NEW FUELS, NEW RULES?

Modelling Policies for the Uptake of Low Carbon Vehicles within an Ethical Framework

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Abstract

This research recognises a conflict between climate change mitigation and a lock-in of carbon-intense lifestyles. The concern is that, in the short term, policies to aid the transition to Low Carbon Vehicles (LCVs) may bring about unacceptable impacts on those amongst the worst-off. The approach that is taken is interdisciplinary, and suggests a novel approach to policy appraisal through combining ethics with a system dynamic model.

An ethical framework is established that claims coercive LCV policies are permitted due to the harms of climate change, but certain groups require protection from impacts on car ownership. This protection could be similar to policy in other sectors, such as tax exemptions for the worst-off. The framework also improves on current practise by offering a new perspective on the limitations of models in policy-making.

Two model case studies examine LCV policies, focused on subsidies and market regulation of electric vehicles. The first is relatively simple and develops basic skills and understanding, but still gives policy insight and explores the sensitivity of results. A more complex second model is used to understand the policy impacts in more detail, and in relation to ethical concerns. Combining the findings of both models suggests that subsidies are only successful in reducing emissions under a failing market and although regulation is more successful it raises the cost of all vehicles, disproportionately impacting the poorest in society. Combining these policies will allow a more even distribution of burdens.

From this, recommendations are made that suggest the policy-maker needs to ensure affordability, protect the vulnerable and distribute burdens. Finally, a framework for an improved approach to modelling and policy appraisal, which incorporates ethics, is proposed. Although the focus of this work is on LCVs, the fundamental approach is transferable to other areas of transport and energy use.

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List of Abbreviations

AFV	Alternative Fuel Vehicle
BAU	Business As Usual
BERR	Department for Business Enterprise and Regulatory Reform
BEV	Battery Electric Vehicle
BIS	Department for Business, Innovation and Skills
CARB	California Air Resource Board
CBA	Cost Benefit Analysis
cICEV	conventionally fuelled Internal Combustion Engine Vehicle
CM	Conditional Marketing
CS1	Case Study One
CS2	Case Study Two
DCM	Discrete Choice Model
DECC	Department of Energy and Climate Change
DfT	Department for Transport
ECCP	European Climate Change Programme
EPA	Environmental Protection Agency
EREV	Extended Range Electric Vehicle
EUETS	European Union Emissions Trading Scheme
EV	Electric Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HFC(V)	Hydrogen Fuel Cell (Vehicle)
HMG	Her Majesty's Government
HMRC	Her Majesty's Revenue and Customs
HMT	Her Majesty's Treasury
ICCT	International Council for Clean Transportation
ICE(V)	Internal Combustion Engine (Vehicle)
ICT	Information and Communication Technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPPR	Institute of Public Policy Research
ITF	International Transport Forum
L	Large vehicle

LCA	Life Cycle Assessment
LCV	Low Carbon Vehicle
LEV	Low Emission Vehicle
LPG(V)	Liquid Petroleum Gas (Vehicle)
M	Medium vehicle
MNL	Multinomial Logit
NAIGT	New Automotive Innovation and Growth Team
NG (V)	Natural Gas (Vehicle)
OECD	Organization for Economic Co-operation and Development
OLEV	Office of Low Emission Vehicles
PiHEV	Plug-in Hybrid Electric Vehicle
R(D)&D	Research and Development (and Deployment)
RAC	Royal Automobile Club
RP	Revealed Preference
S	Small vehicle
SD	System Dynamic
SMMT	Society of Motor Manufacturers and Traders
SP	Stated Preference
TotT	Talk of the Town
TSB	Technology Strategy Board
ULEV	Ultra Low Emission Vehicle
UNFCCC	United Nations Framework Convention on Climate Change
VED	Vehicle Excise Duty
WoM	Word of Mouth
WtC	Willingness to Consider
WTW	Well to Wheels
XS	Extra Small vehicle
ZEV	Zero Emission Vehicle

CHAPTER ONE: INTRODUCTION

Across the world, countries have made political commitments to mitigate climate change through reducing Greenhouse Gas (GHG) emissions. The UK has a legally binding target to reduce emissions by at least 80% from 1990 levels by 2050. As part of this, there is a policy to substantially decarbonise the transport system, an ambitious target that will have an impact practically every UK citizen’s mobility, daily lifestyle and travel decisions. In achieving this, the government envisage a technology transition in passenger cars from the current conventionally-fuelled Internal Combustion Engine Vehicle (cICEV) to Low Carbon Vehicles (LCV)[1], which may use alternative powertrains and fuels. To this end, there are a number of policy measures designed to stimulate an LCV market. Proposed policies target both manufacturers on the supply side and the public on the demand side. However, the effectiveness of such policies and the pathway of technological development are both uncertain and interlinked.

Considering this, and the current cultural and infrastructural lock-in to car ownership for access and mobility, it is the concern of this thesis that, from the perspective of distributional justice, such policies may unfairly burden the worst-off in society and increase existing inequalities. As such, this research engages in philosophical discussion regarding the morality of the situation, in order to develop and justify an ethical framework in which policies should operate. Furthermore, an attempt is made to incorporate this framework into an LCV policy modelling process, so that distributional impacts can be identified in addition to the potential success of LCV uptake and carbon emission reduction. Combining the ethical and empirical approach is a novel and useful addition to the existing suite of policy appraisal tools, which, if adopted by policy makers, could lead to better designed, more holistic and ultimately successful policies.

This introductory chapter first of all sets the context of climate change, transport and the role of the private car in reducing carbon emissions before defining the scope, limitations and objectives of the research, and finally sets out the methodology that has been employed.

[1] In this work LCV encompasses any vehicle with substantially lower carbon emissions than current conventional ICEV.

1.1 Background to Climate Change

The underlying science of climate change has been extensively studied by the Intergovernmental Panel on Climate Change (IPCC), who produce regular assessment reports on all aspects of the subject. In their latest published report, the IPCC concluded that *“warming of the climate is unequivocal”* (IPCC, 2007a). [2] Greenhouse Gases (GHGs) in our atmosphere are necessary for sustaining a climate on earth necessary for life, by trapping the heat from the sun that is reflected back from the earth. The most notable of these are carbon dioxide (CO_2), methane (CH_4) and nitrogen oxides (NO_x).[3] The link between the concentration of these gases in the atmosphere and global temperature has been recognised since the 19th Century (Jacobsun, 2002).

Following this, climate scientists have also proven a link between global temperature and climate or weather patterns (Weart, 2013). Although there is a natural variation in atmospheric GHG concentrations and corresponding global temperature, varying within a 2^oC range, the last time the polar regions of the earth were significantly warmer ($3\text{-}5^oC$) was about 125,000 years ago (Solomon et al., 2007). Average temperatures have gradually risen by about 1^oC since records began in 1850 and 11 out of the 12 years previous to the 2007 IPCC report were the warmest witnessed in that period. GHG concentration has risen rapidly over the past 250 years to unprecedented amounts, and is now over 400ppm (NOAA, 2013), the highest in 10,000 years of human existence. This has been determined through analysing ice cores that have trapped atmospheric gases such as CO_2 for millennia, demonstrated in Figure 1.1**.** The cause of this rise in GHG concentration has been largely due to anthropogenic emissions and the IPCC concluded that;

> *The observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.* (IPCC, 2007b, p.10)[4]

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[2] Although a final draft of a new report is available, it has not been officially published at the time of writing. A released summary for policymakers (IPCC, 2013) suggests that this report reinforces the findings of the 2007 report.

[3] CO_2 dominates GHGs thus exerts the greatest influence on climate change, therefore most attention is paid to CO_2 emissions, which are often referred to simply as carbon emissions. Despite this, non-CO_2 GHG emissions are also important.

[4] The 2013 IPCC summary for policymakers suggests that the certainty in this has grown.

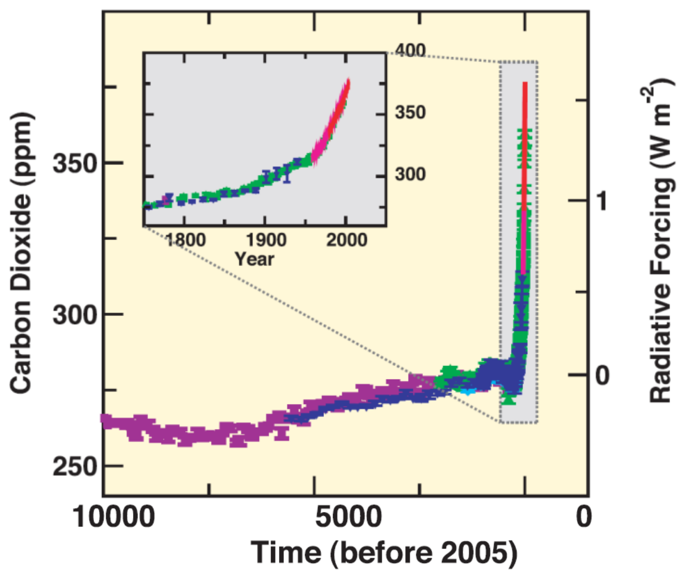

Figure 1.1: Change in atmospheric CO_2 (IPCC, 2007b, p.3)[5]

A recent meta-analysis of peer-reviewed journal papers examining climate change found that of those that took a stance if climate change was due to anthropogenic emissions, 97% concluded in favour (Cook et al., 2013). According to the International Energy Agency (2009a) global anthropogenic GHG emissions grew by 61% from 1970 to 2005 (1.4% p.a.), and the IPCC estimates that in a business as usual situation there will be at least a 25% increase from 2000 to 2030, which would likely result in a global temperature change between 2.5 and 4°C.

It is generally agreed that we are already committed to an increase over 1°C and the Copenhagen Summit of 2009 agreed that we should limit this to 2°C (though a process for doing so has not yet been settled). Temperature has a significant influence over the earth's climate systems. An increase may cause sea level rises through thermal expansion and melting ice caps and sheets, which in turn causes widespread changes in:

> *Precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.* (IPCC, 2007b, p.7)

From these changes, there will be a non-linear response to eco-system damage due to the unknown effects of feedback systems (Rogner et al., 2007). The effects of this are likely to include:

[5] From ice core studies (purple, blue, green) and atmospheric samples (red).

- Massive loss of human life;
- Significant biodiversity loss, including habitats and species extinction;
- Migration of large volumes of people between regions and countries;
- Spread of climate related disease such as malaria;
- Wide spread damage to existing infrastructure;
- Crop and agricultural impacts resulting in famine.

If current trends continue, GHG emissions could double by 2050, leading to a possible 6^{o}C temperature rise (IEA, 2012a). It is widely recognized that to prevent unprecedented changes to life on earth we must limit the concentration of GHGs in our atmosphere by reducing our emissions through new technologies and lifestyle changes.

1.1.1 Political Movement

The first international movement on climate change was the 1992 Rio Earth Summit and subsequent creation of the United Nations Framework Convention on Climate Change (UNFCCC). Article Two of the UNFCCC states the ultimate objective to be;

> *Stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.* (UN, 1992)

As such, the Kyoto Protocol, which has been ratified by 192 countries, is an agreement to set internationally binding emission reduction targets (UN, 2013). Notable exceptions to ratified countries are the United States, and Canada (who left in 2011). Under the Kyoto Protocol, developed countries bear the heaviest burden under the principle of *"common but differentiated responsibilities"*. It was adopted in 1997, and came into force in 2005, divided into commitment periods. During the first period, 2008-2012, the reduction target was an average of 5% below 1990 levels, and for the second commitment period of 2013-2020 it is 18%. These reductions are to be achieved through three main mechanisms; *International Emission Trading* (currently just certain industries), *Clean Development Mechanism* (assisting developing countries with emission reduction projects) and *Joint Implementation* (partnered emission reductions between countries). A set of 15 EU member states had a joint target of an 8% overall reduction under the first period and as part of this the UK target was set for 12.5%. The latest reported figures were for 2011 and the EU-15 had achieved a 14.7% reduction with the UK reducing emissions by 28%, the greatest of any of the EU countries (EEA, 2012).

UN Members meet regularly to discuss progress and extension to the UNFCCC. Other than the Kyoto Protocol, other notable agreements include:

- Bali Roadmap (2007), charting the negotiating process;
- Cancun Agreements (2010), recognising the need to limit temperature increase to 2^{o}C;
- Durban Outcomes (2011), committing to a legally binding plan after 2020, and;
- Doha Climate Gateway (2012), establishing financial and technological support and a target to make post-2020 agreements by 2015.

Further to the UNFCCC and Kyoto Protocol commitments, the European Climate Change Programme (ECCP) was established by the European Commission in 2000. Through this programme, the EU Emissions Trading Scheme (EUETS) was launched in 2005. The EUETS operates a cap and trade mechanism covering emissions from power stations and heavy industries, accounting for 40% of Europe's GHG emissions, and it is set to expand to include further emission sources. In 2009, a Climate and Energy Package became law, setting the "20-20-20" targets of a 20% increase in both the share of renewable energies and overall energy efficiency, and 20% reduction in GHG by 2020 (EC, 2010).

The UK Climate Change Act 2008 sets a legal obligation to achieve an 80% emission reduction from 1990 levels by 2050, through a series of three carbon budgets, and a non-legal target of a 34% reduction by 2020. In order to achieve these targets, the UK is subject to a number of high level policies, which are managed by the Department of Energy and Climate Change (DECC), and set out in 'The Carbon Plan' (DECC, 2011a). More recently a fourth carbon budget has set a 50% reduction target for the 2023-2027 period (DECC, 2011b).

1.1.2 Transport and Private Cars

Globally, the transport sector accounts for around 30% of energy use, according to the International Energy Agency (IEA, 2012b) and, as illustrated in Figure 1.2, is the largest single user of fossil fuels. In 2009, transport was the third largest source of GHG emissions (after energy and industry), accounting for approximately 15% of overall GHG emissions (IEA, 2012a). This had grown by 45% from 1990 to 2007 (ITF, 2010). Within this, road transport makes the most significant contribution to transport GHG emissions (ITF, 2010), and in most OECD countries, these emissions are dominated by passenger cars.

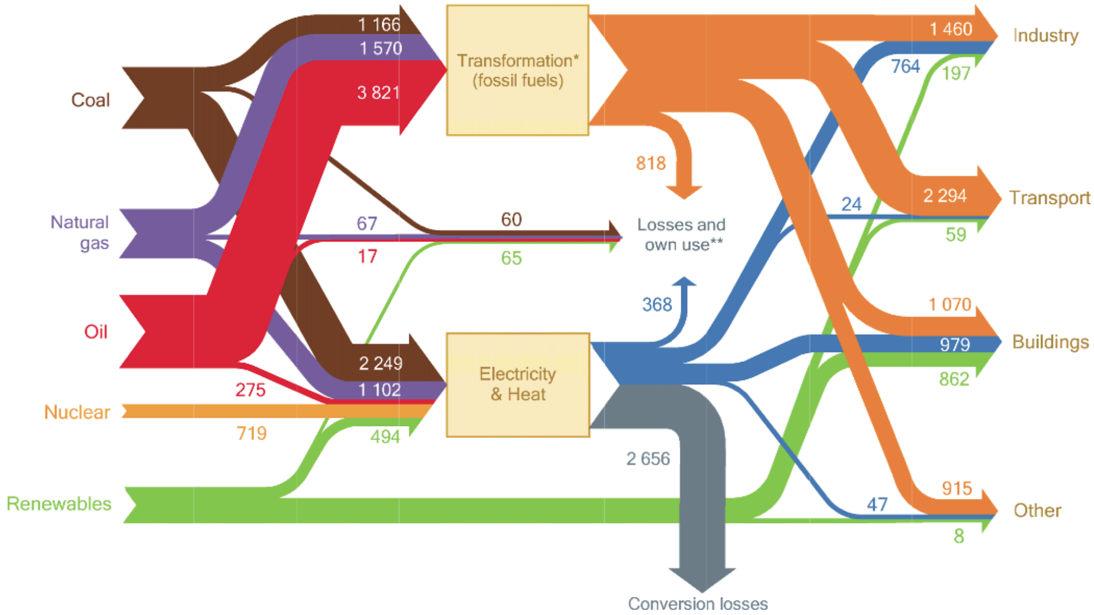

Figure 1.2: The global energy system, 2010 (Mt oil equivalent) (IEA, 2012b, p.62)[6]

As can be seen in Figure 1.3, following the energy sector, transport (not including international aviation and shipping) is the second largest source of CO_2 emissions in the UK (DECC, 2013a). Transport emissions peaked in 2007 but are now only marginally higher than 1990 levels. By end user, transport contributes a similar percentage to total GHG emissions (24%) and has decreased by 1% since 1990. Passenger cars alone account for nearly 12% of UK GHG emissions (DfT, 2012a). Additionally, approximately 75% of UK households have a car, which is the transport mode used most frequently by over half of the population (DfT, 2010).

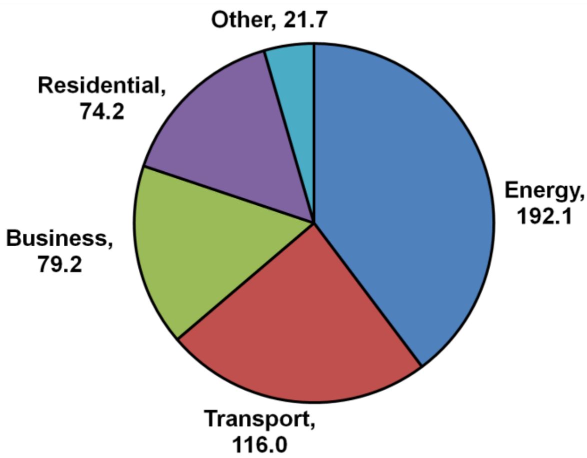

Figure 1.3: UK GHG emissions (Mt), 2012 provisional figures (data from DECC, 2013a)

[6] * Transformation of fossil fuels from primary energy into a form that can be used in the final consuming sectors. ** Includes losses and fuel consumed in oil and gas production, transformation losses and own use, generation lost or consumed in the process of electricity production, and transmission and distribution losses.

