automotive and aerospace industries select materials which will have the lowest impact during the use phase because this dominates the lifecycle of aeroplanes and cars. Motorsport vehicles have a shorter use phase compared to passenger cars or aeroplanes, and therefore component mass reduction has little influence on environmental impact during the use phase of the lifecycle. *Submission 3* identified that the lifecycle phases with highest impact for motorsport are the production of raw materials followed by end of life treatment and manufacturing processes. More emphasis must be placed on assessing the embodied energy and carbon of the raw materials, the ease and variety of options for end of life treatment and the impact of the manufacturing processes that will be used. The research presented in this chapter was focussed on the materials used for manufacturing motorsport composites. It is a summary of work found in *Submission 4: Developing Natural Fibre Reinforced Composites for Motorsport*, *Submission 5: Lignin/Epoxy Powder Coating Resins and Powder Sprayed Natural Fibre Composites* and *Submission 7: A Cost Analysis of Natural Fibre Reinforced Composites*. This research resulted in the publication of two peer-reviewed journal papers by the author.

6.1 Identifying an Alternative to Glass and Carbon Fibre Composites

Fibre reinforced composites are used widely in motorsport due to their exceptional specific mechanical performance, both in terms of strength and stiffness. However this comes with a financial and environmental cost due to the energy intensive methods necessary to manufacture the raw materials and the processes which then turn these into finished components. An environmental impact assessment of some of these materials is carried out in *Submission 3: The Use of Fibre Reinforced Composites in Motorsport*.

The multi-phase nature of composites results in difficulties when considering end of life disposal options; the common methods of treating composites at end of life are landfilling and incineration (Scheirs, 1998). New techniques such as pyrolysis have been attempted, but the resulting reduction in mechanical properties due to temperature related degradation of the fibres and contamination from the process result in them being ‘downcycled’; used in an application requiring lower mechanical properties (McNally *et al*, 2007).

A more sustainable replacement for carbon and glass fibres was therefore investigated, with the following Key Environmental Performance Indicators:

- Embodied energy
- Renewable material content
- End of life disposal options

An evaluation of the available materials was carried out (*Submission 4: Developing Sustainable Materials for Motorsport Composites*); the characteristics of the two most suitable replacements are shown in Table 6.1

Table 6.1: Summary of the Characteristics of Alternative Materials

Material	General Properties	Raw Materials	End of Life Options
Recycled Carbon Fibres	Good mechanical properties High cost	Very high embodied energy Waste material (short fibres)	Recycling of fibres Landfill
Natural Fibres	Mechanical properties comparable to glass Low cost	Renewable materials from natural fibres Low embodied energy	Biodegradable Energy Recovery

The mechanical properties of recycled carbon fibre are attractive, and its origins as a waste material reduces both its cost and environmental impact. However the cost of this material is still higher than that of virgin glass fibre and its availability as short chopped fibres limits the possible applications as a composite reinforcement. Natural fibres were found to be biodegradable, renewable and to have specific mechanical properties which compete with glass fibres. Using the KEPIs to generate scores for each material resulted in the natural fibres being selected for further evaluation.

6.2 Benchmarking of Natural Fibre Reinforced Composites

Composites manufactured from randomly oriented hemp fibres and epoxy and polyethylene terephthalate (PET) filled polyester resins by vacuum assisted resin transfer moulding (VARTM), were tested for tensile strength. Glass and carbon fibre reinforced epoxy samples were also tested for comparative analysis. This work was published in the Journal of Advanced Materials (Wood *et al*, 2010). Full details of the methods and materials used in manufacture can be found in *Submission 4: Developing Sustainable Materials for Motorsport Composites.*

Samples were machined into 'dogbone' tensile samples and then subjected to tensile testing to the appropriate test standards. The ultimate tensile strength (UTS) of each sample is shown in Figure 6.1. The figure clearly shows the relatively poor mechanical properties of a chop strand hemp mat reinforced with either resin compared to the synthetic woven and non-woven materials.

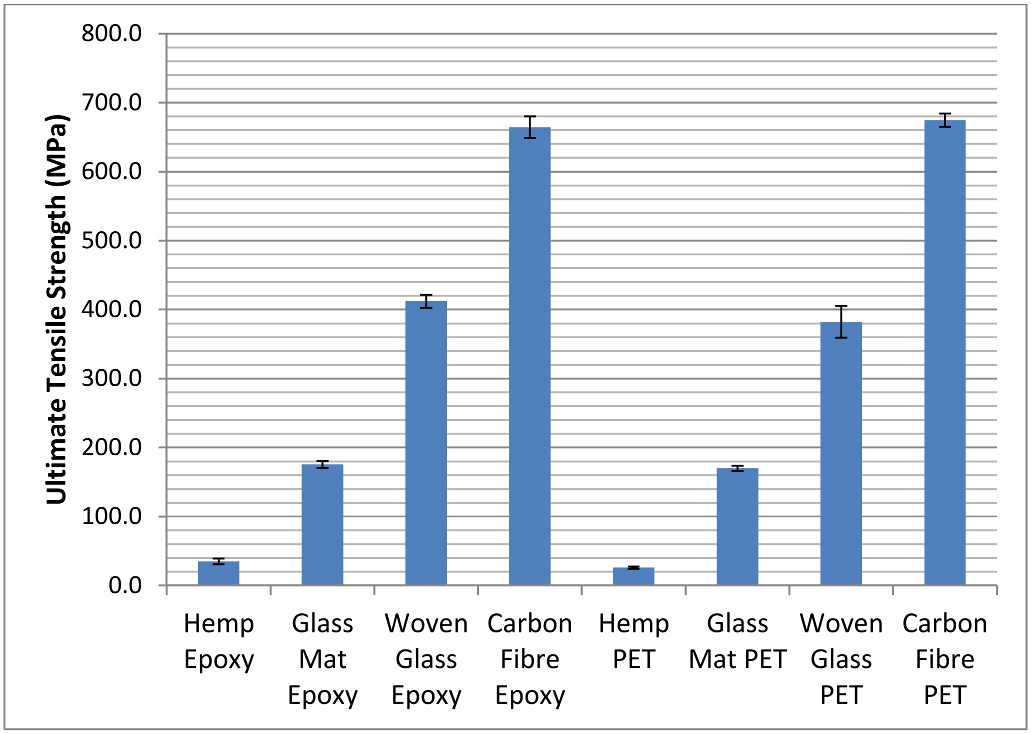

Figure 6.1: UTS for a variety of fibres and resins

The tensile strength of a composite reinforced with chopped strand mat made from hemp fibre is more than an order of magnitude less than that of a woven carbon fibre reinforced epoxy; 34.97MPa compared to 664.43MPa. Woven carbon fibre reinforcement resulted in the highest UTS of the materials tested; the difference in properties of the epoxy and PET-filled polyester resins with this material were within one standard deviation. Woven glass fibre gave the next highest UTS (412.22MPa) followed by chopped strand glass mat (175.6MPa) and finally chopped strand hemp (34.967MPa). These results show that natural fibre-reinforced composites are not able to compete with the ultimate tensile strength of synthetic fibres. This established the opportunity for further research into improving the mechanical properties of these materials to increase the potential uses for them in a motorsport environment.

6.3 Technical Challenges for Natural Fibre Reinforced Composites

The deficiency in strength of natural fibre reinforced composites noted during benchmarking has been confirmed by a number of researchers (e.g. Andersson & Tilman, (1989), Baley *et al*, (2006), Gassan & Bledzki, (1997), Liu *et al* (2007)). The mechanical properties of natural fibres are generally comparable to those of engineering fibres such as E-Glass, however when they are used to reinforce polymer resins the properties of the resulting composite are disappointing. This has been attributed to the interface between the fibre and matrix which in carbon, glass and Kevlar composites is chemically enhanced. Natural fibres adhere to the matrix solely through mechanical interaction, there is no chemical bonding. The hydrophilicity of natural fibres and hydrophobicity of polymer matrices results in a lack of compatibility and therefore poor interfacial adhesion (Zafeiropoulos, 2008). There are a wide variety of treatments that can be used to improve the fibre-matrix adhesion in natural fibre reinforced composites such as mercerisation, esterification and the use of compatibilisers and coupling agents (Joffe *et* al, 2003; Alix *et* al, 2009; Kalia *et al*, 2009; Malkapuram *et al*, 2009; Strong, 2008). The majority of these involve some form of chemical processing to alter the surface chemistry of the fibres, remove physical imperfections, or to act as an intermediary between phases and therefore improve their adhesion to the matrix. These chemical treatments have shown a range of improvements when used to modify the surface of natural fibres, however they reduce the sustainability of natural fibre reinforced composites by utilising additional processes, harmful chemicals and increasing cost.

Lignin was identified as a possible alternative to chemical treatments as a compatibiliser in *Submission 4: Developing Sustainable Materials for Motorsport Composites*. As one of the components of plant biomass and a waste product from paper-making, tens of millions of tonnes of lignin are produced each year (Hatfield & Ralph, 1997; Stevens, 2002). Lignin forms chemical bonds with hemi-cellulose to maintain plant structure. By adding lignin to a resin, there is the opportunity for the lignin to chemically bond with the natural fibre reinforcement and therefore increase the bonding between fibre and matrix. Kraft lignin is removed from wood pulp via addition of sodium hydroxide and sodium sulphide which break down the chemical bonds between the lignin and cellulose, the required component for making paper (Baptista *et al*, 2006). In this form it is a solid brown powder with a range of particle sizes, a micrograph of which is shown in Figure 6.2.

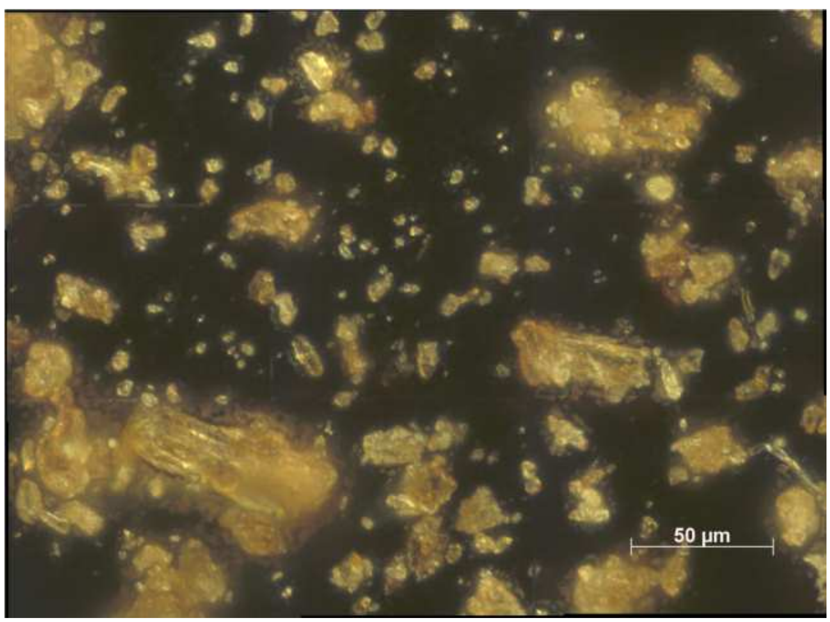

Figure 6.2: Dark field micrograph of Kraft lignin particles

Previous work has shown that lignin can impart beneficial properties to the structure of a composite by dissolving the lignin in aqueous sodium hydroxide (Thielemans *et al*, 2002) or chemical modification of the lignin with butyric anhydride to solubilise it in an epoxy resin (Thielemans & Wool, 2004). However both of these methods require additional chemical processing to the lignin before the composite is manufactured. Lignin has also been utilised in compression moulding techniques to make natural fibre reinforced polypropylene composites (Acha *et al*, 2009; Rozman *et al*, 2000) although this method uses high temperatures which can be potentially damaging to the natural fibre reinforcement and impair the structural properties of the composite.

It was proposed that in its solid state and with no chemical treatment, lignin would improve fibre-to-matrix adherence and structural properties of the resulting composite whilst minimising the addition of processing steps and harmful chemical treatments. The benefits of using this material include:

- Reduction in resin costs due to use of lignin as a low-cost filler
- Replacement of environmentally impactful chemicals with a natural material
- Making use of a waste material
- Potential increase in interfacial shear strength

6.4 Mechanical Testing of Hemp/Epoxy/Lignin Composites

Composites of non-woven hemp fibre, epoxy resin and lignin filler were manufactured by VARTM. The amount of lignin added was varied from 0% to 5% by resin weight in order to investigate the compatibilising effect. Samples were prepared according to relevant standards, and subjected to tensile and Charpy impact testing. The full experimental methodology can be found in *Submission 4: Developing Sustainable Materials for Motorsport Composites*. A summary of the results and key findings from the development of this technology follows.

6.4.1 Tensile testing

The results for the tensile testing are shown in Table 6.2. 2.5% w/w lignin gave the greatest improvement in the tensile properties of the composite. The Young's modulus increased from 3.96 GPa at 0 % w/w to 5.11 GPa at 2.5% w/w and the mean UTS increased from 22.6 MPa to 31.1 MPa for the same addition of lignin.

A further increase to 5% w/w lignin content resulted in no statistical difference in Young's modulus but a reduction in UTS caused by the large volume of lignin particles preventing complete wetting out of the fibre reinforcement. This effect has previously been observed by Thielemans and Wool (2004). This explains the brittle nature of the composite, given that the strain at failure is on average 27% higher for composites containing 2.5% w/w lignin than 5% w/w lignin.

Table 6.2: Tensile Modulus and UTS for Composites

Lignin Content (% w/w)	**Modulus (GPa)**	**UTS (MPa)**
0.0	3.96 ± 0.18	22.63 ± 2.11
1.0	2.91 ± 0.16	20.57 ± 1.15
2.5	5.11 ± 0.39	31.15 ± 2.71
5.0	4.74 ± 0.31	23.37 ± 2.24

There are some interesting changes when lignin is added at a 1 % w/w level. The ductility of the composite is increased compared with both 0% w/w and 2.5% w/w lignin content. However, the tensile strength is reduced indicating there is a plasticising effect of the lignin at that level; increased flexibility but reduced strength and stiffness. This can be attributed to a combination of the interfacial effect between the lignin and the hemp fibres and an effect related to the increased viscosity of the resin causing incomplete infusion of the composite part.

6.4.2 Impact testing

Comparison of the impact properties of the fabricated composites using the Charpy impact test showed that there is an increase in toughness as more lignin was added to the part. With no lignin added the Charpy impact strength was 6.17 kJ m^{-2}, which increased to 10.78 kJ m^{-2} when 1.0% w/w lignin was added. The results of the impact testing are shown in Figure 6.3.

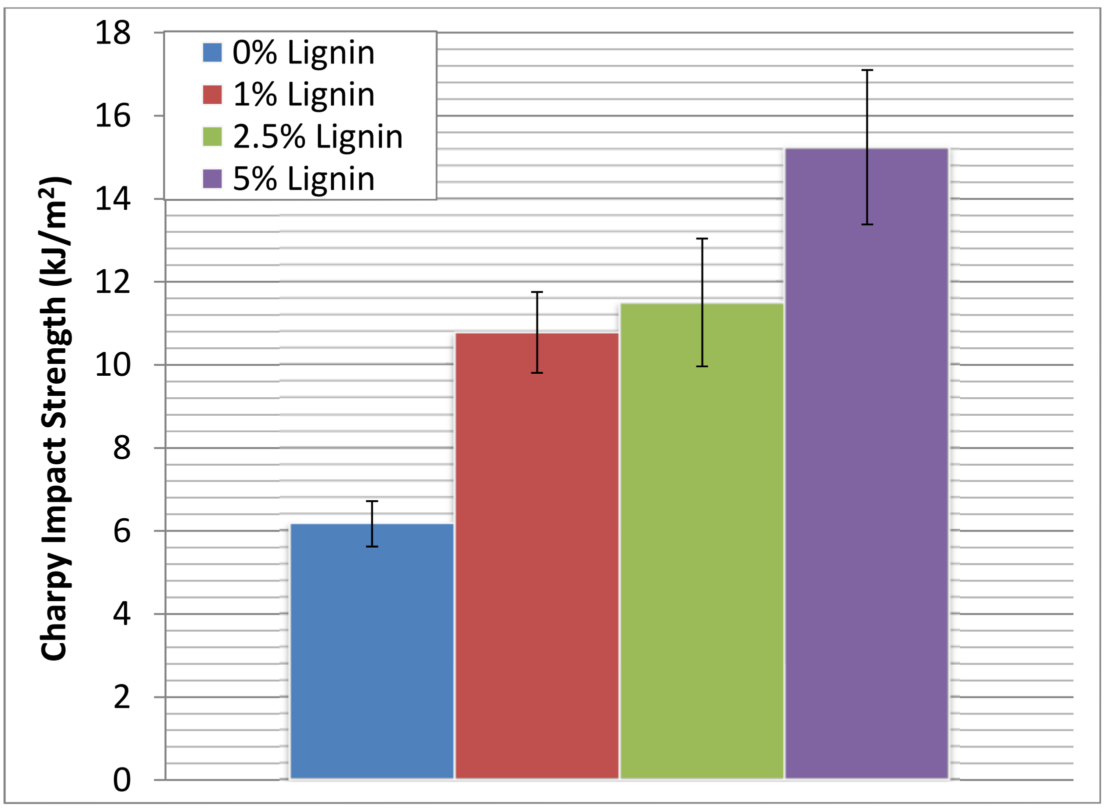

Figure 6.3: Charpy impact test results

Addition of 2.5% w/w showed no statistical improvement over 1% lignin addition. However, increasing the lignin content to 5.0% w/w showed a significant rise in the impact strength of the composite (15.24 kJ m^{-2}). This represents an increase of more than 140% compared to the composite with no added lignin.

The tensile strength and toughness of polymers have been shown to decrease and tensile modulus to increase proportionally with the addition of particulate filler (Karger-Kocsis, 1995). Adding fibre reinforcement tends to increase all of these characteristics (Stokes *et al*, 2000). The present research concerns the addition of fibre reinforcement and a particulate filler, and therefore the effects on the mechanical properties of the resulting hybrid composite are complex. Hartikainen *et al* (2005) used a combination of calcium carbonate and long glass fibres to reinforce a thermoplastic polypropylene matrix. In their experiments it was found that adding calcium carbonate reduced the excellent interfacial adhesion between the polypropylene and glass fibres by introducing voids (porosity) and by coming into contact with the fibres, limiting the surface area of fibre and matrix that remained in contact. If this were the case with the hemp, epoxy and lignin hybrid composites tested in this report there would be a direct correlation between the amount of lignin added and the mechanical properties of the composites; tensile and strengths would decrease in proportion to the amount of lignin added, and the tensile modulus of the composite would increase.

The results show evidence of two effects; the reduction in properties previously described caused by the addition of a particulate phase, and the improvement in properties resulting from improved interfacial adhesion. At up to 2.5% lignin addition, the increase in interfacial shear stress (IFSS) results in an improvement in properties. When the percentage of lignin added exceeds 2.5%, the increase in porosity caused by the concentration of filler is dominant and outweighs the positive effect of increased interfacial adhesion. Further study of the morphology of the fracture surfaces of the composite samples was used to confirm the above hypothesis. Scanning Electron Microscopy (SEM) was used to analyse the failure surfaces of the hemp/epoxy samples after they were subjected to Charpy Impact testing. With no added lignin there was evidence of significant fibre pullout and a lack of interfacial adhesion, as indicated by the red arrows in Figure 6.4.

Figure 6.4: SEM image of hemp / epoxy composite with no added lignin

Adding 5% lignin (Figure 6.5) further increased the interfacial bond strength, demonstrated by instances of matrix failure around fibres (green arrows) and a reduction in instances of fibre pullout. The reduction in tensile strength compared to 2.5% lignin addition was attributed to the increase in porosity shown by the red arrows which has been shown to have an effect on the mechanical properties of composite materials (Madsen *et al*, 2009). A similar effect was detected by Thielemans and Wool (2004) and is a result of large volumes of lignin particles preventing complete wet-out of the fibre reinforcement.

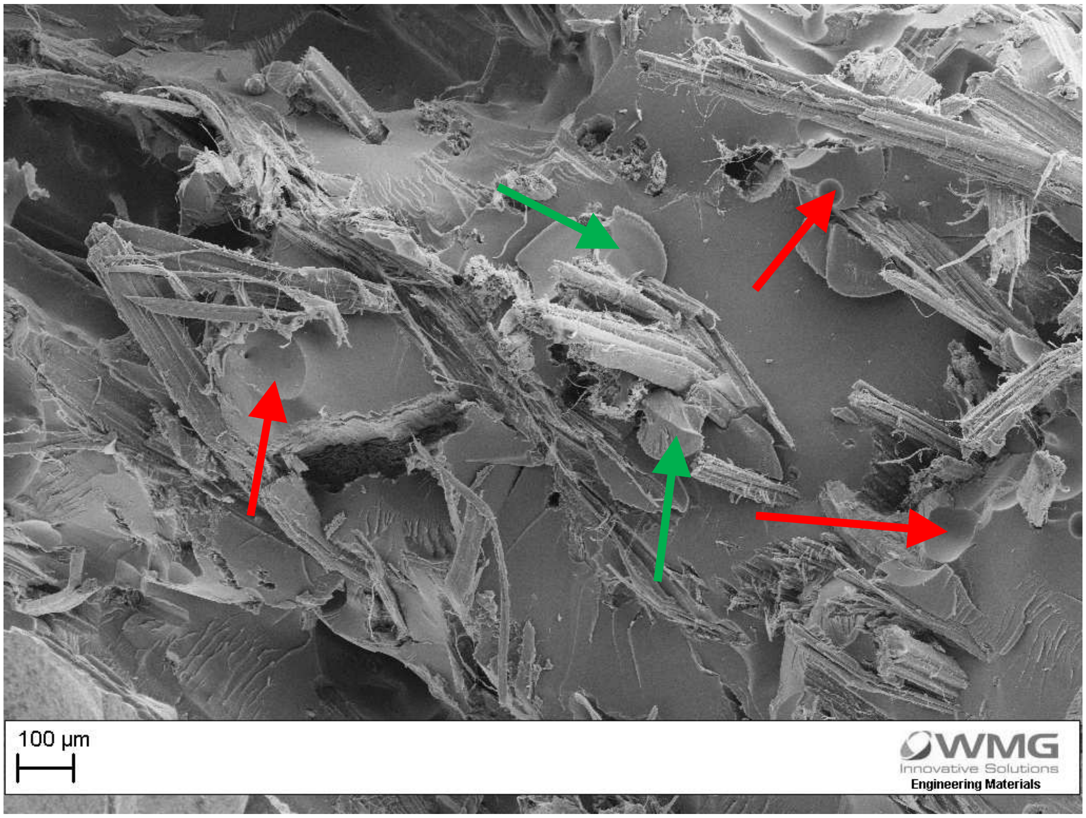

Figure 6.5: SEM image of hemp / epoxy composite with 5% w/w lignin added

Composites made from an epoxy resin and natural hemp fibre reinforcement with varying amounts of added Kraft lignin were fabricated. The addition of lignin was shown to be beneficial towards improving the impact, tensile and flexural strength, although the latter two also showed a decrease when more than 2.5% by weight of lignin was added. This is attributed to the lignin particles preventing complete resin infusion across the hemp mat which subsequently reduces the physical properties.