Conventional ICEV relies on petrol and diesel, fractions of petroleum (crude oil) that can be separated by their different boiling points through a series of processes known as refining (Speight, 2011). Crude oil is produced from reserves across the world at a current rate of around 84 million barrels a day (mb/d), which is expected to rise to almost 100 mb/d by 2035, in response to rising demand (IEA, 2012b). The majority of the increase in production will come from unconventional sources and production efficiencies, as shown in Figure 1.4. Currently, around 50% of crude oil is used in transportation. Most of this is for road transport, and the demand growth in future years will come mainly from transport in non-OECD countries. The amount of proven oil reserves is a much debated issue (Owen et al., 2010), but could be over 1,500 billion barrels, which under current consumption patterns would last just over 54 years (BP, 2012). However, when accounting for unconventional, undiscovered and currently unrecoverable sources of oil actual reserves could reach toward 6000 billion barrels (IEA, 2012b).

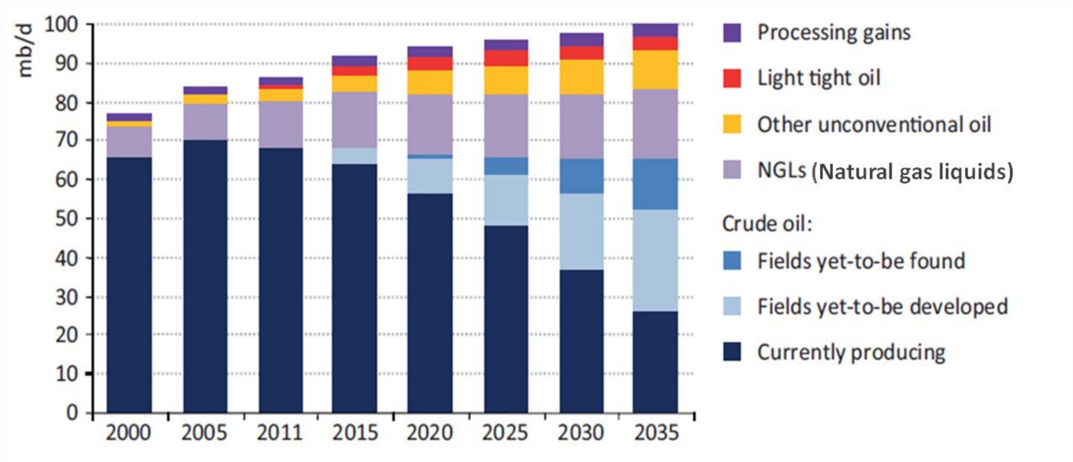

Figure 1.4: World oil supply by type in IEA New Policies Scenario (IEA, 2012b, p.103)

When considering a projected three to four-fold increase in global passenger mobility by 2050 (ITF, 2010), and in particular the well-recognised increase in demand for personal passenger vehicles as economies emerge, this is an area of huge potential for meeting emission reduction targets, or indeed, preventing emissions increases. It is more prudently so when one considers the wealth of options, with significant opportunities to reduce emissions through new technologies, modal shift and behavioural change.

Official predictions vary on the increase in CO_2 emissions from transport, dependent on technologies and policies which are considered. The International Transport Forum (ITF) have suggested that under a business-as-usual scenario, by 2050 total emissions will increase by up to three times, with an increasing proportion (going over 50%) from light duty passenger vehicles (ITF, 2011a). Non-OECD country emissions are suggested to grow by up to 5 times. To avoid this, a large proportion of vehicles will need to use alternative energy carriers, such as electricity and hydrogen, alongside decarbonisation of power supplies (ITF, 2011a). This would need to be in the order of at least three quarters of vehicle sales in the market by 2050 in order to limit temperature increases to 2^{o}C (IEA, 2012a). The 2010 European White Paper on transport envisages zero emission urban transport by 2050, and under UK policy, transport emissions are projected to decrease by around 15% between 2009 and 2030, with almost all cars being “Ultra Low Emission” by 2050 (DECC, 2011a). This presents a significant challenge, as by the end of 2012, less than 3000 pure electric vehicles had been registered in the UK (SMMT, 2013a).

1.2 Scope and Limitations of the Research

This thesis utilises system dynamics modelling to explore policies for the development and uptake of low carbon passenger vehicle technologies. In doing so, there is a specific focus on ethical concerns, from the point of view of climate change and distributional justice. There are however, many other drivers and concerns related to LCVs and alternative decarbonisation options that are not directly considered in this thesis, but it is prudent to be aware of.

1.2.1 Other drivers for LCVs

Climate change is not the only driver for changing the current automobile regime, but policy makers and engineers alike must consider other externalities of the passenger car when introducing new technologies.

Fuel and energy scarcity, security and independence

Most energy and fuel used in the UK is non-renewable, and supply forecasts vary immensely, hence the move towards increasing renewable energy supplies, such as solar, wind and hydro electricity plants and the production of biofuels. Transport already accounts for 30% of world non-renewable energy needs (IEA, 2012b). Crude oil reserves are not distributed equally across nations, but much of it lies in just a few countries. Although this unbalance can promote a fair competitive advantage for these countries, some are politically unstable. In such cases, not only could this risk exploitation of vulnerable nations but also compel engagement with corrupt regimes. A move away from crude oil as a primary fuel for transport towards a fuel or energy supply that can be both produced and managed within a home nation would allow international relations to be more independent from resource needs. The IEA suggest that low carbon energy can lead to greater energy security.

Local pollution

Not all transport related emissions reach the atmosphere and contribute to climate change, but some remain closer to their sources and result in local air pollution, such as photochemical smog. This pollution can be damaging to both the local environment and human health. Current ICEVs also have the problems of noise from vehicles adversely affecting human health, and the toxic effects of petroleum if mishandled. Although LCVs may avoid these issues of local pollution, they may contribute in different ways. For example, upstream emissions should still be considered in terms of their impacts of local pollution and alternative ICEV fuels may have significant particulate and non-GHG emissions impacts, as well as uncertain environmental impacts.

Manufacturers

Although the automobile industry in the UK is comparatively small and the country relies on imports from foreign manufacturers, it is well placed to expand as our vehicle fleet evolves. Many players in the UK automotive industry and supply chain believe that the UK has the opportunity to be a world leader in LCV technologies.

1.2.2 Other Concerns of LCVs

Changing the make-up and attributes of mobility and accessibility by introducing LCVs may bring about new concerns or extend existing ones. From a more forward-looking perspective, addressing these concerns and introducing sustainable solutions may prevent a replication of destructive western travel habits in some currently developing countries.

Wider sustainability impacts

Some aspects of LCV technologies may be unfeasible for long term use due to impacts on environment, society and economics. These concerns include nuclear safety and waste, resource extraction, habitat degradation and lifestyle choices.[7]

[7] See Literature Review Part A for more details.

Road safety and congestion.

There were almost 2000 road deaths in the UK in 2012, the lowest figure since records began and the rate of road deaths per vehicle miles travelled has halved over the past decade (DfT, 2013a). Any replacement powertrain or fuel must be as safe, if not more so, for passengers, pedestrians and other road users, as at present. One concern is due to the lack of noise related to the EV to warn pedestrians (particularly those with hearing impediments), [8] and another is the safe handling of highly explosive H_2. Further to this, with increasing numbers of cars on the roads, average speeds are decreasing, making journey times longer. For instance 19 seconds were lost per mile due to congestion in 2010 (CBI, 2012). Ways to avoid encouraging further congestion should be considered in LCV technology development.

Economics

In the UK, transport is the highest household expenditure (ONS, 2012) indicating the importance of transport and our dependence on it. Any substantial or too rapid change in how much it costs to own and run a vehicle may have an adverse impact on daily life, which if widespread, could disrupt the economy as we struggle to reallocate our spending or amend our travel habits. In addition, a large income to the UK government currently comes from duties on fuel and vehicles, and improved vehicle efficiency alone is expected to reduce government income in the region of 1% of GDP pa by 2030 (CBI, 2012). This could require a substantial shift in tax burdens or contribute to further economic uncertainty and crisis.

1.2.3 Alternative Policies

The focus of this work is specifically on the replacement of conventional ICEV in the private passenger car fleet by LCVs to decarbonise the transport system in developed countries. The impact of non-passenger vehicles, used car markets, fleets and company car schemes will not be explicitly considered.[9]

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[8] This may be in conflict with noise pollution concerns, so a careful balance must be sought.

[9] Although this restriction may appear distorting as fleet vehicle sales make up approximately 50% of new car sales, and used car sales make up approximately 70% of all sales (SMMT, 2013a), it is assumed that any benefits arising from LCV policies will help build the used car market and learning can be transferred to fleet related policies. Though there exists significant uncertainty regarding the residual values of new LCV technologies and markets it is clear that a strong used LCV demand is needed for high residual values that sustain the new LCV market (Element Energy, 2013). The implications of this will be briefly discussed in the model conclusions.

In developed countries like the UK, at the heart of transport carbon reduction policy is a desire to influence a change in travel and behaviour habits across the nation to reduce the amount we travel and choose alternative modes of transport when we do (DECC, 2009; 2011a; DfT, 2009b; EC, 2011). These so-called ‘softer’ policies are an important element to the wider context of transport decarbonisation (Gross et al, 2009) that this work does not directly address. As such, it is an assumption of this research that LCV policies divert no funding or resources away from these other legitimate policy options, particularly those detailed below. This may be a somewhat simplistic assumption as the policy objectives may be in competition, so the practicalities should be addressed in future research.

Modal shift

It is widely recognised that a move away from single occupancy vehicles towards public transport (buses, trains and ferries run on low carbon fuels), and active modes (walking and cycling) is an important part of decarbonising transport emissions. Evidence suggests that investment in public transport and infrastructure for active modes, leads to greater participation as public perceptions of convenience, utility and safety are raised (Atkins, 2009). Although it is difficult to determine the cost effectiveness of this policy option (Schroten et al., 2011), a recent UK project that improved travel awareness and planning in three towns led to a 9% reduction in car driver trips over a four year period (Sloman et al., 2010).

ICT and land use planning

Road transport emissions can be reduced by better use of Information and Communication Technology (ICT) to plan traffic routes, manage congestion and introducing novel techniques such as Intelligent Transport Systems (ITS) (Grant-Muller and Usher, 2013). ICT can also be applied to encourage use and integration of alternative modes of travel, for example through the increasingly wide-spread provision of smartphone applications for route-planning, cycle hire and public transport information, or displaying environmental information to assist in decision making (Brazil and Caulfield, 2013).

Eco-driving and maintenance

Fuel consumption can be reduced by up to 20% by better driving styles and vehicle maintenance at a relative low abatement cost (Schade et al., 2011). Educating drivers on the importance of this and the most effective techniques, as well as introducing supportive technologies and understanding the impact of real-world driving conditions (Ropkins et al., 2009), is already prevalent in business fleets, who have witnessed noticeable reductions in fuel use (DfT, 2009b). This does have implications to be managed regarding rebound effects as cost savings can translate into increased travel (Atkins, 2009).

Reducing the need to travel

Encouraging people to consider alternatives to making a trip of any sort may prevent hundreds of unnecessary journeys, and is one of the core areas considered in knowledge reviews of low carbon policies (Gross et al., 2009; Skinner et al., 2011). For example, ICT can reduce the need to travel through teleconferencing facilities, internet shopping and home-working (DfT, 2009b). Though this has potential benefits of increased social inclusion for groups with mobility difficulties, care should be taken to avoid further social isolation for those without internet access and a decline in important face-to-face human relationships (Kenyon et al., 2002).

1.3 Research Objectives

The overarching objective of this research was to investigate an approach to modelling LCV uptake policies, which incorporates an ethical framework that identifies distributional impacts. Sub-objectives in achieving this were to:

1. Evaluate current and projected LCV technologies and uptake policies;
2. Examine and critique existing LCV uptake models;
3. Develop arguments related to the associated distributive issues to LCV uptake and set out an ethical framework for LCV policy appraisal;
4. Consider the permissibility of modelling in policy appraisal;
5. Propose an alternative policy modelling and appraisal framework that integrates the findings of Objectives 1-4;
6. Provide recommendations for LCV policy prescription.

1.4 Learning Objectives

To complement the above objectives, the following learning objectives were also required:

1. Develop skills and understanding in technological review, policy appraisal, modelling techniques and applied ethics, and;
2. Develop case study examples by adapting system dynamic models to explore issues set out in the research objectives.

1.5 Research Focus and Originality

This research takes a unique inter-disciplinary approach integrating technological review, policy appraisal, modelling techniques and applied ethics. It contributes to policy development by proposing a novel approach to modelling LCV uptake policies that incorporates an ethical framework, aiding researchers, policy makers and automobile manufacturers. Although models of LCV uptake exist, there are no known studies that explicitly appreciate the wider ethical implications of findings in the way that is proposed in this research. Further to this, very few compare or combine supply and demand policies within the same study as is performed here. Drawing from the work carried out in this research, an improved policy appraisal framework has been proposed, which is transferable to other areas of public policy. In addition, this work will make an original contribution that will help advance philosophical discussion in the burgeoning fields of both climate and transport ethics, specifically regarding the practical aspects of policy making in relation to LCVs and modelling.

1.6 Methodology

What follows is a high level description of the methodological process carried out in order to achieve the objectives set out for this thesis, as presented in Figure 1.5. This is designed to give the reader an understanding of how the areas of work integrate and what methods were applied to carry out the necessary work. The strands of the research were carried out in parallel, and findings fed back into each to refine observations and methods. Furthermore, the skills and understanding of the multi-disciplinary areas of research also had to be developed in parallel. Thus, methodology has evolved throughout the research, culminating in the chapters presented later. Further details on specific methodologies are provided in the separate chapters.

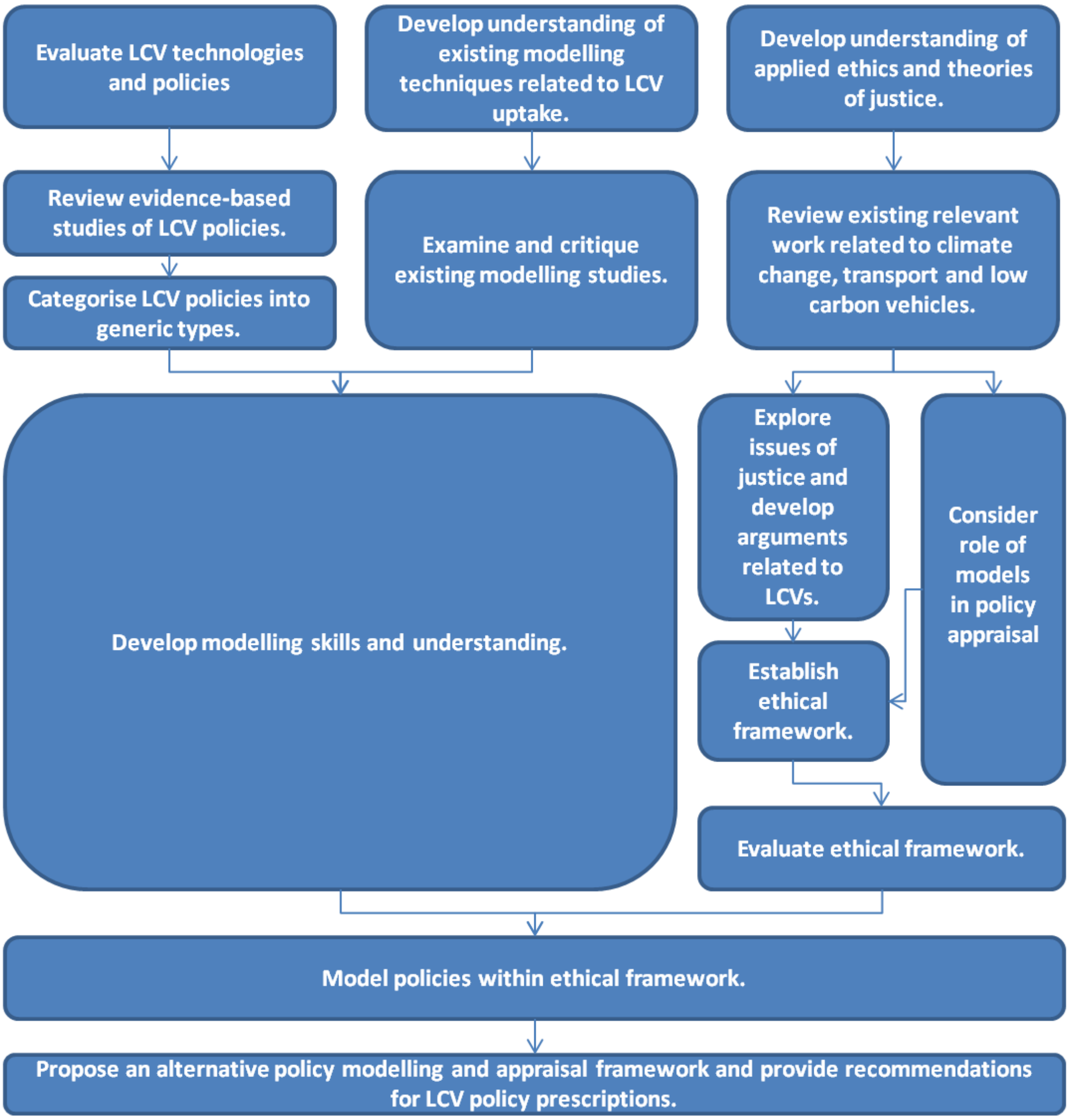

Figure 1.5: Methodological overview

The research commenced with a literature review that was required to build knowledge and develop skills in the four main disciplines of this research; technology, policy, modelling and ethics. To begin, the relative potential of different LCV technologies and barriers to their uptake were explored. Following this, policies that were being implemented to overcome uptake barriers were identified, and existing evidence based studies of such policies were reviewed. Scrutiny of policies led to the generic categorisation of policies using a deductive thematic analysis, allowing a more manageable assessment. This evaluation of technologies and policies elucidated the research gaps to focus on in the remainder of the research. Once the understanding of LCV technologies and policies was established, a literature review of modelling techniques and existing studies of LCV uptake was carried out. This involved detailed criticism of the studies in order to further refine the research focus and methods. Finally, understanding of ethics, theories of distributional justice and equity in transport was acquired through literature review of philosophical material, providing a firm background for the development of the ethical framework.

The implications of LCV technologies and policies were then considered from the point of view of distributional justice, in order to form the basic structure of arguments that create the ethical framework. Applying a philosophical approach, claims were explored by presenting logical arguments and drawing from established related work. The question of what is an appropriate practical approach to appraising policies for the uptake of low carbon vehicles was addressed. In answering this question, it was necessary to establish the issues of distributive justice that may arise from such policies, and an appropriate method of deciding which policies to implement. The issues of justice were addressed by defending two claims; 1) that coercive policies are permissible due to the harms of climate change, and 2) that there are special groups that require protection from these policies. Further to this, philosophical examination of the application and limitation of using models for policy appraisal was carried out. Once the ethical framework was established, it was felt that it would be further strengthened by evaluation of the approach being taken. Thus, a workshop and expert survey were arranged to establish what, if any, interdisciplinary consensus there may be on these issues. The outcomes of these were subjected to basic qualitative and quantitative analyses.

As the focus of the research was to carry out policy modelling, a case study exploration exercise of a basic system dynamic model of LCV uptake was carried out while the basic ethical arguments were being established. There was a dual advantage in this in that basic modelling skills could be developed alongside establishing understanding of sensitivities of modelling and low carbon vehicle attributes. Being able to do this before the ethical framework was ready for implementation meant that more basic issues could be explored. A simple model of LCV uptake, focusing on the demand side (and specifically customer interactions), which was discovered in the literature review, was adapted and expanded in order to do this. The model, which included ICEV and two pro-electric vehicles types, was calibrated to UK data and run over a time frame of 40 years. Two policies of interest, subsidies and manufacturer regulation, were subjected to initial sensitivity testing in this model, looking at the impacts on carbon emissions, vehicle sales, government spending and revenue.

The findings from the first case study then led to the development of a second case study. In this case study another existing model, which was based in California and also identified in the literature review, was chosen for development. In order to account for the distributional impacts highlighted within the fully established ethical framework, a key requirement of this model was to be able to have within the model some indication of segments of society. In Case Study Two, vehicles (ICEV and three pro-electric models) are available in four segment sizes (from extra small to large). An approach was taken that these size segments are proxies for income, so this model could be used to explore the impacts of LCV policies on specific segments of society, which particularly included the poorest. A further advantage compared to the first case study was the inclusion within the model of detailed manufacturer regulations which were identified in literature review and framework evaluation as being a policy to explore. Specific scenarios of subsidies and manufacturer regulations were developed and tested within the ethical framework through impact on carbon emission and opportunity for car ownership.

Finally, findings from the literature review, the development and evaluation of the ethical framework, and from both case studies were then fully integrated in order to make recommendations for policies and to propose an alternative methodology for policy appraisal.

The remainder of this thesis reflects this methodological process, and is set out as follows, and described in Figure 1.6.

- **Chapter Two** is the literature review of relevant studies to provide further background and identify research gaps relevant to this research. This is divided into four parts, covering technology, policy, modelling and ethics.
- There are two parts to **Chapter Three.** In the first, an ethical framework for LCV policy appraisal is established**.** Issues of distributive justice relating to climate change, car ownership and the impact on the worst-off are explored, defending two claims. Arguments are presented for the permissible use of modelling in policy prescriptions. The second part presents descriptive results from a survey and workshop of experts in the field of low carbon vehicles across the disciplines of technology, ethics and policy that was carried out to evaluate the ethical framework.
- **Chapter Four** is the first case study of LCV uptake. This is a simple model that explores basic sensitivities and attributes to help build skills and understanding.

- The second case study is presented in **Chapter Five**. It is more complex than the first case study and incorporates the ethical framework developed in Chapter Three, as policies on both supply and demand sides are modelled, with a proxy indicator of impact on the poor through changes in purchase cost in vehicle segments.
- Finally, **Chapter Six** is the Conclusion. This brings together the discussions held in each Chapter. A proposal for an improved modelling approach that incorporates the ethical framework is presented, as well as advice to policy makers and suggestions for future work.

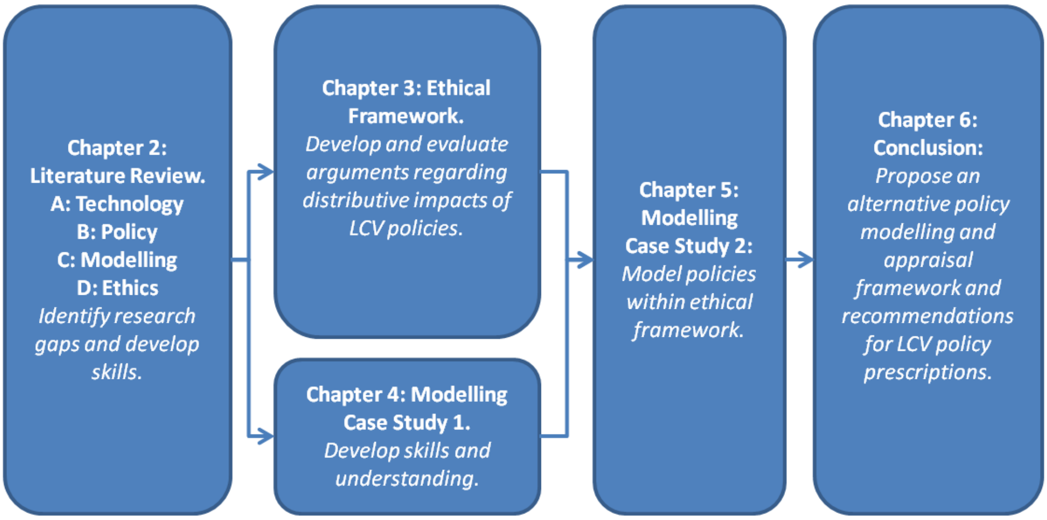

Figure 1.6: Chapter overview

CHAPTER TWO: LITERATURE REVIEW

This Chapter is divided into five sections. The first four cover each element that forms the foundation of this interdisciplinary research. The conclusions from each are then brought together in the final section that sets out the research gaps and objectives. This review establishes that the period of study is limited to the near to mid-term, and as such focuses on pro-electric vehicles. Five generic policies for LCV uptake are identified and existing models of LCV uptake are explored. The findings show that there are none with explicit consideration of distributional impacts, and few that compare policies on the supply and demand sides. Literature on ethics and equity in transport reveals that there is little philosophical dialogue related to transport, and no previous work related to LCVs, though it is discussed more fully from a sociological viewpoint.

PART A: TECHNOLOGIES AND FUELS

2A.1 Overview

This section summarises the main Low Carbon Vehicle (LCV) technology and fuel options currently being researched, trialled or developed. In order to reduce Greenhouse Gas (GHG) emissions (and address other drivers discussed in the introduction Chapter), the conventionally-fuelled Internal Combustion Engine Vehicle (cICEV) must be made more fuel efficient or replaced by an Alternative Fuel Vehicle (AFV).

The conventional fuels for ICEV[10] are petrol or diesel, derived from crude oil. Alternatives that may be used (with some engine modifications) are other combustible hydrocarbon liquids and gases. This includes natural or synthetic gas and its derivatives or biofuels produced from plants and waste materials. The alternative powertrain to an ICE is the electric motor. Electric Vehicles (EV) can be powered by either a rechargeable electric battery (Battery Electric Vehicle - BEV) or a hydrogen fuel cell (HFCV). These are also termed Zero Emission Vehicles (ZEV), as they do not have tailpipe emissions when in operation. It should be noted, however, that this term is misleading, as there are still emissions related to the generation of the electricity or hydrogen, as well as to the production and dismantling of the vehicle itself. Additionally, we currently have on our roads hybrid electric vehicles (HEV), which have both electric motors and ICE, some of which can be plugged in to charge the battery (PiHEV). Figure 2.1 shows predictions for changes in sales of these technologies up to 2050.

These alternative fuels and technologies are not new. For example, it is widely known that the diesel ICE was designed to be run on peanut oil, the electric vehicle (EV) was a market leader at the turn of the 20th century (Struben and Sterman, 2008), steam powered cars held early land speed records (Riley, 2004) and a number of other alternative ICEV fuels emerged following the 1973-74 oil embargo.

[10] Note the distinction between the generic ICEV (that may be fuelled by various fuels) and the specific cICEV which is only fuelled by petrol or diesel. Where ICE is used this refers to the powertrain itself rather than as part a vehicle.

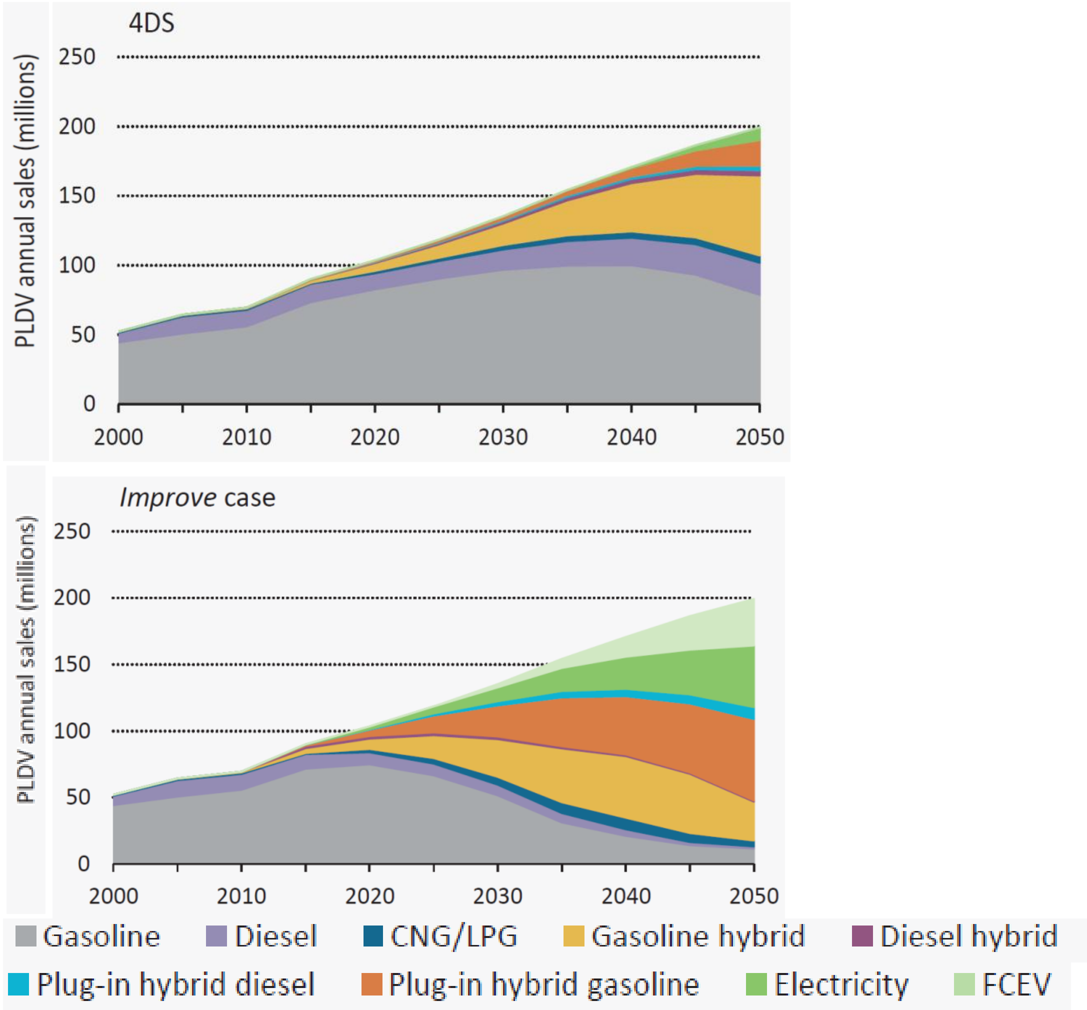

Figure 2.1: Predicted sales of passenger car technologies to 2050 (IEA, 2012a, p.443)
TOP: Capped 4°C rise scenario of existing and upcoming policies
BOTTOM: Capped 2°C rise scenario with technological improvements

2A.2 The Internal Combustion Engine

The Internal Combustion Engine (ICE) has dominated road transport for over a century. It was originally derived from the steam engine, and its fundamental operation has had little change over time (van Basshuysen and Schafer, 2004). In an ICE, rotational motion is created by pistons driving a crankshaft. The pistons operate through a four-stroke cycle powered by combustion of a fuel in compressed hot air. There are two types of ICE, *Spark Ignition* (SI) and *Compression.* SI engines are fuelled by petrol, and operate at a constant volume with combustion ignited by a spark generated in the engine. Diesel fuels the compression engine, which operates at constant pressure and a higher compression ratio than SI engines, relying on auto-ignition of the fuel. These differences are due to differing chemical properties of the two fuels that determine the fuel's characteristics such as compression, knock resistance, density and combustion. Therefore, each has provided different opportunities for engine optimisation and efficiency.

2A.2.1 Conventional ICE Fuels

The dominant vehicle fuels at present are petrol for an SI engine (commonly known as gasoline in the USA) and diesel for the compression engine. Both fuels are widely available at filling stations across the world. There are almost 9000 in the UK, and 98% of postcodes are within a 10 minute drive time of one (Deloitte, 2012). Depending on the size of the vehicle a typical range is between 300 and 600 miles, with diesel vehicles being slightly higher due to higher energy content and better fuel efficiency.

Both Petrol and Diesel engines produce harmful emissions that are sent directly into the atmosphere as a result of the combustion process. The emissions include CO_2, CO, NOx, unburnt hydrocarbons (HCs) and particulate matter (PM). Current legislation and new fleet averages are shown in Table 2.1. In the UK the current split of conventional fuelled ICEV on our roads is generally accepted as 70% petrol to 30% diesel, though a recent study suggests that this is closer to 60:40 (Tate, 2010). New car sales of diesels are now just over 50% of market share (SMMT, 2013a), and this is reflected in the fact that petrol sales have fallen at around 5% per annum since 2005 whilst diesel sales have grown around 1.5% pa (DECC, 2013b). It is likely that this shift towards Diesel has been partly due to its better fuel economy during a period of rapidly rising fuel prices, and also a growing public awareness of its lower GHG emissions coupled with increasing climate conscience.

GHG	EU legislation (EURO 5)[a] g/km (tailpipe)		UK fleet new car average[c] g/km (tailpipe)	
	Diesel	**Petrol**	**Diesel**	**Petrol**
CO_2	130 by 2015[b] and 95 by 2020[b]		133.1[d]	
CO	0.5	1.0	0.22	0.36
NOx	0.18	0.06	0.15	0.03
HC	0.05	0.1	0.01	0.03
PM	0.005	0.005	0.001	Negligible

Table 2.1: ICEV emissions[11]

11 [a](EC, 2007), [b](EC, 2009a), [c](VCA, 2011), [d](SMMT, 2013a). CO_2 is a fleet average, all others are per vehicle.

Low Carbon cICEV

Carbon emissions from cICEV have been reduced since EU legislation was introduced in the early 1990's (Andrews, 2009). Non-carbon emissions have also been drastically reduced due to the introduction of unleaded petrol and the advent of emission controls such as catalytic convertors, three way catalysts and particulate traps (Riley, 2004). In addition, cICEV emissions continue to be reduced through increasing fuel efficiency of the vehicle or producing cleaner burning fuels. Incremental powertrain improvements, as set out in Table 2.2, have the potential to increase overall efficiency by up to 30% in the short term (King, 2007).

Technology	Efficiency Saving (%)	Cost per vehicle (£)
Direct injection and lean burn	10-13	200-400
Variable valve actuation	5-7	175-250
Downsizing engine capacity	10-15	150-300
Dual clutch transmission	4-5	400-600
Stop-start	3-4	100-200
Stop-start with regenerative breaking	7	350-450
Electric motor assist	7	1000
Reduced mechanical friction components	3-5	Negligible
Lightweighting chassis	10	250-500
Low rolling resistance tyres	2-4	50-100
Improved aerodynamics	2-4	unknown

Table 2.2: Technologies to improve ICE fuel efficiency (King, 2007)

Fuel efficiency can be increased through either engine or chassis improvements, both of which lead to less fuel being used thus reducing the associated emissions. Many improvements in the combustion efficiency of fuel can be made through engine control modifications such as variable valve timings and direct injection. Other improvements can be made in thermal efficiency and friction losses. Efficiency improvements can lead to downsizing of vehicles, but may also lead to undesired effects such as increased vehicles miles travelled. The new techniques are often highly computerised, making engine maintenance more difficult. Further improvements can be made through modifying the vehicle with after-treatments in the exhaust, reducing weight and frictional drag (e.g. aerodynamics and tyre resistance), and through the application of soft hybrid technologies, such as regenerative breaking. These improvements have cross over with AFVs, which could also benefit from requiring less energy to drive the vehicle forward. Finally, conventional fuels can be further cleaned by processing and refining crude oil with improved methods to produce fuels with more efficient compositions for combustion, and free of impurities (Lane, 2006).

2A.2.2 Alternative ICE Fuels

A number of alternative fuels are being used in the ICE today. Although there is lots of potential for emission reduction, as will be explored in the following sections there are many problems to overcome. Together these mean more expensive vehicles, with often reduced utilities compared to cICEV. These problems include:

- Reduced energy content compared to conventional fuels;
- Lack of supportive infrastructure for delivery and storage;
- Modifications to the engine required due to chemical properties, and;
- Environmental and safety impacts, in both production and use.