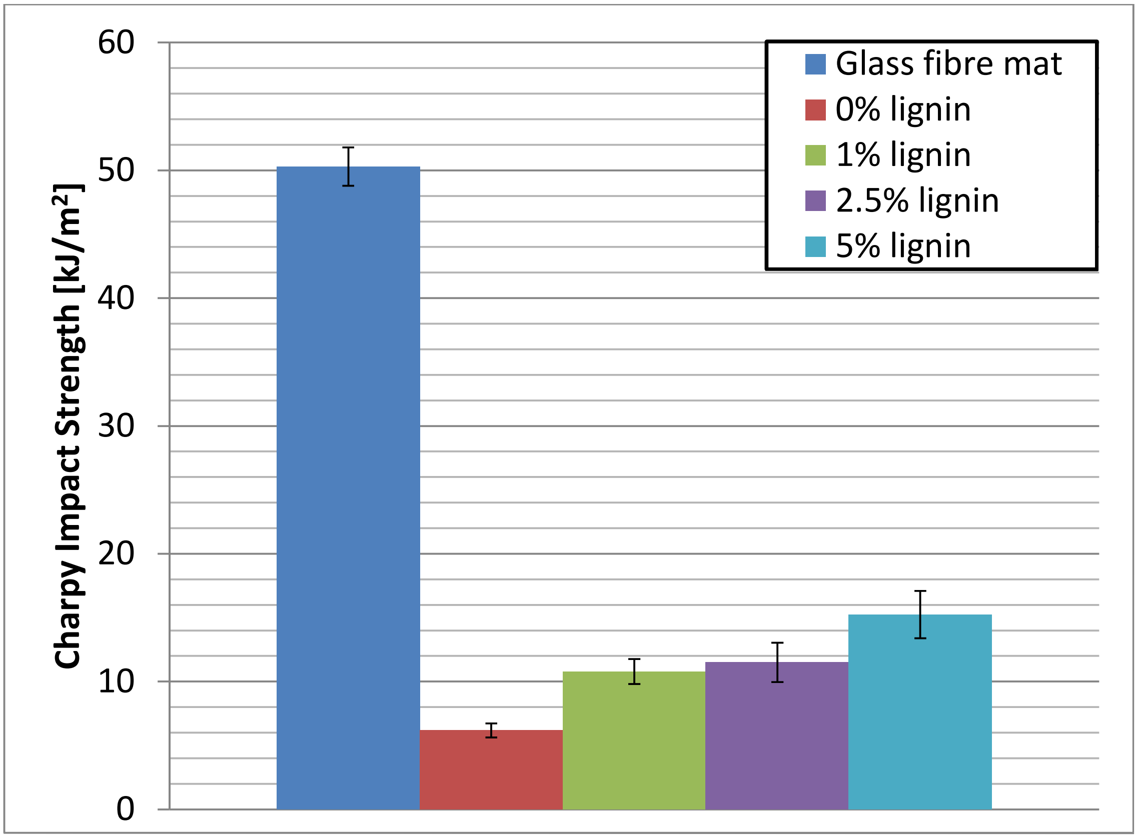

Figure 6.6: Impact of Development Using HPS2

Figure 6.6 shows the improvement in material performance from the hemp/epoxy composites developed using the first generation HPS process to the hybrid hemp/epoxy/lignin composites developed using HPS2. Although the mechanical properties of natural fibre composites are still below those of glass fibre composites, the improvement in impact strength, tensile strength and modulus resulting from the work carried out in this research means that NFRCs can be used in a wider variety of motorsport applications. This work was published in Composites Science and Technology (Wood *et al*, 2011).

6.5 Financial Analysis of Natural Fibre Reinforced Composites

The mechanical properties of hemp/epoxy/lignin composites have been shown to be suitable for non-safety-critical applications in motorsport through a rigorous mechanical testing programme. In order to prove their economic sustainability, a cost analysis of a component made from carbon, glass and natural fibres was undertaken and can be found in *Submission 7: A Cost Analysis of Natural Fibre Reinforced Composites*. A summary of the results of this cost analysis is given here. The product considered was a Formula 3 wing mirror (Figure 6.7); these are commercially available made from both Nylon and carbon fibre. The potential market for these mirrors was predicted to be 4,000 units.

Figure 6.7: Carbon Fibre F3 Wing Mirror

Figure 6.8: Hemp/Epoxy Wing Mirror Shell with 5% Lignin Compatibiliser

Cost analysis of wing mirror shells manufactured from injection moulded Nylon, autoclaved carbon fibre and VARTM natural fibre composite showed that for low production volumes, the lower tooling costs of composite components result in lower costs than injection moulded components (see Table 6.3).

Table 6.3: Cost Analysis Summary

	Nylon	Carbon Fibre	Hemp Fibre	Hemp w/5% Lignin
Tooling Cost (4,000 units)	£18,000	£2,000	£2,000	£2,000
Cost/unit	£3.25	£51.01	£8.70	£9.16
Total Cost (4,000 Units)	£31,000	£206,040	£36,800	£38,640
Mass of Mirror	35g	20g	28g	28g

Manufacturing 4,000 mirror shells from hemp/epoxy/lignin natural fibre reinforced composite (NFRC) would result in an 82% cost reduction compared to carbon fibre and a 16% increase in costs compared to injection moulded Nylon.

However, NFRC wing mirrors (Figure 6.8) were 7g lighter than Nylon, a reduction in mass of 20%. The carbon fibre mirror had a mass of just 20g, representing a 43% reduction in mass compared to Nylon and a 29% reduction compared to NFRC. This allows a premium of £2.04 per gram of mass reduced to be charged for carbon fibre wing mirrors compared to Nylon. By applying this premium to NFRC mirrors a potential retail price of £44.74 was established.

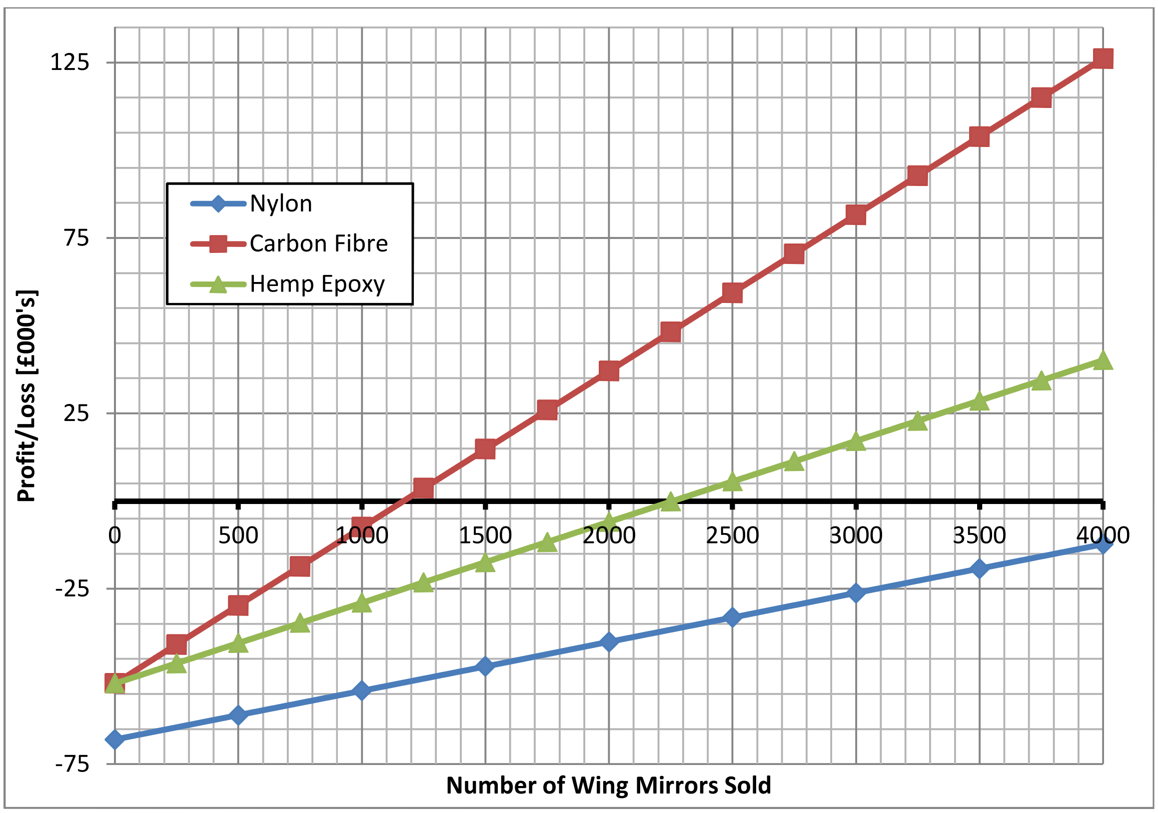

Figure 6.9: Breakeven Analysis for F3 Wing Mirror Production

Breakeven analysis (Figure 6.9) showed that Nylon wing mirrors would not become profitable within the expected production volume of sale of 4,000 units, whereas NFRC would break even after approximately 2,250 and carbon fibre after 1,150 units.

NFRCs provide the attractive compromise of a reduction in mass compared to Nylon wing mirrors, with lower production and capital costs than carbon fibre, and with the additional benefit of an increased renewable material content compared to either alternative.

6.6 Novel Manufacturing Process for Natural Fibre Composites

Current manufacturing processes for synthetic composites such as autoclave moulding are designed to maximise the mechanical properties of these materials, but have high energy footprints which are unattractive for more sustainable alternatives such as Natural Fibre Reinforced Composites (NFRCs). *Submission 5: Lignin/Epoxy Powder Coating Resins and Powder Sprayed Natural Fibre Composites* was a feasibility study intended to identify possible alternative processing routes for NFRCs. This identified powder coating as a potentially innovative manufacturing solution. Natural fibre reinforced composites were successfully manufactured using a novel electrostatic powder coating process (Figure 6.10).

Figure 6.10: Novel Powder Spray Composite Manufacturing Process

The overall mechanical properties of powder sprayed natural fibre reinforced composites were found to be uncompetitive with engineering composites due to processing difficulties resulting in poor wet-out of fibres. The process was successfully demonstrated, although further work is required in order to develop the technology beyond the scope of the Engineering Doctorate research programme. The development of novel resins filled with lignin was required for this process; their suitability for use as a powder coat was investigated.

6.6.1 Novel use of Lignin as a Filler in Powder Coating Resins

Powder coating resins are used on a variety of motorsport components to inhibit corrosion and prevent damage. Typical filler materials for these resins include calcium carbonate and barium sulphate (Pittman, 2010). A collaboration was instigated with Sonneborn & Rieck Ltd, a manufacturer of powder coating resins and paints. The collaborating company produced a range of powder coat formulations (see Table 6.4) with lignin replacing calcium carbonate as a filler.