Biofuels

The International Energy Agency (IEA) predict under their *"BLUE Map"* scenario that 27% of transport energy will come from biofuels by 2050 (IEA, 2011). Biofuels are currently the most used alternative ICEV fuel across the world, with many countries having in place mandates or targets for biofuel blends in their cICEV fuels (IEA, 2011). As such, global production of biofuels in 2011 was almost 60 million tonnes of oil equivalent (mtoe) (BP, 2012) growing rapidly over the previous decade (from around 10mtoe). North America is the highest producing region, and globally bioethanol production dominates that of biodiesel.

There are various types of biofuels, depending on feedstock and production (Singh, 2011). First generation are those which are prepared from a biomass that is usually part of a food chain, forming bio-ethanol from sugars, starches and cellulose. Common examples of these are wheat, corn or sugarbeet. Second generation biofuels can be prepared from cellulosic non-food crops, such as waste products (e.g. wood chippings, municipal waste or cooking oil), and can produce alcohols or synthetic fuels (notably bio-diesel) using advanced technologies. Conventional biofuels are first generation bioethanol, and some second generation biodiesel and biogas. Finally, the newest of biofuels are 3rd generation, formed from algae. In addition to the advantage that algae is not a food crop, it has a number of other potential benefits, as it can grow on marginal non-agricultural land, absorb significant quantities of CO_2 (e.g. from power stations or industrial processes), and purify water. Algae are also extremely fast growing and a high yield crop for biodiesel, with great potential for scale up to industrial quantities. However, it requires abundant quantities of sun or synthetic light and is not yet commercially viable (Campbell, 2008).

Biofuels are thought to have substantially lower GHG emissions than petrol or diesel on a life cycle basis (Scacchi et al., 2010) as CO_2 is captured in the growth phase. As such, it is envisaged that biofuels could contribute 20% of transport emissions savings by 2050 (IEA, 2011). However, there is much uncertainty due to the effects of indirect land use change (RFA, 2008) and because life cycle emissions are dependent on the production process (MacLean and Lave, 2003). This uncertainty is demonstrated in Figure 2.2, which also suggests that some forms of biofuel may actually lead to an increase in emissions compared to conventional fuels.

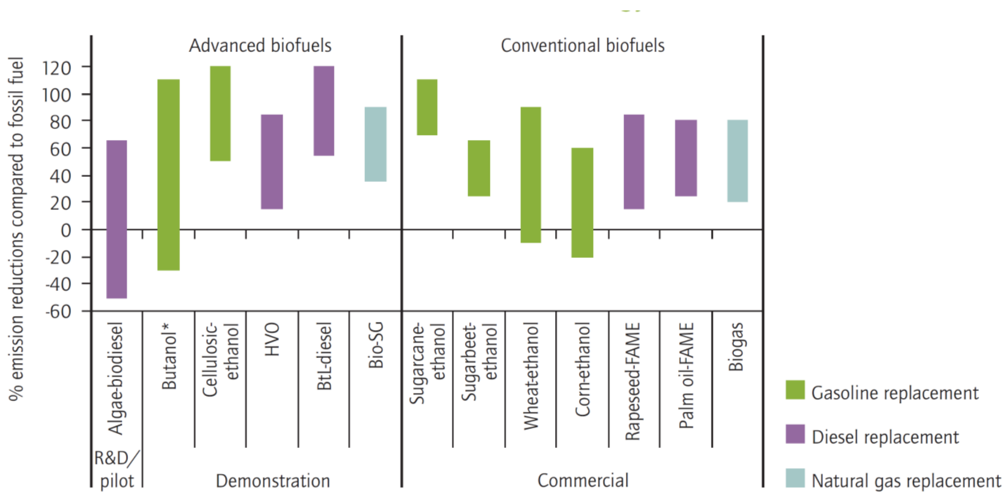

Figure 2.2: Lifecycle GHG balance of biofuels (IEA, 2011, p.16)[12]

Biofuels are renewable, can potentially provide energy security to individual countries, and are generally less toxic than conventional fuels (Singaram, 2009). However, despite this, there are a number of negative effects of biofuels on long term sustainability. These include the direct effects of degradation of habitats and local environment, the societal impact on labourers, and of most concern are the human rights regarding food security and changes in land use (NCB, 2011). Additionally the land area required to grow enough crops to replace all transport fuels would be significant (MacKay, 2008). These concerns are mainly (though not exclusively) related to first generation biofuels. The Gallagher Review (RFA, 2008) concluded that there is a future for biofuels in the UK but we shouldn’t aim for more than 5.75% of supply until more sustainable processing technologies are widely available.

[12] The assessments exclude emissions from indirect land-use change. Emission reductions of more than 100% (i.e. leading to negative emissions, or carbon absorption) are possible through use of co-products. Bio-SG: Bio-synthetic gas, BtL: biomass to liquids, FAME: fatty acid methyl esters, HVO: hydrogenated vegetable oil.

Biofuels tend to have a lower energy content (around 20-30MJ/l) than petrol or diesel (30-40MJ/l), leading to less power and lower ranges than cICEV (Singh, 2011). The costs associated with biofuels are concerning, with carbon abatement costs predicted to be in the region of 80 - 600 £/tCO_2e (set against an appraisal price of £87/tCO_2e), and the cost to UK motorists by 2020 in meeting EU obligations (10% of transport energy from renewable sources) is predicted to be around £1.3b/year (Bailey, 2013).

All biofuels are subject to the Renewable Transport Fuel Obligation (RTFO), which has evolved since it entered into force in 2008, and EU Renewable Energy Directive (RED) (DfT, 2012b). Currently, large fuel suppliers in the UK must have 5% by volume of their road transport fuel as biofuels in 2013/14 and meet up to 25% of this obligation with Renewable Transport Fuels Certificates (RTFCs) or pay into buy-out funds. Under the RED, biofuels must achieve at least a 35% GHG emission savings (compared to conventional fuels) and not be made from land with high biodiversity value or materials with high carbon stock. From the introduction of the RTFO in April 2008 to April 2013, over 7 billion litres of biofuels have been supplied in the UK and 4 billion RTFCs have been issued.[13] The proportion of bioethanol has increased over time, as have the percentage from the UK and the GHG savings.

Gaseous Fuels

Hydrogen gas, Natural Gas (NG) and Liquefied Petroleum Gas (LPG) can all be used to fuel modified spark ignition ICEV with potentially lower carbon emissions than petrol. The first attempt to use an ICE for road transport was actually designed to be run on a Hydrogen/Oxygen mix (Eckermann, 2001). Nowadays, a standard ICEV can run on hydrogen gas with little modification though with some problems, including reduced power and embrittlement of iron in the combustion chamber (Andrews, 2009). There is a slightly higher thermal efficiency than for NG, and this has the advantage of no need for after-treatment with the only emission being water and trace amounts of hydrocarbons from the lubrication oil (Riley, 2004). Further information on Hydrogen as a fuel is provided in Section 2A.3.2.

NG (mainly methane) and LPG (mainly propane) are hydrocarbon fuels with a lower carbon content than petrol and their gaseous forms ensure more complete

[13] Compiled by the author from DfT biofuel statistical releases available from: https://www.gov.uk/government/organisations/department-for-transport/series/biofuels-statistics.

combustion. However, their “well-to-wheels” (WTW) GHG emissions are similar (Edwards et al., 2011). Most NG or LPG cars are dual-fuel operation that may also be fuelled by petrol. No dedicated vehicles are mass produced and many vehicles have been converted from regular petrol engines (Riley, 2004). Only 0.2% of licensed vehicles in the UK are fuelled by NG (DfT, 2012c). NG is utilised as compressed, liquefied or adsorbent natural gas. There are thought to be abundant reserves of methane, predicted to last up to 230 years at current rates (IEA, 2012b), and the supplies are evenly distributed across different nations (Yeh, 2007). There are currently around 16 million NG vehicles globally (ENGVA, 2012), and it is most widespread in Pakistan and Latin America, accounting for 70% and 25% of fleet respectively (EC, 2011a). LPG was the first mass produced alternative fuel (EC, 2011a) and is already widely used, especially in heavy duty vehicles, and the UK saw a noticeable uptake by business with subsides introduced in the early 2000s. Since subsidies ended and due to a lack of infrastructure, many companies did not continue their use. In 2013 there were 1,500 forecourts selling LPG in the UK (NGC, 2013). LPG is most popular in Armenia where it accounts for up to 30% of vehicle fuels (IEA, 2010).

2A.3 The Electric Motor

An alternative to the ICE is the electric motor, which generates power through electro-magnetic fields – converting electrical energy into mechanical energy to create rotational motion for the vehicle’s wheels. Electric motors are already widely used in many applications (EC, 2011a). This is much more simple mechanically than the ICE but requires a more complex operating system for the vehicle (Riley, 2004), though ICEV is becoming increasingly more electrified. The electrical current for the motor can be obtained by onboard electro-chemical batteries or fuel cells. The former will require re-charging from grid electricity, whereas the latter is powered by hydrogen. Technically these are not ‘fuels’ but energy carriers.

Development of electric vehicles (EV) began at the same time as the ICEV, and it was a market leader at the turn of the 20th century (Struben and Sterman, 2008). However, despite its advantages over the ICEV in ease of operation, quietness, cleanliness and power transmission, ICEV secured the dominant position in the early 20th century as it was less expensive, fuel was more readily available, had a longer range, and also gained a reputation as being more ‘manly’ than the then EV (men were the majority of early adopters) (Mom, 2004). Over the past century, there were many EV ventures, none of which achieved more than a niche market position before eventually failing. There were particular periods of interest during the two world wars as ICEV were commandeered for the war effort, the 50's and 60's as electricity became more widely available and environmental conscience more prevalent then in the 70's due to the oil crisis. As no GHG or local pollution emissions are produced on board EVs, and they do not necessarily rely on fossil fuels (though this is dependent on electricity source), interest has been renewed in recent years. Currently, there are over 320 R,D &D projects, with nearly €2b of funding, related to EVs in the EU alone (Zubaryeva and Thiel, 2013).

2A.3.1 Battery Electric Vehicles

A Battery Electric Vehicle (BEV) has an on-board battery, which is rechargeable through an external electricity supply, to power the electric motor. As such, although there are no emissions at the point of vehicle use, upstream emissions associated with operation from the electricity supply are dependent upon power generation mix. As we move towards a decarbonised or decentralised electricity supply, this should become less of a problem. For example, a carbon intensity of 300g CO_2/kWh (similar to a gas power station) could save 10tCO_2 over a lifetime of a vehicle compared to cICEV, whereas the same vehicle with an extreme carbon intensity of 600gCO_2/kWh (similar to coal power plants) would actually increase emissions by about the same amount (ITF, 2011a).

Typically, BEVs have a range of up to 100 miles on a full charge of 6-8 hours at present. This is a major disadvantage when compared to cICEV, and causes 'range anxiety'[14] for drivers, especially when considering the current lack of available recharging infrastructure. The BEV therefore is not a direct replacement for the ICEV as it would require a change in driver behaviour and practises. Although the range would be within a usual daily commute, and cars are often idle overnight when they can be charged, those without off-street parking or atypical driving patterns may be disadvantaged. Other options to overcome this are fast charge technology or battery swapping. Fast chargers can cut recharge time to between 1 and 3 hours, and there were nearly 2,000 installed in the UK by 2013, but they are not generally suitable for home charging. Rapid charge, of up to 80% of the battery in 15 minutes to an hour, is being increasingly introduced but is expensive and the long term impact on battery life is uncertain (Rowney and Straw, 2013). A final

[14] "*The fear people have about the distance an EV can drive and the concern that the range may not be enough to reach their destination*." (SMMT, 2011)

option for charging is in-motion wireless charging, which allows battery charging through inductive coils under the road surface, but several challenges exist for this including technological development and health and safety risks, as well as the infrastructural requirement for road electrification (Wu et al., 2011). This is the most immature and uncertain option for charging. Battery swap is an alternative to charging, but faces problems of safety (particularly in the transfer process) and compatibility with different manufacturers approach to battery placement. Although this option is favoured by a leading US electric vehicle firm, Tesla, who offer a 90 second battery swap (Rogowsky, 2013), there are concerns over economic feasibility following the bankruptcy of the leading swap station provider (Steinberg, 2013). Another issue to be explored further is understanding the impact that charging will have on the electricity grid, as no new generation capacity is expected for at least twenty years, due to construction timelag (EC, 2011a). As such, there is much research being carried out to understand this impact and drivers' charging habits, such as the EA Technology "I2EV" project.[15]

The other major barrier to BEV adoption is its relatively high purchase cost compared to an ICEV counterpart. This is due largely to the cost of batteries. As such, developing a battery which is both small and light enough to fit in a passenger car and provide enough power to the motor to allow comparable speeds and range has been the focus of much research and the greatest advance has been in the use of lithium ion batteries (EC, 2011a). Rechargeable batteries have been in development for over 150 years, but it has only been in recent times that they have become suitable for mass production of BEVs (Larminie and Lowry, 2012). Newer battery materials, including nickel, lithium or sodium, have a large range of specific power and energy (IEA, 2012a). More recent experimental developments include metal-air batteries which are non-rechargeable but instead electrodes are changed, giving a potentially similar range for BEV to cICEV (Yang and Knickle, 2002).

Assuming that it is likely that battery technology will continue to develop, cost reductions would be expected. As this occurs, new challenges are likely to develop, such as improving battery life time and supply chain issues. Most notably, limitations in raw materials may be a major limitation to EV production. Though natural reserves (e.g. Lithium) should be sufficient until recycling techniques are improved or alternative materials are developed (EC, 2011a), concerns remain over potential exploitation of countries where these natural resources are located.

[15] Known commercially as 'My Electric Avenue': http://myelectricavenue.info/

Nevertheless, automobile manufacturers are taking the opportunity to capture the BEV market as early as possible, with a number of models becoming available. Manufacturers have opted for different approaches to capturing the market. For example, Renault reduce purchase cost by leasing the battery to the customer separately and Nissan have produced a high-end specification BEV to specifically attract early adopters of technology.

2A.3.2 Hydrogen Fuel Cell

Hydrogen is the most abundant element in the universe and has a very high energy density. In its chemical reaction with oxygen it creates only energy and water vapour. This makes hydrogen an attractive prospect as a clean fuel. However, as hydrogen is very reactive, it does not exist naturally on its own, and requires a great deal of energy to release it from any compound. The hydrogen fuel cell, shown in Figure 2.3, was invented in the mid 19th century and creates an electric current by chemically combining hydrogen and oxygen. There is a wide range of fuel cell types with great potential as an energy device, though only low temperature Proton Exchange Membrane (PEM) fuel cells are suitable for vehicles (Pistoia, 2010).

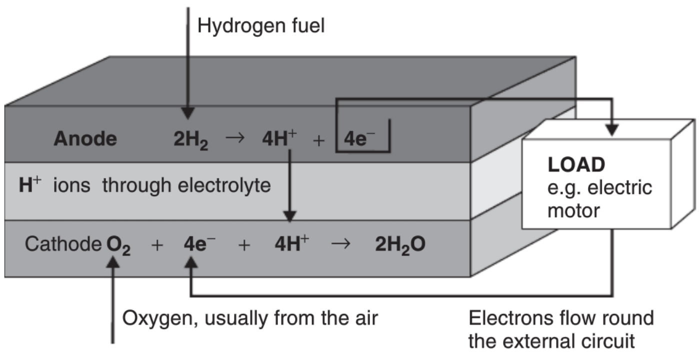

Figure 2.3: Hydrogen fuel cell (Larminie and Lowry, 2012, p.90)

Numerous barriers exist in the commercial viability of Hydrogen Fuel Cell Electric Vehicles (HFCV). As such, there are currently only prototype vehicles in production, even though the first was built in the early 1990s (Sperling and Cannon, 2004). Most automobile manufacturers have produced demonstration models, and the *Honda FCX Clarity* was introduced in small numbers for leasing (not purchase) in California and Japan in 2008, though is not yet mass produced. HFCVs have a similar performance and range to cICEV, increasing its attractiveness to drivers. When first introduced, purchase cost is expected to be high. This is due to the manufacturing costs of fuel cells, accounting for almost half the predicted costs of a HFCV (Martin; et al., 2010).

The more prevalent barrier for HFCV (and Hydrogen ICEV) is the lack of an established hydrogen economy with low cost and low carbon hydrogen production, transport and storage. This ‘hydrogen economy’ is unlikely to emerge before 2030 (IEA, 2012a). The production of hydrogen requires large amounts of energy from electricity, making its place as a low carbon fuel reliant on a decarbonised electrical network. Currently most hydrogen is produced from hydrocarbons (usually natural gas, but also other fossil fuels or biomass) or through electrolysis of water. This is not an efficient use of the resources as more CO_2 would be produced in the production of hydrogen from natural gas than if it were burnt directly, or from the electricity required in electrolysis (Riley, 2004). There is currently a lot of research being given to the latter using solar cells – zero carbon photolytic splitting of water to create hydrogen. At present there is a very large spread in WTW energy and GHG balance between hydrogen production pathways (Edwards et al., 2011).

Although hydrogen can be delivered at filling stations in a similar method to petrol or diesel, there is no transportation infrastructure. Southern California has a small refuelling network and by 2013 the UK had only one station, though refuelling at home may be an option. Storage of hydrogen also remains to be a problem. In a gas phase it occupies a lot of space, so the energy required to store it at reduced volumes is up to 40% of the energy content of hydrogen itself (DuPont, 2010). This requires storage at higher pressures or in larger tanks than conventional fuels. These issues may be overcome by onboard reforming of hydrocarbons or water electrolysis, but these technologies are still relatively immature. There are also a number of safety concerns and perceptions regarding transport and storage of hydrogen, as it is so reactive. One of the reasons for this is the relative low ignition energy of 20mJ, compared to that of petrol which is 240mJ (Foley, 2001).