Table 6.4: Composition of Powder Coating Resin Formulations

Formulation	Epoxy resin and hardener [%]	Lignin [%]	Black Dye [%]	PTFE (%)
A	99	0	1	0
B	98	1	1	0
C	89	10	1	0
D	>73	25	1	<0.5

The formulations were sprayed onto steel test panels as shown in Figure 6.11. Testing of the surface revealed that surface gloss and roughness could be modified by varying the content of lignin used in the formulation. Full results from this testing can be found in *Submission 5: Lignin/Epoxy Powder Coating Resins and Powder Sprayed Natural Fibre Composites*.

Figure 6.11: Test Samples of Powder Coat Formulations

Replacing 1% of the fillers currently used in powder coatings with lignin would result in cost savings for the powder coating industry of up to £1.73 million. The addition of 25% lignin filler to an epoxy powder coating resin resulted in a non-reflective, high-friction surface coating which could have applications in motorsport such as high-grip coatings on pedals and floor panels. Surface gloss of the coated component also reduced with increasing lignin content, resulting in a powder coating formulation suitable for applications where low glare is required. As a waste product from the paper industry and also a renewable resource, lignin could replace the fillers currently used in powder coating resins as a low cost, more environmentally friendly alternative.

6.7 Summary of Innovative Sustainable Motorsport Composites

In order to evaluate the potential applications of natural fibres in motorsport, composite samples were manufactured from glass, carbon and hemp fibres and epoxy resins. Initial mechanical testing of these composite materials showed that the properties of hemp fibre reinforced composites are inferior to those reinforced with glass or carbon fibres, which has previously been attributed to the poor adhesion between the fibre and matrix.

The novel addition of 2.5% by weight of untreated Kraft lignin to the hemp reinforced epoxy resulted in a 29% increase in tensile modulus, a 37% increase in ultimate tensile strength and an 86% increase in Charpy impact strength. 5% lignin addition resulted in a further 32% increase in impact strength, but with a reduction in tensile strength and modulus.

These improvements to the mechanical properties of the composites indicate an improvement in the fibre/matrix adhesion. This interfacial effect was validated through the use of scanning electron microscopy, which showed evidence of reduced fibre pullout and an increase in resin remaining attached to fibres at fracture surfaces. The specific mechanical properties of the lignin-treated composites were approaching those of glass fibre hence there are several opportunities to make use of renewable or waste materials in composite applications.

By using the HPS2 process, natural fibre reinforced composites were identified as a viable alternative with the highest environmental performance. The mechanical performance was improved through the addition of lignin, a sustainable and biodegradable waste product. This work demonstrated that natural fibre reinforced composites could be used as a replacement for fibreglass in motorsport applications.

A novel manufacturing process for natural fibre reinforced composites based on powder coating technology was successfully developed and demonstrated through a feasibility study. The mechanical properties of the resulting composites were not competitive with existing manufacturing methods therefore further developmental work is required in this area.

A novel filler for powder coating resins has been introduced which can be used to vary the renewable content, reduce the cost and change the surface texture of epoxy powder coats. These resin formulations have wide applications throughout motorsport where surface coatings are used for anti-glare, grip and resistance to corrosion and abrasion. Lignin, as a waste product from the paper industry and also a renewable resource, could replace the fillers currently used in powder coating resins as a low cost, more environmentally friendly alternative. The replacement of 1% of calcium carbonate or barium sulphate with lignin in epoxy powder coatings would result in annual cost savings to the industry of up to £1.73 million.

6.8 Impact of the Innovation

Research into sustainable composites instigated in this Engineering Doctorate has led to the development of a new area of research for WMG. Sustainable motorsport projects which have directly resulted from the work in the research programme include the WorldFirst F3 car and further development of natural fibre reinforced composites.

The use of natural fibre reinforced composites for energy absorption structures for motorsport has been the subject of research within WMG, and resulted in a publication (contributed to by the author) in Composites Science and Technology (Meredith *et al*, 2011).

The innovative demonstration of natural fibre reinforced composites in motorsport applications led to interest from several companies. The author was requested to give advice and consultancy to Lotus Engineering during a meeting at WMG in late 2007. This was followed by the launch of the 'Eco Elise', a car which featured hemp/epoxy body panels (shown in Figure 6.12) that was launched in July 2008 (Lotus Engineering, 2008).

Figure 6.12: Lotus Eco Elise (Lotus Engineering, 2008)

In addition to the automotive industry, the author was contacted by Ian Dawson, team manager of the British Eco Racing Team's Radical SR9 LMP1 prototype racer shown in Figure

6.13. Consultancy was provided, with the result that the prototype ran with hemp/epoxy body panels while competing in the 2008 Sebring 12 Hours endurance race (evo, 2008).

Figure 6.13: British Eco Racing's Radical SR9 LMP1 Racecar (evo, 2008)

Research from this Engineering Doctorate has been effectively disseminated and shown to give benefit for the automotive and motorsport industries.

7 Innovative Use of Biodiesel as a High Performance Fuel

The recent increase in the use of diesel engines in forms of motorsport such as the *24 Heures Du Mans* (Bamsey, 2008) and World Touring Car Championship (WTCC) (SEAT Sport UK, 2007) has demonstrated there is demand for the compression ignition engine in this field. Such is the success of the diesel powered cars at Le Mans that it has been suggested that the regulations are biased in their favour (Bamsey, 2008). This is due to the power and fuel efficiency advantage that they are able to achieve, allowing faster lap times but also fewer pit stops. For endurance racing, this combination is difficult to beat with a gasoline-fuelled car.

Diesel fuel is sourced from crude oil, and is therefore unsustainable in the long term. *Submission 1: An Introduction* identified biodiesel as an area of further research. Biodiesel is the name given to an alternative fuel for diesel engines which is manufactured from natural oils or fats. It is typically manufactured using a chemical reaction known as transesterification which involves mixing the natural fats with methanol and a base metal catalyst. The resulting fatty acid methyl esters (FAME) are known as biodiesel. Biodiesel could provide an excellent alternative to diesel fuel for motorsport. The research presented in this chapter of the Innovation Report is covered in great detail in *Submission 6: First Generation Biodiesel as a Motorsport Fuel*; this section provides a summary of the research carried out in this area.

7.1 Identifying Opportunities in Biodiesel Research

Fuels manufactured from the useful part of a plant such as the seed, oil, or fruit are known as first generation biodiesel. The problem with these crops for automotive biodiesel production is that the agricultural land that they grow on and the crops themselves could be used to produce food (Pimental *et al*, 1988; Brown, 2006; Runge & Senauer, 2007). However, the same limitations do not apply to motorsport; the volume of fuel used for motorsport is insignificant compared to the global road transport fuel demand, hence first generation biodiesel could provide a low cost, sustainable motorsport fuel without creating competition for agricultural land. An alternative to plant-based feedstocks are waste fats such as used cooking oil (UCO). Second generation biodiesel is produced from waste biomass. Making use of waste biomass such as the stems of food crops requires extensive chemical processing such as the Fischer-Tropsch process in order to extract useful fuels, therefore the economic and environmental sustainability of these feedstocks is uncertain (Sie & Krishna, 1999). The use of waste oils and fats, however, provides an excellent alternative to first generation biodiesel feedstocks for motorsport.

The opportunity presented by using biodiesel lies in its unique chemical structure. The esters produced through transesterification have hydrocarbon chains of different lengths and of different levels of saturation; both factors which have been shown to affect the properties of biodiesel (Anslyn & Dougherty, 2006; Knothe, 2005). Biodiesels are therefore highly 'tuneable' fuels due to the range of feedstocks available, each of which result in different fuel properties.

Table 7.1: Biodiesel and Diesel Fuel Properties

Test	Standard	EN590 Diesel	Beef Tallow B50	Soybean B100
Kinematic Viscosity (mm^2/s)	EN ISO 3104	2.80	3.62	4.27
Gross Calorific Value (MJ/kg)	-	44.8	43.24	40.50
Cetane Number	EN ISO 5165	52.0	63.9	64.1

A selection of fuel properties of biodiesel blends and petrochemical diesel fuel are shown in Table 7.1. Of particular interest are the cetane numbers (CN) of the fuels. Biodiesels typically have higher CN than diesel, which directly affects their combustion quality. The CN of biodiesels increases with chain length and saturation, but viscosity also increases with saturation (Knothe *et al*, 2003) which presents a challenge if attempting to extract the maximum performance from a biodiesel fuel.

An increase in CN results in less ignition delay and efficient combustion of the fuel/air mixture and hence a shift in the time at which peak in-cylinder pressure occurs. Providing this is achieved at the appropriate crankshaft rotation, a corresponding increase in power is possible by allowing the engine to operate at higher speed. This improvement in combustion quality compared to diesel could be used to offset the lower calorific value and therefore efficiency of biodiesel fuels, as well as improving their performance.

7.2 Technical Challenges Facing the Use of Biodiesel in Motorsport

The period during which fuel has been injected into the cylinder and started to mix with the compressed air but has not yet ignited is known as the ignition delay. The ignition delay of a fuel is partly due to its combustion quality, indicated by its cetane number (CN). Higher CN corresponds with a reduction in ignition delay and could therefore help to limit the formation of NO_x (Nitrogen oxides) by preventing Nitrogen reacting fully before combustion ends.

However, previous research has shown that emissions of nitrogen oxides (NO_x) from biodiesel are higher than EN590 diesel fuel (Canakci, 2007; Dorado *et al*, 2003). NO_x has been linked to high peak in-cylinder temperatures which can be caused by advancing the injector timing; injecting fuel at a larger crankshaft rotation before TDC. The increase in NO_x emissions is therefore an indication that biodiesel fuels require injector timing to be optimised.

Previous research has shown that varying the injection timing has an effect on the power, torque and fuel consumption of diesel engines running on vegetable oil-based fuels (Nwafor *et al*, 2000; Yahya & Marley, 1994), however these studies did not investigate the effect of retarding the start of injection (injecting fuel closer to top dead centre (TDC)) to take advantage of the higher CN and improved combustion quality of biodiesel fuels.

Biodiesels with high cetane numbers would be likely to be selected as motorsport fuels due to their increased combustion quality. Due to the relationship between CN and chain length of fatty acids, it is likely that this would also cause viscosity to increase (Harrington, 1985; Knothe, 2005). High viscosity fuel causes the spray characteristics from the injector nozzle to change, affecting combustion quality and reducing power (Wang *et al*, 2010).

The viscosity of biodiesel tends to be higher than that of mineral diesel (Tat & van Gerpen, 1999; Knothe & Steidley, 2005), despite the transesterification process used to manufacture it, which significantly lowers the kinematic viscosity of the animal fat and vegetable oil feedstocks. The kinematic viscosities of a range of biodiesel fuels and petrochemical diesels measured at 40^{o}C are shown in Table 7.2 (Alptekin & Canakci, 2008).

Table 7.2: Viscosities of Biodiesel Fuels and Petrochemical Diesel (Alptekin & Canakci, 2008)

Fuel	Viscosity [mm^2/s]
EN590 Diesel	2.7109
Waste Palm Oil Biodiesel	4.2802
Sunflower Oil Biodiesel	4.0303
Soybean oil Biodiesel	3.9713
Corn Oil Biodiesel	4.1769
Canola Oil Biodiesel	4.3401
Cottonseed Oil Biodiesel	4.0568

The literature has shown, therefore, that variation in power, torque and fuel consumption are commonplace when using biodiesel as a fuel (Rakopoulos *et al*, 2006; Alptekin & Canakci, 2008). Where the literature is lacking is in providing methods for overcoming this variation and maximising the main performance advantage of biodiesel fuel; a high cetane number and therefore superior combustion quality compared to diesel.