2A.4 Hybrid Electric Vehicles

As a bridge between ICEV and BEV, there are a number of Hybrid Electric Vehicles (HEV) on our roads. These reduce the range anxiety associated with BEV and allow familiarisation with new technologies, having both an ICE fuelled by conventional fuels and an electric motor powered by a battery. Although these vehicles require more power as they tend to be heavier than other vehicles, reduced tailpipe emissions are realised due to the times when the car is driven by the electric motor, and the application of soft hybrid technologies (such as regenerative breaking and stop/start). Types of HEV in comparison to the ICEV and BEV, are shown in Figure 2.4.

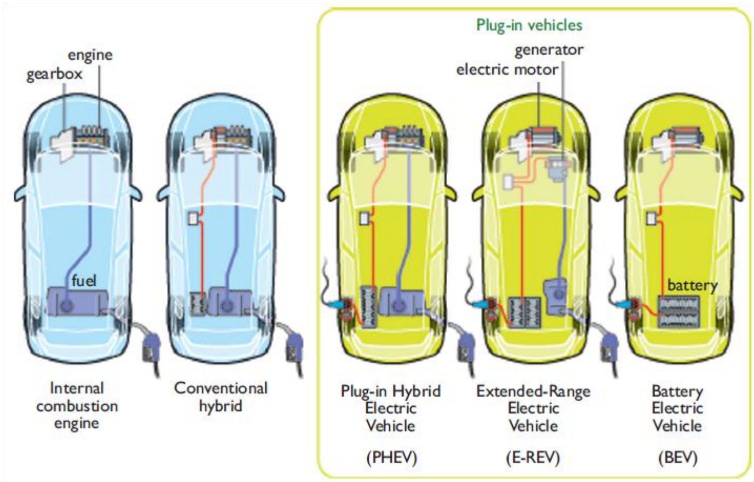

Figure 2.4: Schematics of vehicle types (OLEV, 2011, p.13)

The dominant, conventional, hybrid vehicle is the parallel hybrid, where either the electric motor or ICE can deliver power to the wheels through a mechanical transmission. There are a number of commercially available full hybrids, including the Toyota Prius, which was released in 1997 and is now the biggest selling car in California (Ohnsman, 2013) and has achieved over 5 million sales worldwide (Toyota, 2013). The battery is charged by the ICE and when it has enough charge it can direct the motor to drive the vehicle. Due to the size of the battery this is usually just at low speeds and for short distances, such as in urban driving. The more sophisticated hybrid operating systems power and efficiency can be optimised by drawing from both the motor and ICE in accordance with driving conditions (Larminie and Lowry, 2012).

Recently there has been the introduction of the Plug-in Hybrid Electric Vehicle (PiHEV), where the battery can also be charged through an external supply, similar to a BEV. This means that further fuel efficiencies and emission reductions may be realised, reducing dependence on fuel. For example, if a PiHEV is charged every night and short journeys are typical, refuelling may be very infrequent as the engine would only be used in longer journeys. Efficiencies of PiHEV are sensitive to the range of the battery (IEA, 2012a).

In a series hybrid, which is less typical (Larminie and Lowry, 2012) the vehicle is only driven by an electric motor that can be powered by an ICE or an on board battery recharged from an external electrical supply. A variation on this that is commercially available is the Extended Range Electric Vehicle (EREV), the Vauxhall Ampere / Chevrolet Volt. In this, the motor is only powered by the battery, which in turn may be recharged externally or by an ICE generator. It has a larger battery than other PiHEV, with a pure electric range of 40 miles, and can operate as a pure electric vehicle, series hybrid or parallel hybrid, depending on driving conditions (Larminie and Lowry, 2012).

As hybrid vehicles essentially have two powertrains (and operating systems), this makes them heavier than their ICEV or EV counterparts. This extra weight requires more energy to power the vehicle forward. This means that a small, light fuel-efficient ICEV, which requires much less energy, could be more fuel efficient and have lower emissions (and likely a lower overall environmental impact as it is simpler and requires fewer raw materials). Such considerations need to be appreciated when developing new technologies, and will be addressed in the case studies of this research.

2A.5 Other Technologies

There are a number of other technology options that are being developed by niche manufacturers as concept cars but are not considered further in this research. Examples of these are the Jaguar C-X75 (Jaguar, 2013), which has a separate electric motor for each wheel and the batteries are driven by diesel fuelled gas turbines rather than an ICE, and the novel fuel ‘liquid air’ which is already used extensively in industrial applications (CLCF, 2013; Lewis, 2013). This is air that has been cryogenically cooled into a liquid that then drives an engine as the liquid heats up and expands into a gas. There are also some BEVs being developed with integrated solar panels to charge the battery but it is limited by the development of solar cell technology, and reliability of solar radiation, meaning that it may only be realistic as an auxiliary power source (Giannouli and Yianoulis, 2012).

2A.6 Comparative Emissions

From the point of view of this research, the driving interest is the reduction of the overall amount of GHG emissions associated with our passenger cars. The alternative technologies and fuels discussed here have potential for lower GHG emissions than cICEV related to their operation. This includes WTW emissions (both tailpipe and fuel production), as well as those related to vehicle production and disposal. Actual emissions are dependent on various technology and policy pathways that also include behavioural change. McKinsey (2009) suggest a potential abatement of 50% of 2005 emissions by 2030, shown in Figure 2.5. As is seen against the no-action baseline, although behavoirial changes and low carbon fuels can make signficant reductions on WTW emissions technological change is required to reduce emissions from current levels. This can account for half of abated emissions by 2010 and over 70% by 2030.

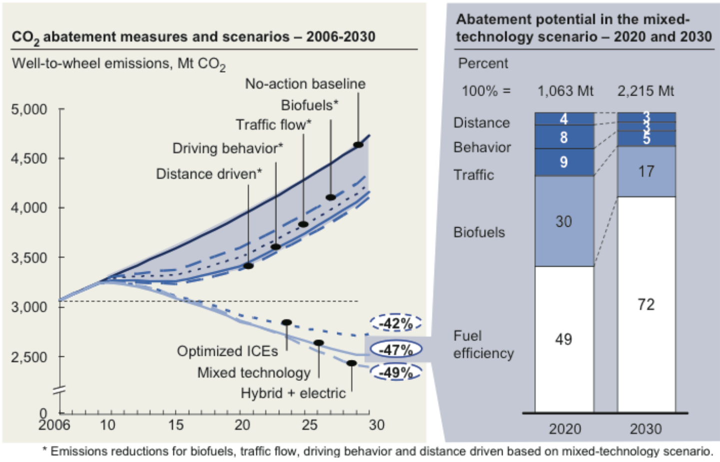

Figure 2.5: Potential abatement from vehicle technologies (McKinsey, 2009, p.6)

There have been numerous studies to determine WTW emissions, and there is a large variety in the findings. An overview of the variation of some estimates has been compiled and is shown in Figure 2.6. These studies consider present or near future technologies, in terms of GHG or CO_2eq, with comparisons of more than one fuel/technology and most were based on single mid-sized vehicles. Variations are due to the variety of assumptions and methods employed, but not all studies were explicit in their methodologies to all the relevant factors. This makes it difficult to explain the ranges in detail or draw comparisons and a complex meta-analysis of these studies is beyond the scope of this research. This is why there is such a large range evident in Figure 2.6, for instance Hydrogen ICEV has a range of 300 gGHG/km (though only over three studies).

Some general reasons for this are nation specific data (e.g. on energy mix/fuel production, fuel feedstock, fuel efficiency, age and use), determination of emissions through standard drive cycles or real world tests, data units (e.g. GHG, CO_2, C, CO_2eq), wider objectives of study (e.g. life cycle analysis, economics) and size or age of vehicle used. For instance, Beer and Grant (2007) considered just bio-ethanol and had twenty six variations from just three feedstocks (wheat, molasses and woodwaste) and emissions varied between 42 and 1,469 gGHG/km. A mean average has been added to the graph to give a feel for the comparison between fuels and technologies, but should not be taken as definitive as any weighting variables are not accounted for. It would suggest that the alternative fuels and technologies are low carbon compared to cICEV, and that BEV currently is the greatest prospect for reducing emissions. Though in considering this, it is important to remember the variation that was found in the studies.

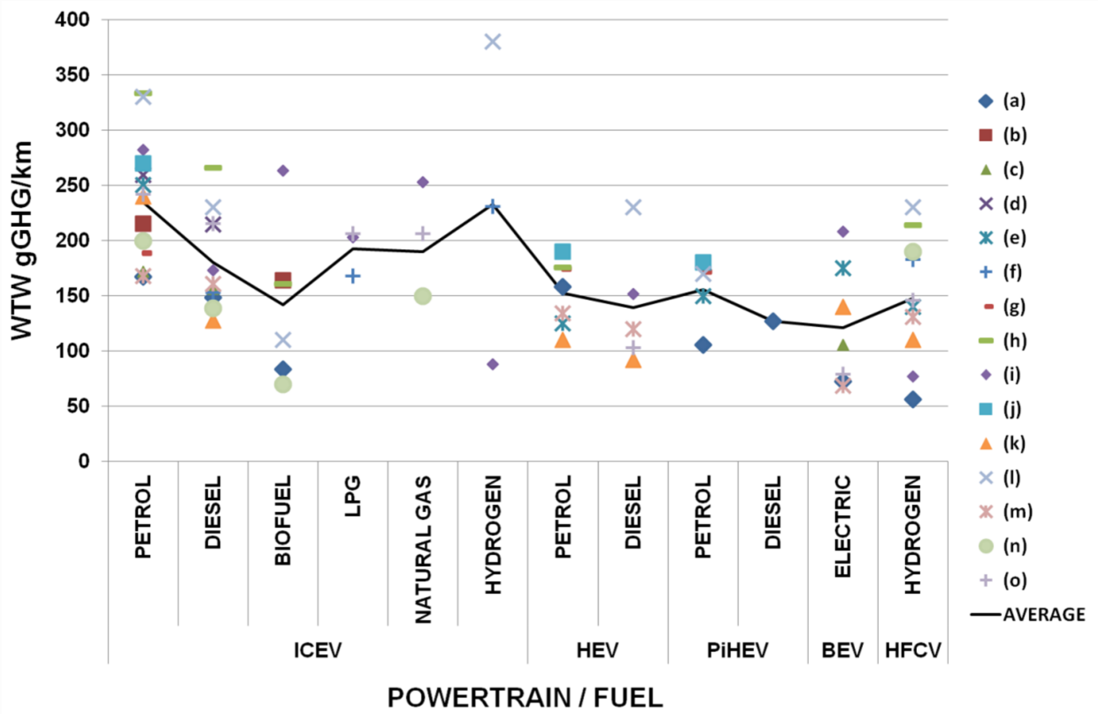

Figure 2.6: Previous studies of vehicle WTW GHG emissions.[16]

Vehicle manufacture and scrappage emissions should also be included in order to consider the whole vehicle life cycle. This was covered in a number of the previous studies, but not all. It is not within the scope of this project to produce a Life Cycle Assessment (LCA) of GHG emissions for each of these technologies/fuels. However, the results of two recent UK-based studies by Element Energy and Ricardo considering life cycle emissions for passenger car technologies are presented in Figure 2.7 and Figure 2.8.

[16] Compiled by author from the following studies: (a) Baptista et al. (2010); (b) Beer and Grant (2007); (c) BERR/DfT (2008); (d) Funk and Rabl (1999); (e) Gao and Winfield (2012); (f) Hekkert et al. (2005); (g) Ma et al. (2012); (h) MacLean and Lave (2003); (i) Michaelis and Davidson (1996); (j) Samaras and Meisterling (2008); (k) Schafer et al. (2006); (l) Stanciulescu and Fleming (2006); (m) van Vliet et al. (2010); (n) Wagner et al. (2006); (o) Yan and Crookes (2010). For biofuels, the studies presented numerous feedstocks, processes and fuel contribution. Only the lowest emission is given for illustrative purposes.

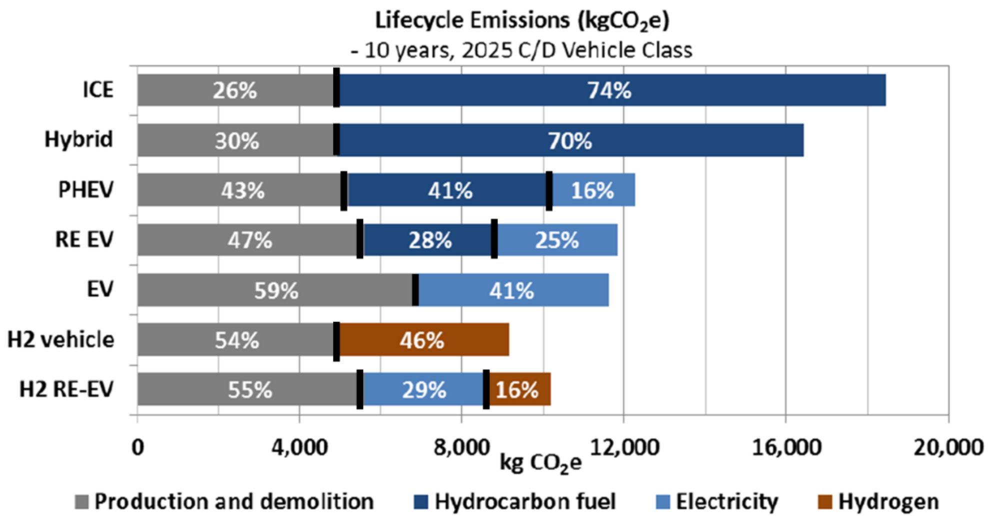

Figure 2.7: Powertrain life cycle emissions[17] (Element Energy, 2011, p.68)

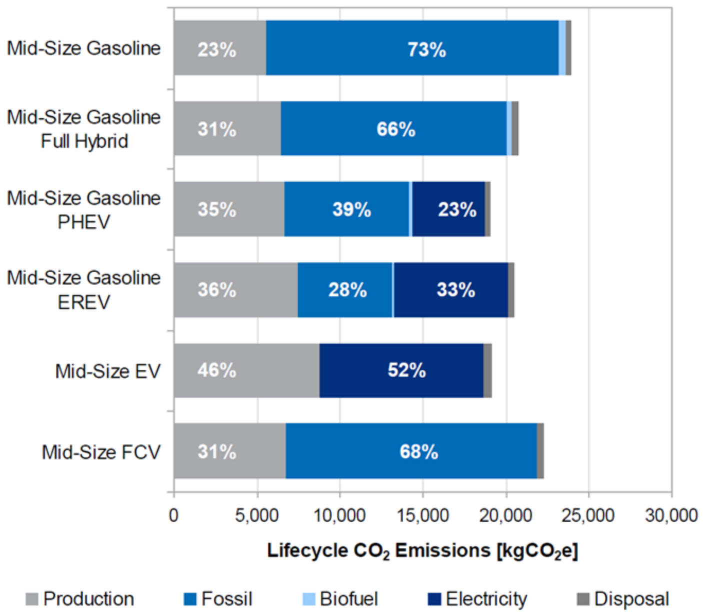

Figure 2.8: Powertrain life cycle emissions[18] (Ricardo, 2011, p.49)

These studies would appear to be relatively consistent when taking into account the fact that Element Energy consider a partially decarbonised grid and Ricardo do not. They both suggest that BEVs have notably greater embedded emissions in production and dismantling than other vehicles, despite having less over a whole life. In fact BEV embedded emissions are 40% greater than cICEV. This indicates that life cycle savings potential of BEV are dependent on car use, and may be even more of a concern when taking into account uncertain battery lifetimes (both studies

[17] C&D segments including production and fuel, 2025, partially decarbonised grid, 150,000km, 10 year lifetime.

[18] 2015 roadmap projections, technology and fuel, including E10, B7 and 500gCO2kWh electricity, 150,000km mileage.

assumed the battery lasts the vehicle lifetime). These extra emissions are related to production of batteries, coming from extraction/processing of the raw materials and the manufacturing process. Interestingly, both studies report that there is little difference between BEV and PIHEV/EREV. This suggests that BEV may only have carbon reduction advantages once electricity is decarbonised.

The difficulty of comparing studies has already been discussed regarding the WTW emissions. As an LCA takes into account production and dismantling in addition, there are further assumptions and data gathering issues that can further complicate study comparison. Thus, it would be a great advantage if a central body were to develop a standard method. Further to this, studies suggest that test-bed values often underestimate emissions compared to “real-world” testing, due to driving habits and traffic conditions (Hardy et al., 2010; Ropkins, 2009). The EU is developing a new test procedure based on real world emissions to replace the current standard test-bed drive cycle (JRC, 2013) and the RAC advocates a move towards LCA emission rating (Kay et al., 2013) One method, proposed by Ricardo (2011), which was used to calculate the data in Figure 2.8, is shown in Figure 2.9. This shows the many considerations to take place in each phase of a vehicle life cycle, including vehicle production, fuel production and distribution, how the vehicle is actually used, and vehicle disposal. For each point in these (condensed) lists, detailed justification and methodologies need to be carried out to calculate associated emissions and ensure accuracy and consistency.