The author's hypothesis was that by taking an innovative approach to start of injection timing when using biodiesel, the performance potential of this fuel could be realised and its impact on the motorsport industry could be demonstrated.

7.3 In-Cylinder Pressure Testing of Biodiesel Fuels

The in-cylinder pressure measurements were taken using a pressure sensor, housed in a glowplug adapter. Tests were carried out on a BMW diesel engine at 2000rpm and 63% accelerator. Full details of the methodology used can be found in *Submission 6: First Generation Biodiesel as a Motorsport Fuel*. Baseline pressure measurements using only the starter motor and no fuel injected were taken to establish the in-cylinder pressures achieved without combustion. These measurements are shown as the "motored" series' in the figures below. The start of combustion is indicated by a sharp increase in pressure compared to the motored values.

In these experiments start of injection (SOI) is indicated by a number of degrees before top dead centre (BTDC). The higher the number, the earlier (more advanced) the start of injection; the lower the number, the later (more retarded) the start of injection. The output torque of the engine was measured and recorded for each SOI point to give an indication of the relationship between in-cylinder pressure and torque for the different fuels.

Tests were carried out on an automotive diesel engine to evaluate the in-cylinder pressures for soybean B100, beef tallow B50 and EN590 diesel (Table 7.1) to gain understanding of the reasons behind the performance differences noted between biodiesel fuels from different feedstocks. These fuels were selected as they represent a broad selection of potential motorsport fuels. EN590 is the standard diesel fuel available at fuel stations across Europe. The choice of beef tallow was intended to allow evaluation of non-food feedstocks as high-performance fuels. Tallow is a by-product of beef production and is produced from rendered fat. The high viscosity of this fat (solid at room temperature) makes transesterification and subsequent blending with diesel a necessity to reduce the viscosity of the finished fuel. A B50 blend was therefore selected. There is a gap in the literature on the properties of soybean derived biodiesel in an automotive engine therefore soybean B100 was selected.

Predictions on the potential performance of biodiesels can be made by examining the chemical composition of their feedstocks. Fatty acid profiles of beef tallow and soybean oil were extracted from the literature and analysed to evaluate the potential of each biodiesel. The major constituent elements of each oil feedstock are shown in Table 7.3. The fatty acids are represented by a capital 'C' followed by a number, representing the number of Carbon atoms in the chain (chain length). The number after the colon represents the number of double bonds; a zero means that the fatty acid is 'saturated'. The higher the number after the colon, the more unsaturated the carbon chain.

Table 7.3: Fatty Acid Profiles of Soybean Oil and Beef Tallow

Fatty Acid	Soybean Oil Composition [%] (Candeia *et al*, 2009)	Beef Tallow Composition [%] (da Cunha *et al*, 2009)
C14:0	0	2.7
C16:0	13.3	25.3
C18:0	4.8	34.7
C18:1	25.5	31.7
C18:2	55.4	0

The fatty acids profile show that soybean oil is significantly less saturated than beef tallow, suggesting it would have lower viscosity. Soybean oil is also made up of a large proportion of long chain fatty acids, indicating its Cetane Number should also be high. Beef tallow is made up of more than 65% saturated fatty acids. This indicates a very viscous fuel, but with a potentially high Cetane Number.

7.3.1 Optimising Start of Injection (SOI) Timing for Biodiesel Fuels

Initial tests compared the pressures generated for each fuel using the standard SOI timing of 11 degrees before top dead centre (BTDC). The results of these tests are shown in Figure 7.1.

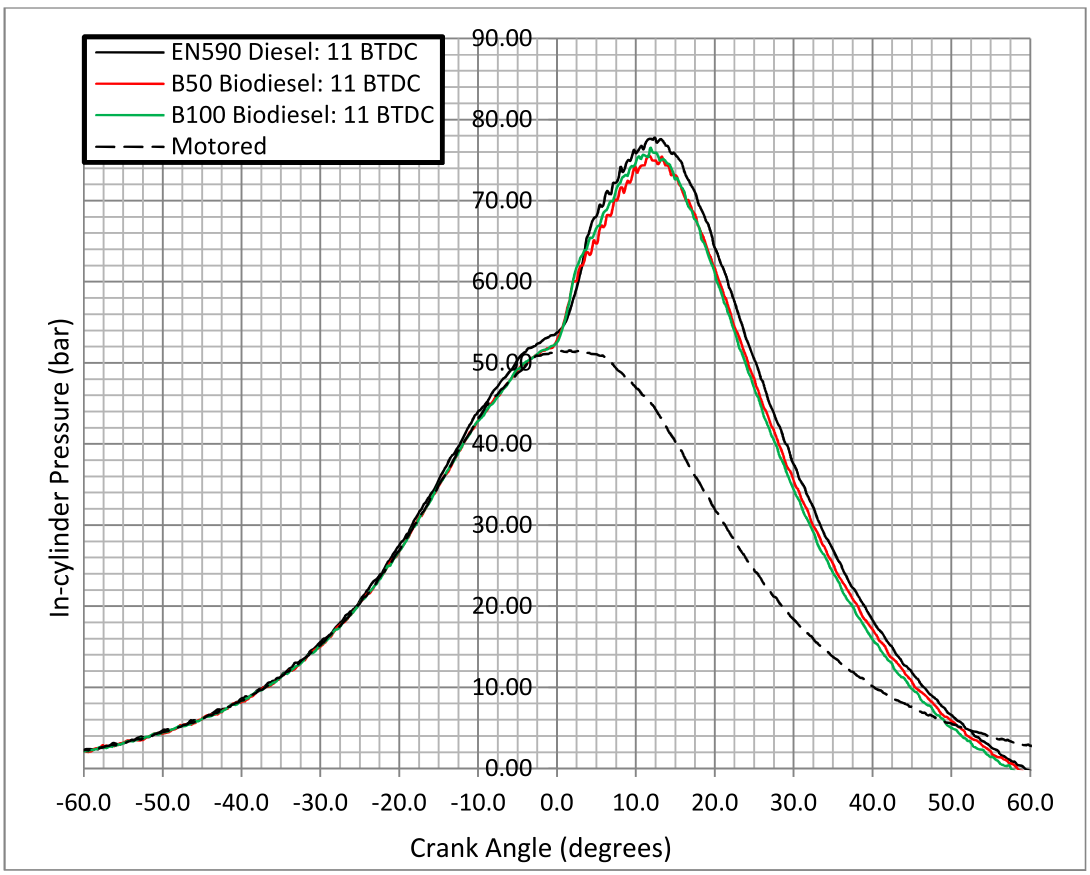

Figure 7.1: In-cylinder pressures for different fuels at 11 degrees BTDC start of injection

EN590 diesel produced the highest in-cylinder pressure using the factory start of injection point of 11 degrees BTDC (77.79bar). Beef Tallow B50 and Soybean B100 produced pressures of 75.59bar and 76.51bar respectively. Figure 7.1 shows that the B100 and B50 blend have a smoother pressure increase after the initial rapid pressure increase caused by the start of combustion, and reach peak pressure sooner than diesel fuel, suggesting a shorter ignition delay and hence a higher cetane number.

Table 7.4: In-Cylinder Pressures and Torques with varied SOI timing

Fuel	Start of Injection [degrees BTDC]	Peak In-Cylinder Pressure [bar]	Torque at 2000rpm [Nm]
EN590	10	74.81	139.83
EN590	11	77.79	143.00
EN590	14	91.62	**144.39**
B50	7	64.77	133.14
B50	9	71.51	**135.85**
B50	10	75.62	135.58
B50	11	75.59	132.19
B100	7	63.04	124.46
B100	9	69.04	124.06
B100	10	73.26	**126.63**
B100	11	76.51	126.57

Table 7.4 shows the in-cylinder pressures and torques for each of the fuels tested using varied injection timing. The highest torque was produced by EN590 diesel at 14 degrees BTDC (144.39Nm), but this corresponded to in-cylinder pressure of 91.62 bar; an 18% increase over the pressure at standard timing. This represented a significant increase which would have risked the durability of the engine at higher speeds, therefore the standard timing of 11 degrees BTDC was retained for EN590.

Using standard SOI timing of 11 degrees BTDC both blends of biodiesel generated lower in-cylinder pressures and resulted in lower output torque from the engine compared to diesel. Retarding the start of injection for B50 biodiesel by two degrees from standard to 9 degrees resulted in a 2.8% increase in peak torque accompanied by a 5% reduction of in-cylinder pressure. Best torque for B100 was observed when injecting fuel at 10 degrees BTDC. This timing resulted in a negligible torque increase but a 4.4% reduction in in-cylinder pressure. The torque outputs at all injection timings when using tallow B50 and soybean B100 were significantly lower than diesel fuel; this was attributed to their lower calorific values.

7.3.2 Comparison Using Normalised Torque and Optimised SOI Timing

The amount of fuel injected was varied for each biodiesel to compensate for the lower energy content of the fuel until the same torque as EN590 diesel was produced at an engine speed of 2000rpm.

To investigate the effect of the reduced calorific value of biodiesel fuel, for the final set of tests the amount of fuel injected for each biodiesel blend was increased until the torque output was equal to that of diesel fuel at the same engine speed. The SOI timing used was that which generated the highest torque using the standard volume of injected fuel for each blend. The SOI and peak in-cylinder pressure for each fuel are presented in Table 7.5.

Table 7.5: In-Cylinder Pressures with Fuelling Adjusted for Equal Torque

Fuel	Start of Injection [degrees BTDC]	Peak In-Cylinder Pressure [bar]
EN590	11	77.79
B50	9	74.38
B100	10	77.12

Figure 7.2 shows the in-cylinder pressures achieved by each fuel when generating 143Nm of torque at 2000rpm. B50 biodiesel had the lowest peak pressure of 74.38bar followed by B100 (77.12bar) and EN590 diesel (77.79bar). The rate of pressure increase for both biodiesel blends is lower than for diesel fuel, and peak pressures occur later in the combustion cycle.

The start of combustion (denoted by the arrow in Figure 7.2 where a sharp increase in pressure occurs) is the same for all fuels. The ignition delay must therefore vary, as the SOI point is different for all fuels. Values for the ignition delay were obtained using the method described by Luján *et al* (2010) which is described in *Submission 6: First Generation Biodiesel as a Motorsport Fuel*.

The engine speed (and therefore rotational speed of the crankshaft) of 2000rpm is known, hence the ignition delay in seconds can be calculated. The ignition delays of each fuel are given in Table 7.6.

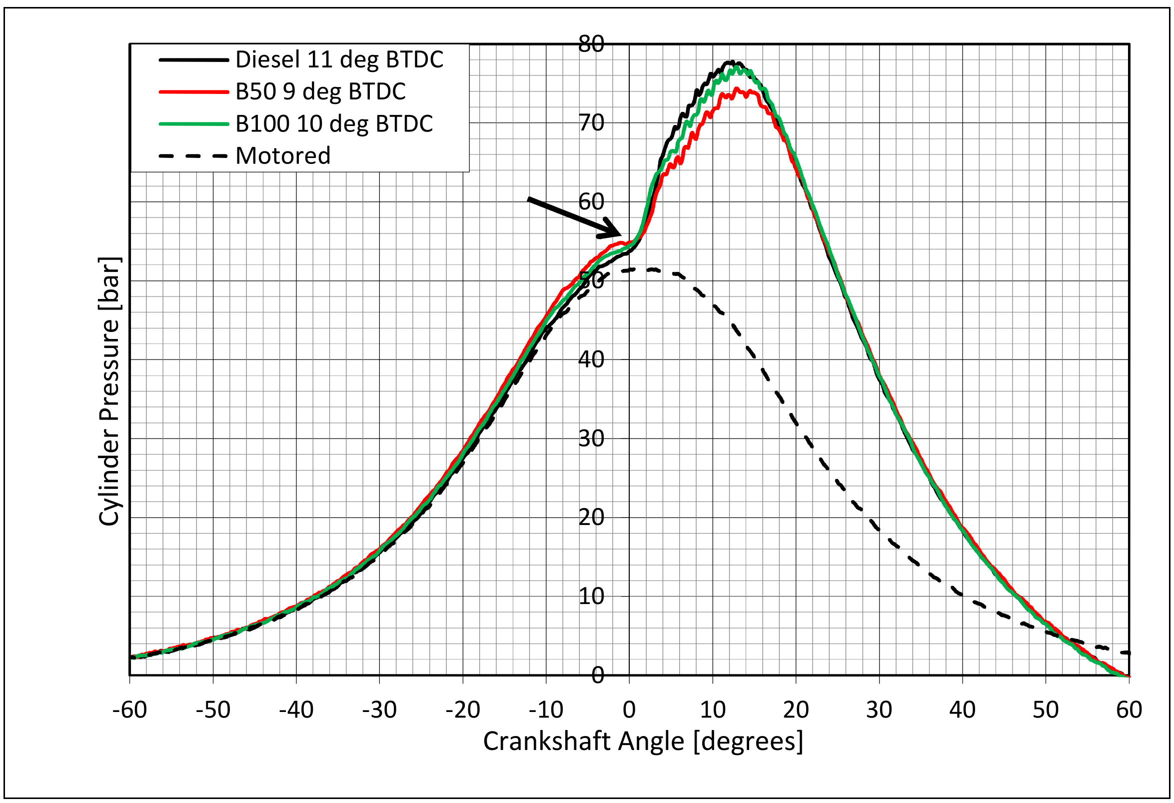

Figure 7.2: In-cylinder pressures with fuelling adjusted for equal torque

The shorter ignition delays of B50 and B100 resulted in lower peak in-cylinder pressures for the same torque, with B50 giving the lowest in-cylinder pressure due to its low ignition delay and hence the ability to begin injection later than either B100 or EN590 diesel. The rate of pressure change using both B50 and B100 was lower than for diesel, the implication of which is reduced engine wear, or in motorsport terms, the potential to increase the output of the engine before critical failure occurs.

Table 7.6: Calculated Ignition Delays of Biodiesels and EN590 Diesel

Fuel	Ignition Delay (ms)
EN590 diesel	1.04
B50	0.94
B100	0.96

Based on the CN of the fuels it would have been expected for B100 to have the shortest ignition delay, followed by B50 and EN590 diesel. The results in Table 7.6 show that B100 had an ignition delay 0.02ms longer than B50. Previous work by Wang *et al* (2010) suggests that this can be attributed to the viscosities of the biodiesel fuels tested (shown in Table 7.1). Higher viscosities lead to a smaller spray angle and reduced air entrainment, and hence poor fuel atomization (Figure 7.3).

Increased viscosity due to poor atomisation has previously been suggested as a reason for extended ignition delay (Rodríguez *et al*, 2011). The longer ignition delay of B100 can therefore be attributed to its higher viscosity. Despite being longer than expected, the ignition delay of B100 was 0.08ms (7.7%) shorter than that of diesel.

A 0.1ms ignition delay may seem insignificant, but at 2000rpm the crankshaft is rotating at a rate of 12 degrees/ms. Therefore the start of combustion for EN590 diesel occurs 1.2 degrees nearer to TDC than B50 biodiesel. As has been shown in this chapter, 1.2 degrees variation in timing can have a significant impact on the in-cylinder pressure and torque output of an engine. Understanding the ignition delay is therefore crucial to the successful implementation of biodiesel as a fuel for motorsport.

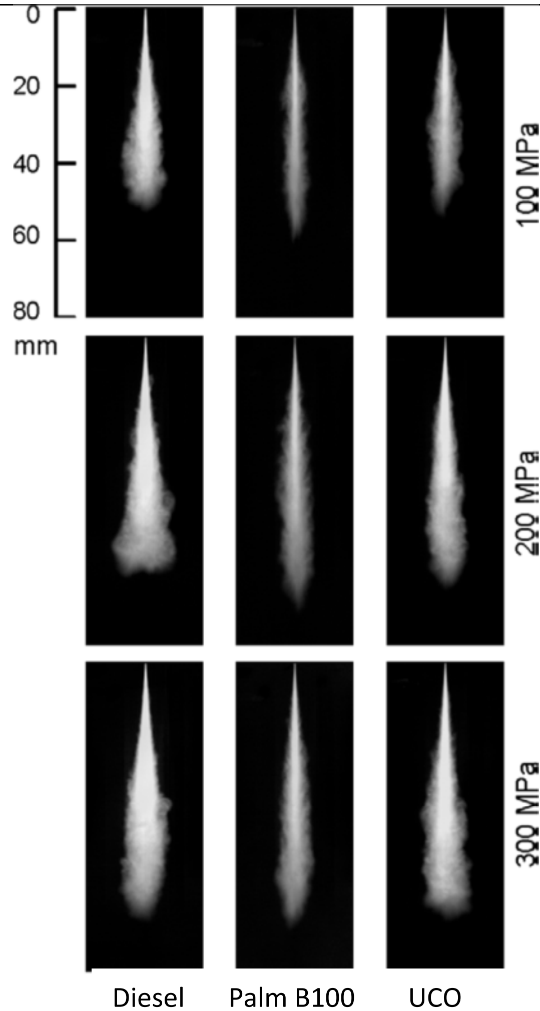

Figure 7.3: Injector Spray Patterns at Different Injection Pressures (Wang et *al*, 2010)

7.4 Summary of In-Cylinder Pressure Tests

Variations in the timing of SOI were shown to have an effect on the torque output and in-cylinder pressure observed in a diesel engine running on EN590 and biodiesel blends. Although the biodiesels tested (a blend of B50 from beef tallow and B100 soybean) have a lower calorific value than EN590 diesel, they also have improved combustion quality resulting from a higher cetane number and therefore have a shorter ignition delay. The decrease in peak pressure for biodiesels compared to diesel fuel can be attributed to the lower ignition delay observed for B50 and B100. With a shorter ignition delay, combustion begins earlier and therefore peak pressures are reduced.

By altering the timing of the start of injection and increasing fuelling to allow for their lower calorific value, tallow B50 and soybean B100 were able to produce equal torque to EN590 at 2000rpm but with lower peak in-cylinder pressure and a shorter ignition delay. The application of this to motorsport is the potential to achieve higher peak power outputs; the shorter ignition delay and more rapid combustion has the potential to be used to raise the maximum engine speed and therefore the peak power output of diesel engines for motorsport. Reduction in in-cylinder pressures for the same torque output allows for further potential performance increases by allowing more fuel to be injected and therefore more torque to be generated before the engine reaches its maximum in-cylinder pressure.

In addition, the lower calorific value of biodiesel compared to diesel would reduce the difference in fuel efficiencies between compression ignition and spark ignition engines noted at the beginning of this chapter (Bamsey, 2008), resulting in a similar number of pit stops being required for cars running on different fuels. This would make the racing closer and therefore a more enjoyable spectacle for the fans watching the race.

7.5 Industrial Impact of the Innovation

The high performance biodiesel testing carried out in *Submission 6: First Generation Biodiesel as a Motorsport Fuel* and summarised in this chapter was carried out by the author at Scott Racing Ltd. The knowledge gained from research for this Engineering Doctorate was exploited by Scott Racing to produce a biodiesel-fuelled engine with motorsport levels of performance and excellent reliability.

Figure 7.4: WorldFirst F3 Car at the 2009 Goodwood Festival of Speed

The innovative approach to development of biodiesel as a high-performance fuel for motorsport was key to exploiting the full potential of the WorldFirst racing car, which completed the hillclimb at the 2009 Goodwood Festival of Speed (Figure 7.4) and ran competitively during practice sessions at a British Racing & Sports Car Club (BRSCC) F3 Series race at Brands Hatch in June 2010. Comparison power and torque curves for the standard diesel and WorldFirst F3 engines are shown in Figure 7.5 and Figure 7.6 respectively.

In its final iteration, the WorldFirst F3 engine produced 151.1kW @ 3575rpm and 424.2Nm @ 2650rpm whilst running on B50 beef tallow biodiesel. This represents an increase in power and torque of 40kW and 125Nm respectively compared to the standard outputs of 111kW @ 4125rpm and 297Nm @ 2725rpm using EN590 diesel fuel.

Peak power and torque occurred lower in the engine speed range compared to the standard engine, and the shorter ignition delay also allowed the engine speed limit to be raised to 4700rpm from the standard 4500rpm limit.