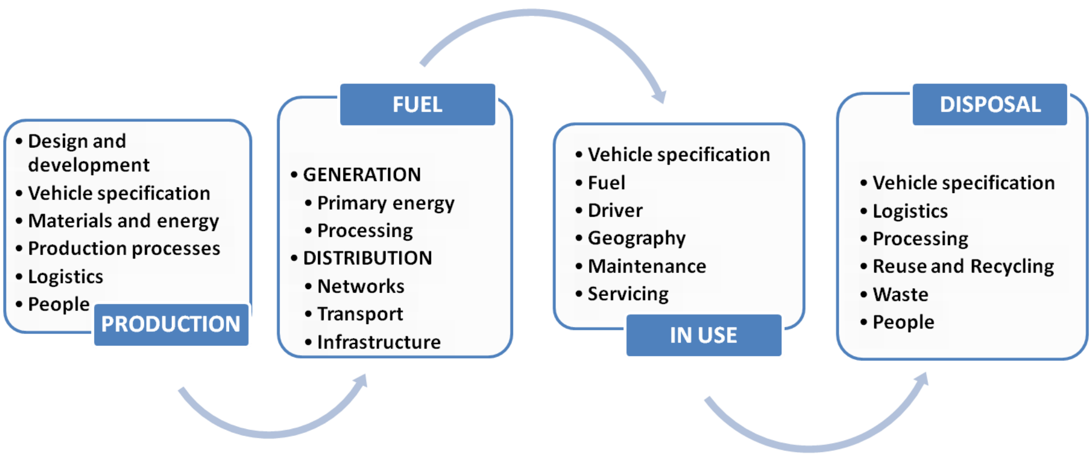

Figure 2.9: Proposed considerations of a passenger vehicle life cycle emissions assessment (adapted by author from Ricardo, 2011)

2A.7 Abatement Costs

Although there is abatement potential at low or negative cost through just efficiencies in cICEV (as summarised in 2A.2.1), the carbon abatement options with most emission reduction potential come at much higher costs. These costs are major barriers to adoption of new technology, as total costs of ownership and thus payback times are much greater for the consumer and high investment is needed from the manufacturer. McKinsey (2000), shown in Figure 2.10, found that efficiencies in conventional technologies achieve emission reduction at negative cost (i.e. savings outweigh benefits) whereas advanced technologies (PiHEV, EV, HFCV) could be at quite significant expense. Biofuels appear to be around cost neutral in both studies. Similar to the emissions accounting, costs are dependent upon methodologies used and aspects of the vehicle technologies that are assumed or considered. For instance, in a similar study by the IEA it was found that doubling the cost of oil has a significant impact on savings potential, and could more than halve the payback time for new technologies (IEA, 2009a).

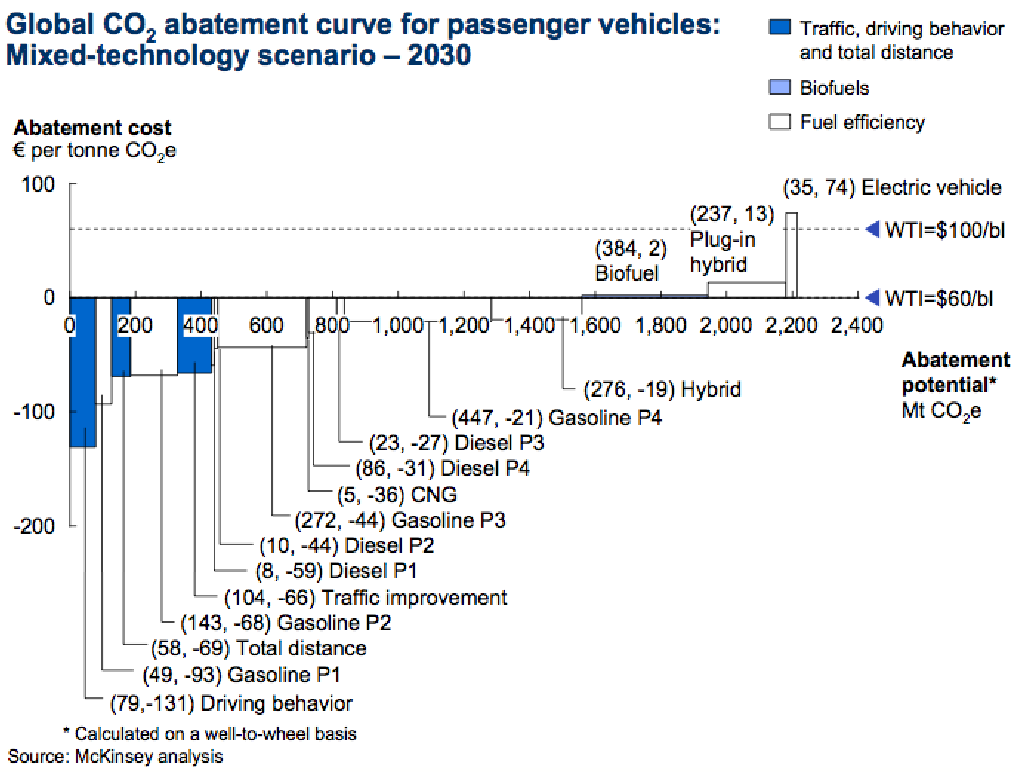

Figure 2.10: Abatement cost curve for passenger vehicle technologies (McKinsey, 2009, p.9)[19]

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[19] P1-1 refers to packages of increasing fuel efficiency. For more information see McKinsey (2009).

2A.8 Conclusion and Research Focus

As has been laid out in this section, although there are many alternative fuels and technologies available, there is not one clear 'winner' when it comes to the introduction of LCVs. Each option still has a number of barriers in technological development, infrastructural provision and/or competitive economics, as well as uncertainties around their emissions and other impacts on sustainability. In order to avoid the GHG emissions that will cause dangerous climate change, this transition must occur despite these concerns. As behavioural change is generally slow and the pace of technology development is uncertain, policies are required to stimulate both of these transitional barriers. The advantages and disadvantages of the technologies are summarised in Table 2.3.Only H_2ICEV, BEV and HFCV can potentially be 'zero carbon',[20] though biofuels could have substantially lower WTW GHG emissions than current cICEV at a much lower cost than the newer technologies.

First generation biofuels are already contributing to the fuel supply, but are unlikely to become a dominant fuel in the long term. This is due to land resource constraints, ethical implications of the use of food crops/land and although biofuels have lower WTW emissions than fossil fuels, they still have similar levels of tailpipe emissions, which should be avoided. However, they do fulfil a necessary component of the transition whilst travel behaviours alter and other technologies mature. Second and third generation biofuels, which overcome some of the ethical issues of first generation biofuels, should continue to be developed in the medium term and take increasing proportions of the fuel used in the ICEV. Natural Gas and Liquefied Petroleum Gas would only contribute marginally to carbon emissions reductions and resource security issues, and so should not occupy more than a niche position within the passenger vehicle market. This could be limited to regions with particular access to supplies over the medium term. Perhaps the only viable long term option for ICEV would be hydrogen, which is not yet available at low cost or low carbon, and has no supportive infrastructure. It is much more likely that if a viable 'hydrogen economy' developed it would be to support HFCV rather than ICEV. However, it may be that even if this is the case remaining ICEV in the fleet at the time could benefit and occupy a small proportion of passenger vehicles.

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[20] Though tailpipe emissions will be zero it is highly unlikely any vehicle could ever be zero carbon considering the overall manufacturing process. Also, renewable energy sources are likely to have embedded emissions somewhere in their lifecycle.

	FUEL	WTW[21] gGHG/ km	ADVANTAGES	DISADVANTAGES
Internal Combustion Engine	Petrol	168-333	Current market leader that drivers are accustomed to, high range and relatively cheap to own and run.	High GHG emissions and local pollution, use of fossil fuels which are non-renewable and increasingly scarce.
	Diesel	128-266	More fuel efficient so slightly cheaper to run than petrol, and lower GHG emissions.	Higher non-GHG emissions and more expensive to purchase.
	NG LPG	70-263 168-206	Slightly lower GHG emissions than cICEV and more abundant fossil fuel than crude oil.	Uncertain non-GHG emissions, no dedicated vehicles or fuelling structure, non-renewable source.
	Hydrogen	88-380	No tailpipe emissions other than water, can work in cICEV	Currently high energy needs for production of hydrogen, no delivery infrastructure and difficult to store.
	Biofuels	110-190	Low GHG emissions due to CO_2 capture in growth phrase. Could use waste products. Algae can be used in water purification. Could lead to resources security but dependent on land or waste availability.	Uncertainty around real world emissions, concerns for sustainability due to land use change and competition with food crops. Unknown local pollution impact.
Electric Motor	Electricity	69-208	No tailpipe emissions, cheap to run. Reduced noise pollution (though this may also cause safety problems).	High purchase cost. GHG emission reductions dependent on electricity mix and battery production. Requires change in driving behaviours due to limited range, no recharging infrastructure, and long recharging times. Battery materials may be unsustainable.
	H_2 Fuel Cell	57-230	No tailpipe emissions other than water, similar attributes to ICEV.	High energy needs for production of hydrogen, no delivery infrastructure and difficult to store. Not yet mass produced, but likely to be expensive. Resource security and sustainability dependent on feedstocks, and fuel cell materials.
Hybrid	Standard	92-230	More fuel efficient so reduced GHG emissions and running costs compared to ICEV.	Dependent on fossil fuels. Heavier than ICEV so requires more energy. PiHEV may still have long recharge times for battery, and emissions dependant on electricity production. Higher purchase cost than the ICEV.
	Plug-in	106-180	Small pure electric ranges possible with zero tailpipe emissions with the PiHEV.	

Table 2.3: Vehicle technologies comparison

21 Illustrative ‘Well to Wheels’ GHG from studies presented in Figure 2.6.

In the short-medium term, BEV need to take a more dominant role, with this transition supported by PiHEV as individuals behaviour patterns adapt to a resource and carbon constraint society. BEV should secure a position as an urban or short-distance vehicle, which would suit the needs of many individuals that choose other transport modes for longer journeys. For this to occur, decarbonisation of electricity supplies, provision of a public charging infrastructure and significant advances in battery costs and energy density are required. In the longer term, HFCV offers the most promising option for a similar level of mobility to cICEV today. This does not however mean that BEVs should be thought of as transitional, as they could still play a major long term role in urban driving or short trips when needed. However, in addition to the barriers of hydrogen production, distribution and storage, fuel cells also require significant advancement. For HFCV to achieve a dominant place in private vehicle technology, a timely technological breakthrough is likely to be required. However, as this is uncertain, reliance should not be on HFCV.

Finally, it is worth noting that not all technologies are currently available and advances are expected to occur over time. The New Automotive Innovation and Growth Team (NAIGT) have developed a roadmap of vehicle technologies in the UK, to help support the UK motor industry. This is shown in Figure 2.11.

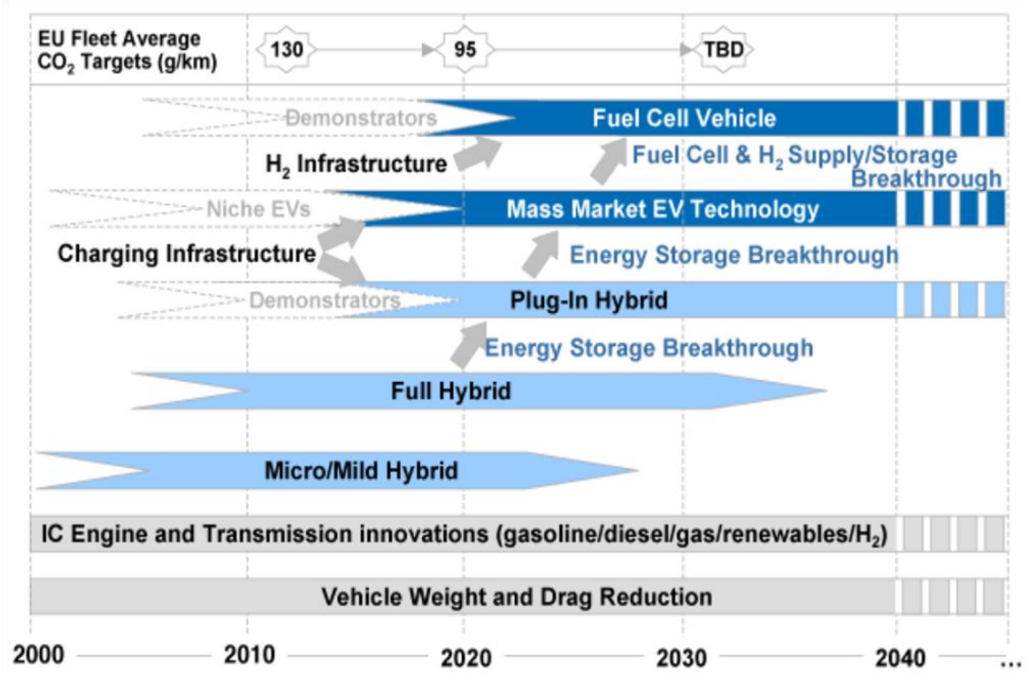

Figure 2.11: NAIGT high level technology roadmap (BERR, 2009, p.45)

There are already HEV, PiHEV and BEV on the roads, and charging infrastructure is being implemented. Technological development and market penetration are closely related as they are both dependent on economies of scale, which are in turn dependent on policy instruments to encourage the uptake, and are interrelated with changes in behaviours and habits regarding mobility and non-personal transport. Also recognised by the NAIGT is the importance of technology breakthroughs in energy storage, fuel cell and hydrogen. The timing of these cannot be predicted or assured.

Having a clear road map such as this in place provides automotive engineers with targets to reach for and allows policy makers to plan for developments in technology. However, the roadmap is specifically aimed at the UK industry, and may not account for the majority of manufacturers, which are outside the country. Although further detail is provided in the common research agenda accompanying the roadmap, ensuring that industry and academia continue to work towards realising the targets is important. It does not by itself provide guidance on what areas to concentrate investment and R&D, and makes assumptions on external influences, such as provision and reliability of infrastructure, supply chain management and public acceptance of new technologies. Therefore, it would be advantageous if similar roadmaps could be developed for these aspects to be combined into a high-level roadmap. In the context of global passenger vehicle trends, developed countries should encourage developing societies that aspire towards car ownership to adopt a similar pathway, but one that can bypass the problems we face now by avoiding a cICEV dominance.

With this in mind the NAIGT roadmap does appear to be a desirable pathway for passenger vehicle technology in the UK, or any car dominated country. This opinion only holds within a wider framework that sees an overall reduction in car ownership and/or car vehicle miles travelled, and a decarbonisation of the electricity network. If we are to avoid dangerous climate change it will be necessary that in addition to modal shift by 2050 the majority of vehicles in the UK are near zero emission.

PART B: POLICIES

2B.1 Overview

As set out in the introduction, climate change agreements developed through the United Nations Framework Convention on Climate Change (UNFCCC) have led to a focus on private passenger cars in many individual state policies. Following this, one of the main goals in the EU White Paper on Transport is achieving a 60% GHG emission reduction, through halving the use of urban ICEV by 2030 then to fully phase-out by 2050 (EC, 2011b). This section provides some wider context on the governance of transport policies related to climate change mitigation then focuses on those regulations, policies and strategies targeted at encouraging the uptake of LCVs. Following this, a review of findings from evidence-based studies regarding these policies is presented and in the conclusion the policies are categorised into generic types. These policies are required to overcome the barriers that currently prevent or deter widespread deployment and purchase of LCVs that were outlined in Part A of this Literature Review.

2B.2 Governance

Regulations, policies and strategies regarding LCV uptake are determined, developed and implemented by political bodies and institutions. Generally (though not exclusively) they are formed at an international or regional level, to be then filtered down and interpreted by countries or local authorities. There are a multitude of agents involved, both governmental and non-governmental, who must work together to achieve this resulting in a complex political environment, as described in this section.

2B.2.1 International

In addition to the UNFCCC and *UN Division for Sustainable Development* (UNDSD), which manage climate change mitigation and GHG emissions reductions (UNDSD, 2013), LCV policy at an international level is managed by the *United Nations Environment Programme* (UNEP) and the *World Forum on the Harmonisation of Vehicle Regulations* (WFHVR). The UNEP leads the UN's efforts on reducing the climate change impact of transport through the *Clean Fuel and Vehicle Partnership* to support developing countries and the *Global Fuel Economy Initiative* (50by50), which includes carbon pricing, fuel economy standards, subsidies, and providing information (UNEP, 2013). The WFHVR (which are managed by the United Nations Economic Commission for Europe) seeks to globally align regulation on all types of vehicles, looking at test procedures, safety and environmental concerns, energy efficiency, measurement and production of alternative energy sources (UNECE, 2013b).

Autonomous international research, publications and policy discussion is carried out through the *International Transport Forum* (ITF), an intergovernmental forum lead through the *Organization for Economic Cooperation and Development* (OECD) which acts as a think tank and research centre for global transport policy (ITF, 2013). The OECD's *International Energy Agency* (IEA) also adds to this debate, due to its interest in reducing oil dependency and GHG emissions (IEA, 2013a). The *Clean Energy Ministerial* provides a further platform on which to promote and share policies, programmes and best practice (CEM, 2013). It hosts the *Electric Vehicle Initiative* with the goal of achieving 20 million EVs on the road by 2020. Also overseeing international automobile activity are the *International Council on Clean Transportation* (ICCT), *Federation International de l'Automobile* (FIA) and the *International Organization of Motor Vehicle Manufacturers* (OICA).

2B.2.2 Europe

The *United Nation Economic Commission for Europe* aligns international agendas regarding climate change and transport in a European and North American context, through innovative vehicle technologies, sustainable biofuels, ICT, consumer information and legal instruments (UNECE, 2013a). Coordination of information and assistance in decision making is carried out by the *European Environment Agency* on behalf of the EU (EEA, 2013).

The *European Commission* manages the regulatory environment for transport of the European Union, through the *Directorate-General for Mobility and Transport* (DG MOVE). DG MOVE develops transport policy for the EU through managing the internal transport market, agenda for technological innovation, building the core infrastructure network and representing EU transport interests on a world stage (EC, 2013a). In the case of LCVs it is assisted by the *European Agency for*

Competiveness and Innovation and works with the *DG's for Energy and Climate Action*. Scientific research to support policy development is carried out in-house by the *EC Joint Research Centre Institute for Energy and Transport*, which is funded through the EC *Framework Programme for Research and Innovation* (to be known as Horizon 2020 from 2014) (EC, 2013b).

EU LCV policy has been further informed by *CARS 21* (Competitive Automotive Research System for the 21st century), *European Green Car Initiative* (EGCI) and *European Technology Platforms* (ETPs). CARS 21 was a stakeholder forum making recommendations to policy and regulatory frameworks for a sustainable and competitive European automotive industry, and within this considered CO_2 emissions and new mobility solutions (EC, 2012a). *CARS 2020* aims to continue the forum and follow up the recommendations (EC, 2013c). The EGCI is a public-private partnership which supports R&D for LCV technologies and infrastructure, through facilitating workshops, collaborative projects and an electrification roadmap (EGCI, 2013). ETPs are industry-led forums recognized by the EC, which define research priorities and enhance competitiveness. The *European Road Transport Research Advisory Council* (ERTRAC) is the ETP for road transport and there is a separate ETP for Biofuels. In addition, the European Automobile Manufacturers' Association (ACEA) represents the interests of the European car industry.