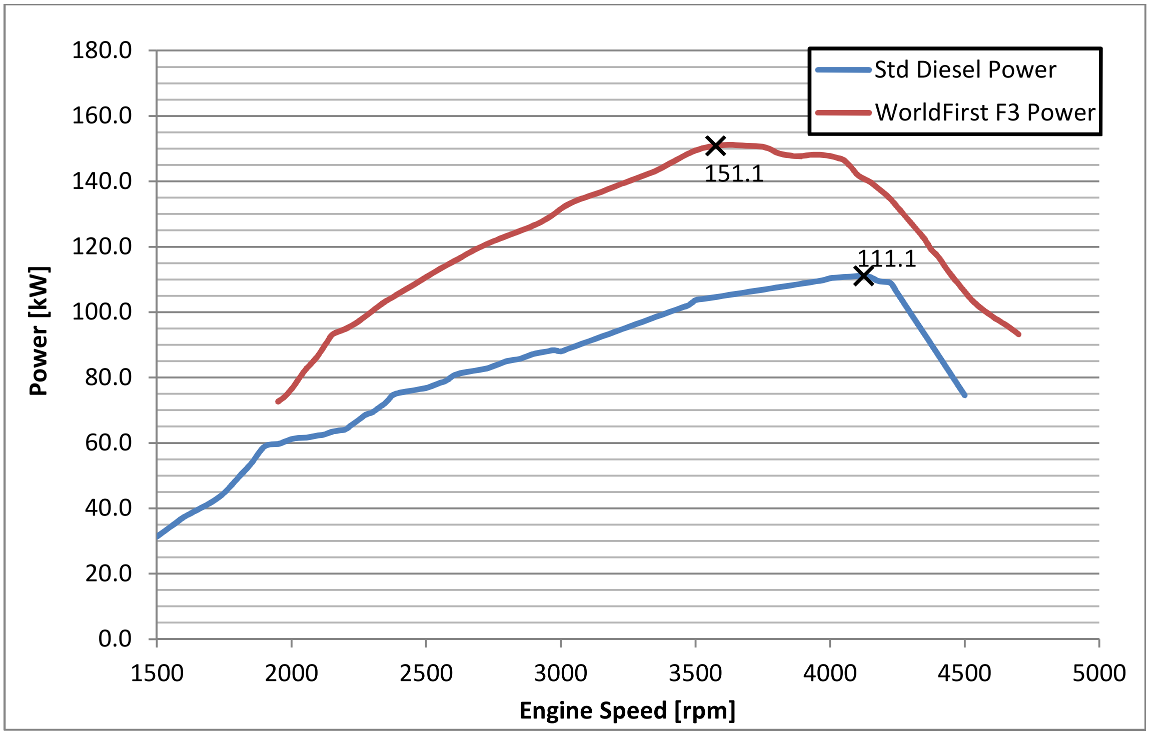

Figure 7.5: Power curves for standard diesel and WorldFirst F3 engines

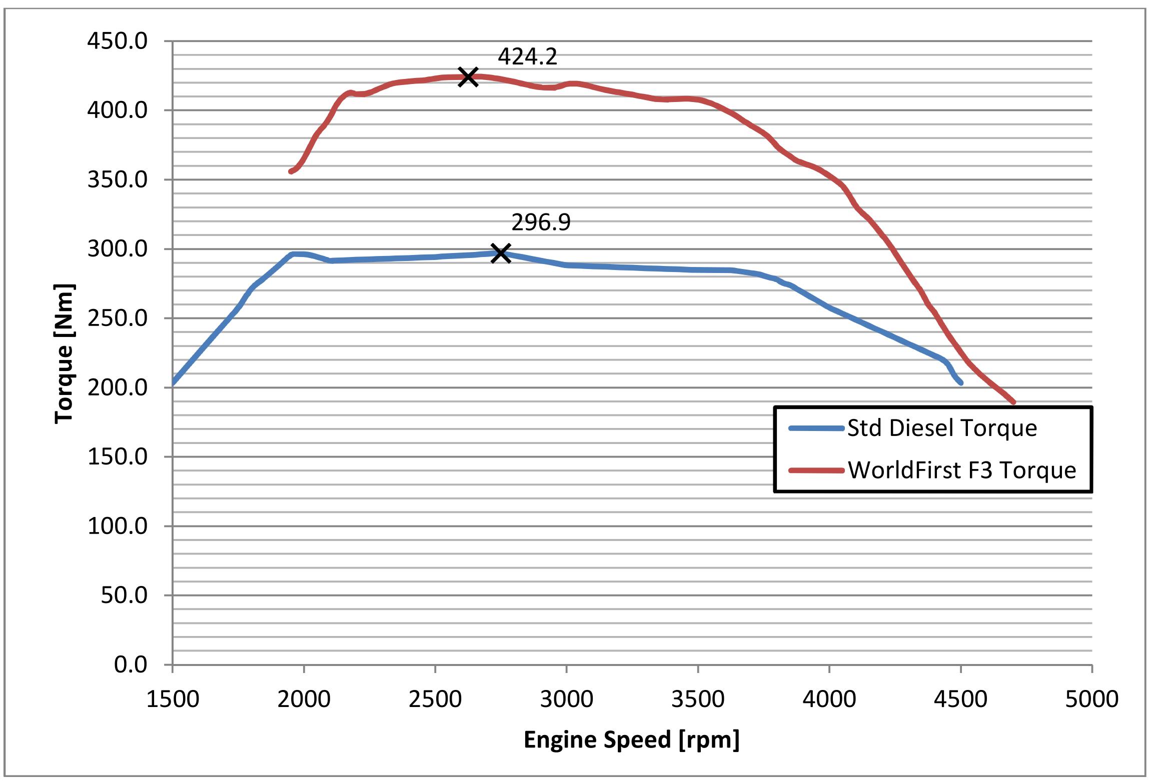

Figure 7.6: Torque curves for standard diesel and WorldFirst F3 engines

This difference in combustion time and changes to the fuelling resulted in the WorldFirst engine producing more than 111kW (the peak power of the standard engine) until 4500rpm. An increased rev limit allows greater speeds to be reached in each gear, thus reducing the number of gear changes necessary and therefore reducing lap times.

The increase in maximum engine speed coupled with at least 85% of maximum torque being available from 2000rpm - 4100rpm resulted in the WorldFirst F3 car being “forgiving” to drive; if the driver selected the incorrect gear, the high levels of torque available at low engine speeds allowed little loss in acceleration. This observation was made by the author during on-track testing and confirmed by professional race drivers who drove the car at Brands Hatch and the Goodwood Festival of Speed (Aaron Steele and Adam Carroll respectively). This allowed the driver to concentrate on taking the correct racing line and on overtaking and defending against the other cars on track. Another benefit of the biodiesel setup in the WorldFirst car was the increase in fuel economy compared to the gasoline-powered equivalent engine. After more than one hundred miles of track testing, the Bosch Motorsport ECU logged an average fuel consumption of 18mpg. This is measured using the number of pulses from the fuel injectors, and is therefore an accurate measure of fuel consumption. Conversations with Adam Airey, the designer of the Lola F3 car on which WorldFirst was based, gave the fuel consumption of an equivalent gasoline-engine car of less than 10mpg (Airey, 2010). A standard F3 car has a gasoline-fuelled spark ignition engine and produces approximately 157kW and 200Nm of torque (Cooper Tires British Formula 3 International Series, 2011). The WorldFirst engine therefore develops similar power but more than double the torque which results in superior acceleration and drivability.

If this biodiesel engine package was adopted by a competing Formula 3 team, not only would their performance on track be improved by the torque characteristics of the engine, but the increased fuel efficiency would allow a strategic advantage; either by reducing the amount of fuel carried and therefore saving weight, or by allowing a greater number of laps to be completed between each pit stop, allowing fewer stops to be made during the race. The format of this engine package (2 litre capacity, 150kW power output) also lends itself to use in many other types of racing, such as rallying, sportscar and saloon car racing.

For higher level motorsport, teams often design or purchase engines specifically for their racing application. Due to the lower in-cylinder pressures generated by biodiesel fuel for the same torque output as the equivalent diesel, an engine designed to use this fuel could be made lighter.

The results of the biodiesel research carried out for this Engineering Doctorate were used to great effect when developing the engine map for the WorldFirst Formula 3 car. By altering start of injection timing and fuelling, as well as increasing the maximum engine speed, the diesel engine in this car was able to produce comparable power to a gasoline powered Formula 3 car, but with 125Nm of additional torque and an 80% improvement in fuel economy. This work has therefore demonstrated that first generation biodiesel is a viable alternative fuel for motorsport use and can be competitive with existing motorsport technology.

8 Conclusions

This Engineering Doctorate research programme has provided a considerable contribution to knowledge and demonstrated innovations in a number of areas. The programme itself was based on an innovative concept; the application of sustainable development to the motorsport industry. The aim of the Engineering Doctorate was to identify and develop strategies and technologies to overcome the barriers to sustainable motorsport. This aim was achieved through the development of innovations and contributions to knowledge.

In addition to the individual contributions discussed in this chapter, the research programme in itself is innovative; application of sustainable development to motorsport had not previously been attempted, and has been proven through the research presented in this Innovation Report to have a positive impact.

A key limitation of the research presented here is the need for changes to be implemented through regulation. The regulatory bodies set out the rules which all competitors must follow, therefore their buy-in and cooperation would be essential for any changes to the sustainability of motorsport to be made.

8.1 Tools and Techniques

Novel application of the Triple Bottom Line (TBL) of sustainability to the motorsport industry resulted in identification of three factors influencing the future sustainability of the industry:

- Economic: The existence of secure, long-term sources of funding for motorsport activities, either through corporate sponsorship as is currently the case, or by identifying new sources of income.

The current economic sustainability of motorsport is limited due to the uncertainty in future sponsorship incomes. It is dependent on motorsport continuing to be an attractive target for corporate sponsors.

- Social: Remaining relevant to and generating benefit for society.

Social sustainability is reliant on public engagement and societal relevance; declining viewing figures and public interest in motorsport suggest that this is at risk in the long term unless changes are made.

- Environmental: Creating minimal environmental impact through motorsport activities either now or in future.

Regulatory bodies have made attempts to integrate environmentally sound technologies into motorsport, but with limited success; production of racing cars still involves the use of energy intensive and unsustainable materials and fuels.

Analysis of the TBL of motorsport resulted in the development of a set of guidelines for the adoption of sustainable motorsport. This consists of eight points which the motorsport industry must address if it is to move towards a sustainable future. The barriers to the adoption of these guidelines, and therefore to sustainable motorsport, were identified through the collection of primary and secondary data.

For economic sustainability, the barriers were identified as a reliance on corporate sponsorship and a lack of exploitation of the intellectual property developed by motorsport's R&D activities. Barriers to the development of social sustainability in motorsport were found to be a lack of effective public engagement and minimal societal relevance brought about by diminished levels of technology transfer out of motorsport. The main barrier to environmentally sustainable motorsport was identified as the inferior performance of sustainable alternatives compared to their synthetic counterparts.

The need to address the issue of sustainability was identified. Analysis of motorsport's TBL in conjunction with primary and secondary data gathered on the motorsport industry resulted in the development of a novel strategy for development of sustainable motorsport. This strategy addressed the regulatory challenges facing the motorsport industry without considering the implementation of the TBL at a company or team level.

A technology development tool for sustainable motorsport was introduced to address this gap in the research. Based on a stage-gate model, the High Performance Sustainability (HPS) process was intended to provide flexibility to allow integration with a range of existing product development processes. The first generation of this process was used to develop a revolutionary technology demonstrator; Eco One. As well as generating unprecedented media impact for WMG, Eco One allowed the HPS process to be refined and developed into a second generation process entitled HPS2.

This process was successfully used in the development of the WorldFirst Formula 3 car, a sustainable motorsport demonstrator, project managed by Dr. James Meredith from WMG, which was a direct continuation of Eco One.

8.2 Innovative Sustainable Technology Development

In order to prove its innovation, individual sustainable technologies were developed using the HPS2 process. Academic research was limited to two areas of technology; composites and fuel.

8.2.1 Innovative Sustainable Composites for Motorsport

Innovative natural fibre reinforced composites were introduced as a potential replacement for glass and carbon fibre composites. The novel addition of 2.5% by weight of untreated Kraft lignin to the hemp reinforced epoxy resulted in a 29% increase in tensile modulus, a 37% increase in ultimate tensile strength and an 86% increase in Charpy impact strength. 5% lignin addition resulted in a further 32% increase in impact strength, but with a reduction in tensile strength and modulus.

These improvements to the mechanical properties of the composites indicate an improvement in the fibre/matrix adhesion. This interfacial effect was validated through the use of scanning electron microscopy, which showed evidence of reduced fibre pullout and an increase in resin remaining attached to fibres at fracture surfaces. The specific mechanical properties of the lignin-treated composites were approaching those of glass fibre, hence this work demonstrated that natural fibre reinforced composites could be used as a replacement for fibreglass in motorsport applications. Cost analysis of hemp/epoxy/lignin composites in the manufacture of a low volume Formula 3 wing mirror shell showed that natural fibre reinforced composites would result in a lighter, more profitable product than nylon, and would contain a significantly higher proportion of renewable materials than a carbon fibre equivalent. The adoption of these materials is therefore competitive with the economic and environmental performance of the synthetic alternatives.