2B.2.3 UK

The political structure for transport issues in the UK involves a number of governmental departments, including the *Department of Energy and Climate Change* (DECC), *Department of Transport* (DfT) and *Department of Business, Innovation and Skills* (BIS). Together these co-sponsor the recently created *Office of Low Emission Vehicles* (OLEV), and non-governmental bodies such as the *Technology Strategy Board* (TSB) and the *Committee on Climate Change* (CCC). *Her Majesty's Revenues and Customs* (HMRC – the UK tax authority) and *Her Majesty's Treasury* (HMT – ministry controlling public spending) also influence LCV policy as they are responsible for setting and managing both Vehicle Excise Duty (VED) and fuel duties. A House of Commons Select Committee on transport meets regularly to discuss all issues related to transport policy. OLEV leads on national policy regarding *Ultra Low Emission Vehicles* (ULEV – emissions below 75g/km) on behalf of its co-sponsors. These are discussed in more detail later in this section but include the plug-in vehicle infrastructure strategy, grants for vehicles and charging points, research programmes and awareness raising. In addition OLEV supports the manufacturing and supply chain and R&D of LCV technologies, and as part of this, improvement of efficiencies of conventional technologies (OLEV, 2013a). The DfT coordinates all other regulation relating to LCVs, including fuel duties and taxation, biofuel research, car labelling, advertising, and social research. It is also responsible for reduction of carbon emissions from transport via other means, including modal shift, smarter choices, travel plans, freight, aviation and shipping. In addition, local authorities have some degree of devolved responsibility for encouraging LCV uptake, though mainly through local air pollution drivers, for example through low emission and congestion zones (DfT, 2013b).

The *UK Automotive Council* (UKAC) brings together senior level industry and government players to oversee the development of a coordinated approach to the automotive sector, within two groups - supply chain and technology, aiming to create a business environment to encourage investment, develop roadmaps, create sustainable supply chains, provide a public voice, and achieve a government and industry partnership (UKAC, 2013). Alongside this, the *Technology Strategy Board* (TSB) is the UK national innovation agency, working across government, business and research to remove barriers to technological advancement through the *Ultra Low Carbon Vehicle Innovation Platform*, which invests in and promotes UK-led R&D and supply chains (TSB, 2013). Both the UKAC and the TSB are supported by the *Society for Motor Manufacturers and Tradesmen* (SMMT), an industry led organisation which coordinates research and response to regulation to support and promote interests of UK motor industry, both home and abroad (SMMT, 2013b).

Further support for LCVs comes from other government-backed and non-governmental organizations. *CENEX* (Center of Excellence for Low Carbon and Fuel Cell Technologies), are sponsored by BIS and are a delivery agency designed to promote the market development of fuel cell and low carbon technologies for transport applications (CENEX, 2013a). The *Low Carbon Vehicle Partnership* (LCVP) who facilitate engagement between industry and other stakeholders to develop markets, build consensus on optimal pathways, influence policies, and encourage R&D and commercialisation of technologies (LCVP, 2013). Research in LCVs is facilitated and reported through industry, government and private agencies, such as the *Engineering and Physical Sciences Research Council* (EPSRC), *Royal Automobile Association Foundation* (RAC), *UK Energy Research Centre* (UKERC), *Energy Technologies Institute* (ETI) and *Institute for Public Policy Research* (IPPR).

2B.2.4 Summary

As has been outlined in this section, there are many agencies involved in the development of LCV policy. This demonstrates the immense co-ordinated support for the introduction of LCVs and the recognition for the need of such policies in doing so. Furthermore, it emphasises the intervention that is being made to encourage both manufacturers to develop LCVs and the public acceptance and purchase of the new technologies. The following section looks at the regulations, policies and strategies that have arisen through these efforts.

2B.3 Regulations, Policies and Strategies

At present, high level LCV policies are generally designed to be technology neutral. In reality, many policies tend to focus specifically on the introduction of plug-in vehicles. Previous policy attempts have been made in the past for natural gas (and its variations) but are largely discontinued in regions where they were unsuccessful. More recently there have been many policies focused on the R&D of biofuels and related synthetic fuels, (which has applications other than transport) but these are marred by the sustainability issues discussed in the previous part of this Chapter, which are yet to be resolved. However, other than R&D support, little is currently being promoted regarding hydrogen fuel cars, with the reason being that both fuel cell technology and sustainable hydrogen production is in its infancy. Longer term policies do however recognise the importance of HFCVs.

2B.3.1 Europe

Creating a common transport policy has always been at the centre of European Commission activities, since its inception through the Treaty of Rome in 1958 (van Reeven, 2005). The European Climate Change Programme (ECCP) was established by the European Commission in 2000, and launched its second programme in 2005 with "*CO_2 and Cars*" as one of its six working groups (EC, 2013d). Through this programme, the EU Emissions Trading Scheme (EU ETS) was also launched in 2005, but to date does not cover road transport emissions. As described previously, the 2009 Climate and Energy Package, which includes transport concerns, set targets to increase both the share of renewable energies and overall energy efficiency by 2020 (EC, 2013e).

Legislation specifically designed to stimulate the LCV Market are brought together under the *Common Transport Policy* and the *White Paper on Transport: Roadmap to a Single European Transport Area* (EC, 2011b). Within the white paper, there is a vision for 2050 with a 60% cut in transport emissions, a substantial modal shift from road and cities free from conventionally fuelled cars. To support and develop the legislation, there have also been a number of other policy strategy documents produced over the recent past, as set out in Table 2.4.

Document	Description	Outputs (relevant to LCVs)
European Strategy on Transport and Environment (EC, 1999a)	A council report on the integration of environment and sustainable development into transport policy.	• 'Polluter Pays' infrastructure charging • Average vehicle emissions of 120gkm
White Paper: European Transport Policy for 2010 (EC, 2001)	Based on the 1999 strategy, sets out 60 transport policy measures to be adopted by the EC and an action programme to 2010.	• Harmonisation of road taxation • Introduction of external costs • Research framework programme • Diversifying transport energy • Rationalisation of private car use
An EU Strategy for Biofuels (EC, 2006)	Sets out seven policy areas for the development of production and use of biofuels in the EC.	• Stimulate demand • Ensure environmental benefits • Develop production and distribution • Expand feedstock supplies • Enhance trade opportunities • Support developing countries • Support research and innovation
The Cost and Effectiveness of Policies to Reduce Vehicle Emissions (JTRC, 2008)	Round table discussion on the combination of instruments currently used, if they are in line with goals and how goals ought to be defined.	• GHG abatement in transport should be done by combining carbon or fuel taxes with standards. • There is a need for more research
EU Transport GHG: Routes to 2050 (Skinner et al., 2010) (Hill et al., 2012)	Project to engage European stakeholder and experts in identifying, prioritising and developing key future policy measures.	• Both technical and non-technical solutions are required • A wide range of policy instruments and early action is necessary.
Multi-annual roadmap and long-term strategy (EC, 2011c) and European Roadmap for the Electrification of Road Transport (ERTRAC, 2012)	Defines road map and common R&D objectives of EGCI stakeholders.	• Energy storage systems • Drive train technologies • Vehicle system integration • Grid integration • Safety systems • Transport system integration • International cooperation
Research and innovation for Europe's future mobility: Developing a European transport-technology strategy (EC, 2012b)	Summarises and reviews research and innovation in the EU transport sector.	• Better align research and innovation with policy goals • Pioneer innovative sustainable technology • Find an appropriate balance between policy instruments

Table 2.4: European policy strategy documents

These documents have all recognised the importance of reducing transport, particularly road transport, carbon emissions. In order to do this a co-ordinated and long-term approach must be taken. The level of detail or focus has varied. For example, the emphasis on electrification has increased over more recent years, and the strong need for research and innovation (specifically by manufacturers) has been increasingly recognised. Relevant legislation arising from EU policies and strategies includes the following:

Fuel Quality Directive (EC, 1998; EC, 1991; EC, 2009b)
This sets quality standards for petrol and diesel, including emission standards for vehicles. These standards commenced in 1993 with 'Euro 1' set in the 1991 Directive 91/441/EEC. The 1998 Directive set out Euro 4 and the current standard is 'Euro 5', which is to be superseded by 'Euro 6' in September 2014. These latest standards were set out in Table 2.1. The 1998 Directive was revised in 2009 and also set out, complementary to the Renewable Energy Directive, a requirement to reduce GHG intensity of road transport energy, and sustainability criteria for biofuels.

Car Labelling Directive (EC, 1999b)
Through this cars must be labelled with information regarding their fuel efficiency and carbon emissions at the point of sale. Furthermore, this information should be available to users online and in promotional literature, and an annual guide should be produced.

Renewable Energy Directive (EC, 2009c)
This regulation requires that by 2020 there should be a 10% reduction in GHG intensity of vehicle fuel. This includes increasing the proportion of biofuel from a sustainable source clearly demonstrating a net life-cycle GHG reduction. New technologies and Clean Development Mechanism credits can also be taken into account.

Clean Vehicle Directive (EC, 2009d)
The Clean Vehicle Directive sets out a requirement that energy and environmental impacts are taken into account for vehicles purchased by public bodies to aid promotion of cleaner vehicles. This is to be achieved by setting technical specifications and/or the internalisation of external costs.

Passenger Car Emissions Regulation (EC, 2009a; EC, 2013f)

This legislation sets mandatory emission reduction targets for new cars, with a fleet average of 130gCO_2/km by 2015, 95 gCO_2/km by 2020 and a 2025 target to be agreed by 2015. These are set using a limit value curve according to vehicle mass, and are to be phased in between 2012 and 2015. This will increase the proportion of manufacturer's cars to be included in the average from 65% to 100%. Emissions are currently tested using standard drive cycles and test beds but the EC are seeking more realistic testing procedures.

An 'emissions premium' must be paid if the average fleet target is exceeded. Manufacturers are fined in the order of €5 for the first g/km of exceedance, €15 for the second g/km, €25 for the third g/km, and €95 for each subsequent g/km. From 2019, the first g/km of exceedance will cost €95. Eco-innovations cannot be demonstrated under type approval tests, so manufacturers can be granted up to 7g/km of emission credits if independently verified. Extra incentive will be given for cars <50g/km - each will count for 3.5 vehicles in 2012/13, 2 by 2020, and 1 by 2023. These "supercredits" were originally set to be phased out by 2016, which was viewed to be unrealistic by manufacturers. To prevent compromising overall targets, there is a 2.5g/km cap on that contribution. E85 (85% bioethanol blended petrol) vehicles will be considered as 5% lower, provided 30% of filling stations offer E85, though this is somewhat out of automobile manufacturers control. Each manufacturer gets an individual target based on average vehicle mass of newly registered cars, though manufacturers can pool together. Smaller manufacturers who produce between 10,000 and 30,000 vehicles a year can apply for a target of 25% of 2007 emissions. Also those who produce between 1,000 and 10,000 can propose their own targets (subject to approval) and the smallest manufacturers (<1,000 vehicle a year) are exempt.

2B.3.2 UK

The major piece of legislation that informs climate change policies across all sectors in the UK is the Climate Change Act 2008, which created DECC and is responsible for setting our regulations and strategies to achieve our carbon reduction targets and ensure a smooth transition to a low carbon economy. Regulation is in place in the UK related to LCV uptake, some of which incorporates interpretation of EU legislation at a UK level, includes:

- Vehicle Excise and Regulations Act 1994
- Energy Act 2004
- Renewable Transport Fuels Obligations 2007
- Renewable Obligations Order 2009
- Biodiesel Duty Regulations 2010
- Carbon Budget Order 2011
- Finance Act 2011

DECC introduced the *UK Low Carbon Transition Plan* (DECC, 2009) and *Low Carbon Transport: A Greener Future* (DfT, 2009b) in 2009, setting out a number of policies across all sectors in the UK, which includes transport and pledges to support the shift to new fuels and technologies, promoting lower carbon choices and using market mechanisms. This was replaced in 2011 with *The Carbon Plan: Delivering our Low Carbon Future*. Within these documents, the UK government envisages that almost every car will be an *"Ultra Low Emission Vehicle"* (ULEV), which is near zero emission by 2050. This involves a mixture of electrification of our personal vehicles and the use of sustainable biofuels. Both BEV and HFCV will be supported, assuming a complementary decarbonisation of power stations. As it is not seen to be certain which fuels and technologies will be most sustainable, policy is technology-neutral. It is also hoped that through this the UK automotive industry could be well-placed to be a global leader in ULEV. The government has committed £400m to support the uptake of ULEV up to April 2015.

Current policies were preceded by various reports, most notably the *King Review of Low-Carbon Cars* (King, 2007; King, 2008), which was carried out in response to the *Stern Report* (2006) on the Economics of Climate Change. This set out not only the potential for CO_2 reduction but also recommendations for action. Other reports influencing these policies include the *Gallagher Review on Biofuels* (RFA, 2008), the previous government strategy, *Powering Future Vehicles* (DfT, 2002), and reviews by non-governmental organisations (Foley, 2003; EST, 2002). Many of the policies suggested in these reports and set out in *A Greener Future* have been echoed or expanded upon in other reports in more recent years (Hanley and Buchanan, 2011; Lane, 2011; Rowney and Straw, 2013; Kay et al., 2013; CCC, 2010). Some key policies and strategies that have been adopted recently include:

Public Procurement and Demonstration

The Low Carbon Vehicle Public Procurement Programme was launched in 2007 to fund the trial of over 200 ULEV in public fleets to raise profile and gather 'real world' information. In the second phase of the programme, 500 further vans were made available for purchase with a discount grant from OLEV (CENEX, 2013b). The ULEV Demonstration Project (run through the Low Carbon Vehicle Innovation Platform), trials 340 cars in 8 locations across the UK. Initial findings from this found that the experience, performance and range of BEVs were greater than anticipated by participants, but range anxiety still exists (TSB, 2011).

Low Carbon Vehicle Innovation Platform

The need to support innovative R&D and UK industry is echoed in many policy documents. The Low Carbon Vehicle Innovation Platform was launched in 2007 and run by the Technology Strategy Board to carry out feasibility studies and run bids for collaborative research and development projects set and match-funded by industry and government (OLEV, 2013b).

Plug-in Vehicle Grants

Purchase subsidies on a ULEV recognise the barrier of high purchase cost and make whole life costs more comparable to conventional vehicles. OLEV reported nearly 5,000 claims were made up to June 2013 (OLEV, 2013c). The grant is 25% of purchase cost up to £5000 for cars (available since January 2011) and 20% of purchase cost up to £8000 for vans (available since February 2012). Full electric, plug-in hybrids and hydrogen-fuelled cars are eligible if they meet certain criteria on type approval, emissions, speed, warranty. safety and performances.

Infrastructure Development

The *Plugged-in Places* scheme matched funding with 8 consortia in different UK locations to install and monitor charging infrastructure between March 2011 and March 2013. By the end of this period, 4000 charging points had been installed, with the greatest uptake in London and the North East (OLEV, 2013d). Recognising the need to develop a suitable recharging infrastructure, the government published the Plug in Vehicle Infrastructure Strategy in June 2011 (OLEV, 2011). This includes removing barriers for investment, identifying appropriate locations, encouraging both home and work-place charging, and developing a consistent, safe and easy recharging network. In February 2013, £37m was announced for installing both private and public charging points (OLEV, 2013e).

UK H_2 Mobility

Launched in January 2012, this project brings together automobile manufacturers, energy providers, infrastructure business and the retail sector to evaluate opportunities and barriers for hydrogen fuel cell vehicles (HFCV), in order to develop an action plan for commercial roll-out. The first phase report on the potential of HFCVs in the UK was released in April 2013 (OLEV, 2013f).

Local Authority Schemes

Local authorities are well placed to encourage LCV take up, not only by easing planning for infrastructure, but also through exemptions from schemes such as congestion or low emission areas, high occupancy or bus-only lanes and free or reduced parking. Currently ULEV are eligible for a 100% discount from the London congestion charging scheme. As further schemes are set up, exemption could help promote the use of ULEV and the creation of zero emission cities.

Taxation

Vehicle Excise Duty (VED) is an annual tax paid by vehicle owners for operating the vehicle. Since April 2011 it has been based on a CO_2 emission band, before which it was based on engine size. Separated into 13 bands, vehicles emitting less than 100gCO_2/km pay nothing and highest emitting vehicles (>255g/km) pay £460, with higher costs in the first year of registration. Additionally, there are duties on the cost of fuels which are set in the Annual Budget, partly determined by the external costs of their climate impact. As the fleet is decarbonised there are concerns of a loss of revenue to the government if vehicle taxes are kept so oriented towards emissions. Therefore there is considerable interest being paid into the possibility of road or carbon pricing, or methods of taxing new fuels.

Scrappage schemes

Between April 2009 and February 2010 the UK government introduced a car scrappage scheme which gave motorists a £2000 discount for a new vehicle in return for scrapping their old one if it was over 10 years old (Harari, 2009). This was partly to remove less efficient vehicles from the UK fleet and also to support the UK car industry during an economic depression.

Information campaigns

Relevant and authoritative information provision that complements other policies is seen as a necessity. Therefore, underlying other policies are a number of initiatives designed to inform the public of carbon emissions related to vehicles and the utility which different technologies could offer, such as through the Energy Saving Trust (EST, 2013).

Support to the Automotive Industry

All government supply-side policies in the UK are managed by the Technology Strategy Board. The automobile industry in the UK adds about £9.5b to the UK GDP (DfT, 2009a), so it is crucial that the move to LCVs does not adversely impact such a major contribution to the economy. Moreover, with the right investment, the UK could be well placed in becoming global market leaders in LCV technologies. The New Automotive Innovation and Growth Team (NAIGT) has developed a roadmap to achieve this (see Part A), which will inform the Government on policies, who have already committed over £2b to support the automotive sector.