8.2.1.1 A Novel Composites Manufacturing Process

To supplement these materials, alternative manufacturing methods were investigated to avoid compromising their environmental sustainability through the use of energy intensive processes such as autoclave moulding. Powder coating technology was identified as a potentially innovative manufacturing solution. Natural fibre reinforced composites were successfully manufactured using a novel electrostatic powder coating process, although further work is recommended to develop this feasibility study into an industrial process.

Associated with the novel manufacturing process described above, lignin was introduced as a filler for powder coating resins which can be used to vary the renewable content, reduce the cost and change the surface texture of epoxy powder coats. These resin formulations have wide applications throughout motorsport where surface coatings are used for anti-glare, grip and resistance to corrosion and abrasion. The replacement of 1% of calcium carbonate or barium sulphate with lignin in epoxy powder coatings would result in annual cost savings to the industry of up to £1.73 million.

8.2.2 Innovative Use of Biodiesel as a High Performance Fuel

An innovative approach to the use of biodiesel as a high performance fuel was adopted for the testing of biodiesel blends for motorsport. The measurement of in-cylinder pressures allowed the timing of start of injection and fuelling to be optimised for biodiesel, resulting in equal torque to petrochemical diesel but lower in-cylinder pressures and shorter ignition delay. This gives the potential to achieve higher peak power outputs; the shorter ignition delay and rapid combustion have the potential to be used to raise the maximum engine speed and therefore the peak power output of diesel engines for motorsport. Reduction in in-cylinder pressures for the same torque output allows for further performance increases by allowing more fuel to be injected and therefore more torque to be generated before the engine reaches its maximum in-cylinder pressure.

The results of this research were applied to the engine in the WorldFirst Formula 3 car. This diesel engine produced comparable power to a gasoline powered Formula 3 car, but with

125Nm of additional torque and an 80% improvement in fuel economy. This work demonstrated that innovative use of first generation biodiesel results in a viable alternative fuel for motorsport which is competitive with existing motorsport technology.

8.3 Exploitation and Dissemination of the Research

Various dissemination methods were used in order to maximise the impact of the research. Academic recognition of the research led to the author being invited to sit on an expert panel at an international conference, and the publication of three peer-reviewed journal publications and a book chapter (see *Publications* in the Engineering Doctorate portfolio). The research was therefore of publishable quality and provided a contribution to knowledge.

Coverage through the international media including television coverage, newspaper articles and radio interviews generated significant public interest in the research (see *Disseminating the Innovation* in the Engineering Doctorate portfolio), validating the concept that sustainable motorsport can be used to engage the public, and also increasing the impact of the research beyond academia.

Effective dissemination of the innovations allowed the research to be exploited through development of industrial collaborations. Research presented in this Engineering Doctorate led to recognised expertise in sustainable motorsport, resulting in WMG being named as an official supplier of sustainable body panels for the Lola Drayson all-electric racecar, and providing consultancy to automotive and motorsport companies to allow the research to be applied in an industrial context.

The impacts of this work are the establishment of industrial collaborations, conference attendances, peer-reviewed journal publications, and dissemination of research through the development of academic courses and extensive media coverage.

8.4 Future Work

This Engineering Doctorate has resulted in significant innovations and contribution to knowledge in the field of sustainable motorsport. The necessity to limit the scope of the research to make it practical to achieve during the research programme resulted in research questions which should be addressed through continuation of the research.

8.4.1 Tools and Techniques

The strategy and HPS2 technology development process were demonstrated through their application to sustainable motorsport demonstrator projects; the average time required to introduce a new process into a company is five years (O'Connor, 1994), which would have been beyond the timescales of the Engineering Doctorate. Implementation of these tools and techniques within a range of motorsport companies would allow the processes to be refined to make them applicable across a range of companies.

8.4.2 Natural Fibre Reinforced Composites

Research in this area was focussed on the natural fibre which was commercially available at the time in the UK; randomly oriented hemp. Continuation of this research into a wider variety of woven natural fibres including jute and flax is currently underway at WMG, with special focus on the use of natural fibres for energy absorption structures. The randomly oriented fibre mat used for this research undergoes very little engineering before its use as a composite reinforcement. This is in stark contrast to glass and carbon fibres which are engineered to give the best possible mechanical performance. Further work should be focussed on the use of woven natural fabrics, which are likely to better exploit the excellent strength of individual natural fibres.

In order to investigate the properties of natural fibres which have undergone further processing, the author has instigated a research collaboration between WMG, Birmingham University and Elmira Ltd; a company who have developed a bio-based resin and cellulosic bamboo prepreg composite after consultation with the author on the potential market for these materials in motorsport. This collaboration is ongoing, and is expected to result in journal publications in 2012.

8.4.3 Powder Spray Composites Manufacturing

Although powder spray composites were manufactured using this process, their mechanical performance was lacking due to the difficulty of achieving wet-out of the fibres. A continuation of this feasibility study to investigate the effect of using different formulations of powder coating resin as the matrix would allow a greater understanding of the potential of these materials.

8.4.4 High Performance Biodiesel

The research in this Engineering Doctorate was concerned with achieving competitive performance from biodiesel fuels made from existing feedstocks. The natural progression of this work is to investigate the development of crops specifically for biodiesel use. The fatty acid profiles of biodiesel feedstocks can be derived from chemical analysis, giving an insight into the relationship between oil composition and biodiesel performance. Existing oils could be blended to produce a theoretical ‘ideal’ fatty acid profile, which would be validated by performance testing of the resulting fuel. Plant breeding strategies could then be developed in order to generate a new crop with the required fatty acid profile for high performance biodiesel production.

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Appendix A1: Eco One - The Environmentally-Friendly Racing Car

In order to test the validity of the process developed in this submission, the author project-managed the development of a single-seat racing car using the 1st Gen HPS process. The car was requested for an event at the Eden Project (an educational charity and visitor attraction which focuses on educating people about the importance of sustainability (Eden Project, 2010)), in Cornwall, UK, to showcase fuel-efficient and low carbon passenger cars. The organisers requested a project which demonstrated how university research could be used to advance the viability of sustainable materials for automotive applications.

Background

As timescales and budgets did not allow the development of a vehicle from the ground up, an existing racing car built for the Formula Student undergraduate engineering project was used as a base for conversion (Figure A1.1). This was chosen for its simplicity, low mass and small size which meant that there was significant scope to replace components for sustainable alternatives as well as easily transporting the car to different events using a commercial van.

Figure A1.1: Formula Student car used for conversion

The Formula Student car, designation W5, was a small single-seater consisting of a tubular steel spaceframe with a mid/rear mounted, four-cylinder motorcycle engine and gearbox. The specification of the car is shown in Table A1.1.

Table A1.1: Specification of W5 Formula Student Car

Specification	
Chassis type	Tubular Steel Spaceframe
Engine type	In-line 4 cylinder, 4 stroke
Engine capacity	598cc
Engine power	50bhp (approx.)
Suspension	Double wishbones, outboard shocks and springs
Wheels	13" x 7" Compomotive CXR, alloy
Tyres	Avon A45 compound slicks, 7.2/21.0-13
Gross vehicle weight	240kg

The Development of Eco One

Once obtained, the car was then stripped down to identify individual components which could be replaced or modified to improve the environmental performance. The HPS process was then used to identify and select replacements for existing components.

The Key Environmental Performance Indicators set for the car to meet the needs of the Eden Project Green Car Show were:

- Reduction in use of fossil fuels and derivatives thereof
- Increased use of renewable materials
- Reduction in use of toxic or hazardous materials

The Formula Student car was analysed to identify potential improvements in environmental impact in three key areas; powertrain, chassis and bodywork. After identifying KEPIs and possible areas where new materials could be implemented, the available sustainable materials were identified and compared against the KEPIs to evaluate their environmental performance.

Powertrain

The gasoline-powered motorcycle engine in the car was functional, and built into the spaceframe of the vehicle, therefore replacing it would have involved reengineering the whole car. Use of the existing engine was therefore essential but an alternative to fossil fuel was investigated. The lubricating oil used in the engine was also fossil fuel based.

An alternative to fossil fuel was required to run in the original gasoline engine of Eco One. Biofuels were the most suitable option, as they are non-toxic, made from renewable sources and contain no fossil fuels. As biodiesel was not practical due to the use of a gasoline engine, bioethanol was selected as the fuel source for Eco One. E85 (15% gasoline, 85% bioethanol) had to be used due to availability; E100 was not on sale in the UK at the time. This nonetheless represented a significant reduction in the amount of fossil fuel required to run the car.

In terms of engine lubrication, an oil manufactured by Fuchs Lubricants was identified which was made entirely from plant oils. This met all of the KEPIs; non-toxic, completely renewable and containing no fossil fuels or derivatives.

Chassis

The majority of parts on the chassis including the spaceframe, hubs, uprights, wishbones and other suspension components were made from steel or aluminium, and therefore potentially recyclable at end of life. The brake pads were identified as containing heavy metals which could be emitted during braking and have been identified as toxic. The Avon slick tyres contained carbon black, a derivative of the petrochemical industry used to give the tyres their black, shiny colour.

All commercially available brake pads contained heavy metals, therefore in order to reduce the toxicity of the parts used on Eco One an experimental compound developed by the EcoPad project at Exeter University was used. This was manufactured from a composite of Cashew Nut Shell Liquid (CNSL) and natural fibres to produce an effective friction material, and met all of the KEPIs due to being made from natural, renewable materials.

A similar problem was encountered when searching for a suitable tyre; all commercially available motorsport tyres contained carbon black as well as polycyclic aromatics and other harmful chemicals. A road car tyre was identified, however, which contained a small percentage of potato starch instead of carbon black and was commercially available. The Goodyear GT3 was designed for low rolling resistance to increase fuel economy. By using no carbon black, it was less toxic and less reliable on fossil fuels than an ordinary tyre, so performed well compared to standard tyres in terms of the KEPIs.

Bodywork

The carbon fibre bodywork, although lightweight, had a high environmental impact due to the energy intensive materials and processes used in its manufacture. The difficulty of disposing of carbon fibre composite materials would have also resulted in an environmental impact at end of life due to the necessity of landfilling the waste. In order to increase the renewable content of the car, fossil fuels and their derivatives had to be replaced wherever possible. Carbon fibre is either made from polyacrylonitrile or pitch as a precursor, both of which are derived from petrochemical sources. It is also a material which requires large amounts of embodied energy, and is difficult to dispose of at end of life. It was therefore not attractive when analysed using the KEPIs, and a replacement was sought. Fibreglass was considered as it is made from silica and is therefore theoretically renewable, but it is an irritant and can be harmful if it is inhaled by the manufacturer. Natural fibres are an alternative to synthetic fibres such as carbon for composites manufacture, and are renewable, typically non-toxic and biodegradable. There are a wide variety of natural fibres available as many are used for the manufacture of textiles, but in the UK the only commercially grown fibre available was hemp. Natural fibre reinforced composites were originally prepared using a polyurethane (PU) resin manufactured from rapeseed oil in order to further reduce the toxicity and fossil fuel content of the composites. A sidepod manufactured using this material is shown in Figure A1.2.

Figure A1.2: Sidepod Manufactured From Hemp Fibre and Rapeseed PU Resin

This material had a rough surface finish and the strength properties were poor; it struggled to support its own weight when manufactured as a large panel. The choice of material was therefore evaluated, and a thermoset epoxy resin was used with the hemp fibres to manufacture further test panels. The mechanical properties of the resulting hemp/epoxy composite were inferior to carbon or glass fibre but were adequate for this application and were therefore used in the manufacture of the bodywork.