Although manufacturing in the UK is small compared to some other nations such as Germany or Japan, it is a world leader in specialist car manufacturing, which can stimulate innovation in the automotive sector and could play "*a decisive global role in developing and manufacturing exciting, low carbon vehicle transportation solutions"* (BERR, 2009, p.9). The UK has a strong tradition of innovation and competiveness, but coordination between industry and academia needs to be less fragmented (BIS, 2013). In order to achieve this, NAIGT recognise that supportive government policy is a key success factor, and in July 2013 the DfT announced a further £500m investment to make Britain a world leader in EV technology and investment in an Advanced Propulsion Centre for development, commercialisation and manufacturing (OLEV, 2013g).

2B.3.3 Other Countries

Outside of Europe, other countries also take their lead on LCV policy from international agencies. Developed and rapidly developing countries are not the concern of this thesis. However, a brief overview of policies in the USA was felt to be appropriate, as it faces similar barriers to Europe.

Climate change policy in the USA trails somewhat to Europe as the USA did not officially sign up to the Kyoto Protocol. It is led by the Environmental Protection Agency (EPA). Greenhouse gases were officially covered by the Clean Air Act in 2007 and the contribution from motor vehicles was recognised in 2009 (CEC, 2012). Although Corporate Average Fuel Economy (CAFE) Regulations had been in place since the 1970s, motivated by the 1973 oil embargo, they are being superseded by new standards that include emissions. The EPA and the National Highway and Traffic Safety Administration (NHTSA), set these standards that are aimed at automobile manufacturers and lead to a projected fleet average of 54.5 mpg by 2025 (from 30.2 mpg in 2011). In addition, the EPA are introducing a Renewable Fuel Standard Program, which in 2013 expects about 10% of fuel to come from renewable sources (EPA, 2013). Individual states translate these into their own regulations, with some states going beyond national standards. The most advanced state is California, which has been promoting ‘clean cars’ for over 40 years through the Californian Air Resources Board (CARB). CARB have introduced policies similar to those in Europe, and are particularly focused on zero emission vehicles (ZEV), which include HEV, PiHEV, BEV and HFCV. The *Advanced Clean Cars Programme* brings together the regulations and standards for introducing low and zero emission vehicles already in place in California (CARB, 2013).

The *Californian Low and Zero Emission Vehicle Regulations* place the onus on the manufacturer to reduce the average fleet tailpipe emissions of GHG through producing more Low Emission Vehicles (LEVs), and by selling increasing shares of Zero Emission Vehicles (ZEVs), by imposing civil penalties on the manufacturers for non-compliance. These penalties are calculated on GHG and ZEV “credits” earned over a time period. Under the LEV component, GHG credits are calculated annually from the difference between the standard government target and actual sales weighted fleet emission average. The ZEV credit target for a company is a ZEV quota that the manufacturer must produce, which is based on a set percentage of non-ZEV sales from the previous six years. Credits are awarded to the company for ZEVs produced and sold. CARB also funds the *California Clean Vehicle Rebate Project*, which is administrated by the California Centre for Sustainable Energy. This provides $42m for the period 2009-2013, and is expected to be extended until 2015, to give rebates of up to $2500 to customers who purchase or lease eligible zero emission or plug-in hybrid vehicles (CCSE, 2013). These policies are the focus of the second modelling case study and therefore further detail is provided in Chapter 5.

2B.4 Evidence-based Studies

This section considers the findings of evidence-based studies of LCV uptake policies that were identified in this research. These include reviews of policy approaches, critical discussion of proposed policies and recommendations for policy improvements. It does not include studies based on models, as these will be discussed in Part C of the literature review. The findings are presented under the categories of supply or demand side policies. Some interventions may cover both sides or interact between them.

2B.4.1 Supply Side Policies

A technology push is required to stimulate innovation and encourage consumer uptake. This requires investment in LCVs and legislation of the automobile industry. Supply side policies are therefore aimed at manufacturers (and suppliers) in order to promote the development of innovative technologies and fuels to market readiness, alongside the creation of a sustainable supply chain. This is important because for mass adoption consumers need to be confident that any new technologies will not only be safe, reliable, economically suitable and fit for purpose, but also that they will continue to be so for the foreseeable future.

From a 2010 round table discussion on stimulating LCV technologies, it was found that although the majority of stakeholders agree that vehicle fuel economy standards (i.e. miles per gallon) are necessary, some argue that manufactures should be made responsible for energy use in transport and are therefore obliged to increase engine efficiency. The report was not clear if this argument was extended to technology quotas. However, they did also note that *"consistency between demand and supply-side incentives is required to keep emission concerns squarely among manufacturers strategic priorities"* (JTRC, 2010, p.15). Further to this automobile manufacturers need certainty in their regulatory environment. This is a factor reflected in other studies. Although focused on renewable energy, in their analysis of innovation systems, Foxon et al (2005) highlight the importance of long-term political support to new technologies, particularly in demonstration and pre-commercial stages. In agreement with this, an ITF discussion paper on the impact of demand-side fiscal measures on the automobile industry agreed that strong and clear long term visibility of political intention in supporting LCVs is important in the medium and long term (Bastard, 2010).

In 2008, the IEA produced a report that reviewed international policies for vehicle fuel efficiency (Onoda, 2008). It identified that although regulatory standards aimed at manufacturers were met in all cases, voluntary programs alone were not capable of meeting emission reduction targets, perhaps because with increased fuel efficiency customers tended to purchase larger vehicles. It was further suggested that "*a poorly designed standard may be worse than no standard at all because it could encourage the adoption of inappropriate technologies"* (Onoda, 2008, p.29), and that as a broad scope, realistic, harmonised test procedures, technology neutrality and regulatory flexibility are required.

Both the IPPR and RAC have carried out extensive literature reviews and stakeholder consultations to understand the role of the UK in the developing ULEV market. The RAC report, although it was focused on the demand-side, suggested that existing industry innovation programmes are hinting at initial success, and strategic niche management shows promise (Lane, 2011). The IPPR agreed somewhat more cautiously and recommended that three areas in critical need of stronger government policy for industry are access to finance, support for innovation and investment in workforce skills (Rowney and Straw, 2013).

In summary, there was a general agreement that car manufacturers are strongly motivated by government policy but need further long term clarity and support. The importance of such strong supply-side policies was emphasised in a paper comparing Natural Gas Vehicle (NGV) policies in eight different countries, where it was found that vehicle availability and reliability could be more important than consumer acceptance in LCV uptake (Yeh, 2007).

2B.4.2 Demand Side Policies

Demand side policy measures create a market pull for innovations and can be defined as "*a set of public measures to increase the demand for innovations, to improve the conditions for the uptake of innovations and/or to improve the articulation of demand in order to spur innovation and the diffusion of innovation"* (Edler, 2009, p.3). Demand-side measures may be hard measures, such as fiscal incentives or construction projects, or softer measurers aimed to encourage certain desirable behaviours, similar to Richard Thaler's 2008 'Nudge' theory. In the context of encouraging the uptake of LCVs, demand side policies are necessary to overcome the barriers of economics, behaviours and perceptions that currently prevent the development of a successful LCV market. From the consumer perspective, the attributes of LCVs are inferior to those of cICEV, principally as purchase costs are significantly higher, and for BEV a much shorter range coupled with lack of infrastructure and long recharge times gives rise to ‘range anxiety’. Further to this the cultural status of a vehicle, or joy of driving may be important for some people.

The IEA, in their review of fuel efficiency policies, concluded manufacturer standards would be more effective if accompanied by policies to stimulate demand. They concluded that fiscal incentives could not only be a powerful tool, but could be cost effective and incentivise manufacturers also (Onoda, 2008). Such measures were reviewed by the ICCT and compared between eight countries (He and Bandivadekar, 2011). They were found to need to be directly linked to CO_2 emissions to be most effective. The design of these is important in success, as identified in a global analysis of fuel-related fiscal measures, and concluded in another ICCT report compiled through a network of leading policy and industry experts (Kodjak et al., 2011). One report (discussed earlier) highlighted that there needs to be coordination of fiscal incentive schemes between countries as the variety that currently exists in Europe alone make manufacturer business strategy planning very difficult (Bastard, 2010). Also, governments need to be mindful of long term taxing of LCVs due to losses from cICEV fuel duty (Kodjak et al., 2011).

The previously mentioned IPPR report suggested that tax increases should be based on median emitting vehicles as high emitters are declining anyway, and target new cars most strongly. In the UK, however, it was reported that tax bands have been too small to distinguish differences in lower carbon ICEV (Lane, 2011). Other recommended tax-related policies, such as road transport carbon emissions trading or road pricing scheme based on mileage, have not yet been implemented so there is no literature available to discuss their actual effectiveness.

The ITF have carried out policy briefs on transport related issues. One reviewed scrappage schemes in France, Germany and the USA, which have been introduced for both economic and environmental stimulus. It concluded that although such schemes can decrease CO_2 emissions, the gains are small as new cars tend to be driven more than the replaced older ones, meaning that it is not very cost effective (ITF, 2011b). Another considered EV purchase subsidies and warned that although subsidies may cover extra costs associated to average lifetime ownership of an EV (compared to an ICEV), in high use cases the user can actually save money at the expense of society (ITF, 2012). Further to this, the conclusion of the JTRC round table discussion mentioned earlier warned that subsidies could be used to increase profits rather than affect supply, and there is a strong argument for avoiding subsidies due to the risk of them being withdrawn before vehicles are fully developed (JTRC, 2010). However, it was also noted that a survey of financial incentive schemes for EVs across Europe found that there is little correlation between the strength of the incentive and EV uptake (JATO, 2011). For instance, Germany had the lowest subsidy but the highest uptake. However, this study did not report what other factors were available that may have affected uptake or interacted with subsidy schemes, such as charge point availability. Despite this, another survey found that 84% of European respondents thought the Electric Vehicle purchase incentives were necessary (Thiel et al., 2012).

Diamond (2009) applied regression analysis to HEV adoption data over time to understand the relationship with policy incentives and socioeconomics across different states in USA, finding sensitivity to state specific characteristics and a strong relationship with gasoline prices. However, on aggregate there wasn’t a significant impact from the introduction of monetary incentives, though in individual states, up-front subsidies appeared to have a stronger effect than rebates. Chandra et al (2010) carried out a similar study and method, but based in Canada and in contrast to Diamond found sales tax rebates had a significant and positive effect, but conclude that this subsidises people who would have bought HEVs anyway.

Many studies suggested that usage incentives, such as providing infrastructure or allowing LCV exemptions from zone charging and restricted lanes can be important purchase incentives (Borjesson et al., 2012; Rowney and Straw, 2013; Hanley and Buchanan, 2011; Lane, 2011; Yeh, 2007). There were exceptions to this that found that such incentives may be area-dependent (Diamond, 2009), and that infrastructure for CNG had a minimal impact in Argentina (Collantes and Melaina, 2011). Car clubs are well suited for LCVs, but it is uncertain if they are commercially viable in the long term (Lane, 2011). In a review of LPGV uptake and the refuelling network, Hu and Green (2011) also used regression analysis of data from a number of countries and identified that fuelling station availability appeared to lead LPGV uptake, but was not strong enough to be self sustaining. Yeh (2007) looked at NGV uptake across various countries, and found fuel availability to critical to success, but also NG price had to be significantly lower than conventional fuels.

A survey consultation regarding local authority incentives was carried out by the RAC and concluded that central government should work with local authorities in arranging schemes to ensure uniformity. As such, these are heavily reliant on government funding (Hanley and Buchanan, 2011). Charging infrastructure provision should be diverse (Rowney and Straw, 2013) and it is necessary to improve the coordination between planning documents regarding LCVs. Public procurement programmes should mirror the EU fleet average targets for maximum effect (Rowney and Straw, 2013), though one study looking at both USA and China found that niche demonstration projects do not necessarily lead to widespread adoption (Zhao and Melaina, 2006).

Lane and Potter (2007) carried out a review of consumer attitudes towards LCV purchase, finding that consumer understanding of fuel economy and emissions is poor and there are psychological factors that influence car purchase, including attitudes, lifestyles, personality and self image. Furthermore, although environmental concern is high, awareness of LCVs is only moderate. This would suggest that policy is needed to improve consumer knowledge and influence decisions. For this, information provision is necessary but is not always sufficient and needs to be accompanied by the other measures on both the supply and demand sides (Lane, 2011). However designing information campaigns is complex. Within policies designed to raise awareness, behavioural studies suggest that there may be a call to design targeted policies to certain segments of society (Anable, 2005; Schuitema et al., 2013). Furthermore, the importance of inter-personal interaction in consumer perceptions, including technology understanding and pro-societal values, was observed through social network surveys (Axsen and Kurani, 2011). Fuel *cost* labelling may be more effective that fuel *economy* labelling as, even though fuel economy is reported as being important, it is not reflected in car choices (though this may change as fuel prices rise) (Anable et al., 2008), and the actual impact of a CO_2 label on vehicle choice may be small (Lane, 2011) or ineffectual in the absence of other policies (Onoda, 2008).

In summary, there have been numerous studies of demand side measures, mainly focused on fiscal measures and behaviours. There is some disagreement in the effectiveness of measures and the interaction between measures, demonstrating the complex political and social environment related to car ownership and use. As many countries are concentrating on fiscal measures it would seem sensible to focus research on such policies.

2B.5 Conclusion and Research Focus

Although this policy review has specifically focused on polices in a UK context, similar policies are being adopted across the Western world. Generally, they have been introduced relatively recently and in many cases their impact is yet to be proven. The ultimate aim of this thesis is to develop a modelling process to assess the success of these policies, in terms of emission reductions and ethical impact, in order to make policy recommendations. To aid in the management of this, it is necessary to categorise the policies into generic types.

2B.5.1 Supply Side Policy Types

Many of the policies have a great deal of emphasis on development of the supply-side, and from this is can be suggested that these policies can be divided into two generic areas, *Competition & Collaboration* and *Regulation*, shown in Figure 2.12.

Figure 2.12: Supply-side policy measures for LCV uptake

Competition and Collaboration

In order to ensure that manufacturers are incentivised and committed to build an LCV market with a common agenda, the government must introduce policies which support both *Competition and Collaboration* in R&D. Competition between companies accelerates R&D, whereas Collaboration assists in overcoming barriers of higher R&D costs and skill shortages. Programmes are introduced which link industry and academia overcoming skill shortages, tackling commercial barriers and harmonising investments. As part of this the training of workforce, through apprenticeships and universities is key. This is made possible through initiatives like the SMMT and TSB, as well as on an international level through symposiums and initiatives. Integrated delivery programmes and competitions encourage consortia to form thus heightening collaboration.

Once vehicles reach a viable stage of development, demonstration of prototype vehicles, to enable mass manufacture and commercialisation may realise further technological challenges which are not yet anticipated, but by which time relationships should be in place which assist in the challenge. Government commitment to future transport technologies is indicated by the encouragement of collaboration between industry and academia, tackling commercial barriers to knowledge sharing and harmonising investment in research programmes.

Regulation

To encourage manufacturers and fuel providers to improve technology, many governments have introduced *Regulation* that requires certain fleet targets to be met regarding tailpipe emissions and technology quotas. These targets are ensured by the application of fiscal penalties to the manufacturer should they not be met and credits should they be achieved. Usually, the targets will be technology neutral, allowing the manufacturer to make their own business decisions on how they should be met. Emission reductions can be met through improvements and efficiencies in ICEV, the application of new technologies and the introduction of lower carbon fuels. This option is currently being given significant attention in both the EU and California who are global leaders in vehicular CO_2 emission legislation. By their nature, such regulations leave strategic business plan decisions to the individual manufacturers, and as compliance is dependent on average emissions, it could still allow high emitting vehicles, which may compromise or contradict messages of the importance of reducing emissions.

2B.5.2 Demand Side Policies

The remaining policies are all aimed at the customer and/or car owner, aiming to influence the purchase decision and force LCVs to take a place as a realistic option within their decision set when choosing a new car. Figure 2.13 shows the measures currently in place or proposed in the UK, indentified as being within one of three categories; *Fiscal Measures*, *Raising Awareness* and *Facilitating Adoption*.

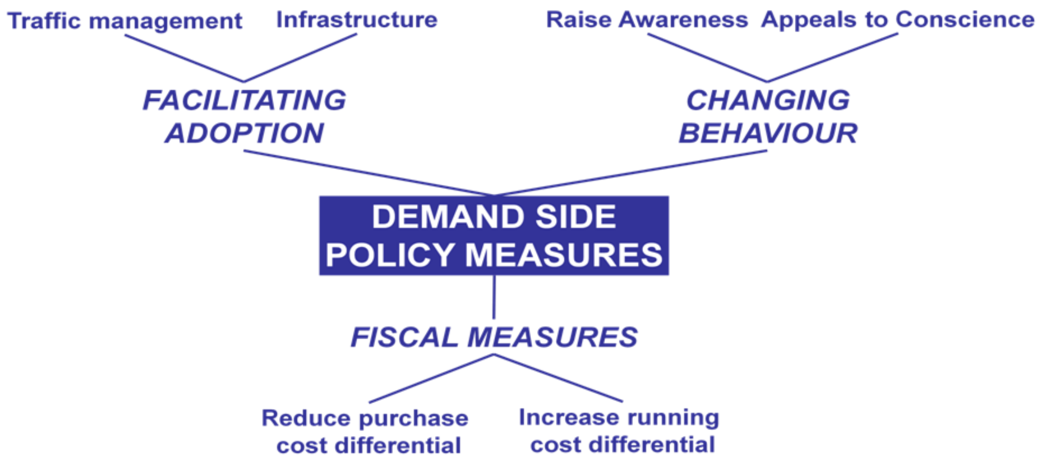

Figure 2.13: Demand-side policy measures for LCV uptake

Fiscal Measures

Fiscal Measures are hard policy instruments designed to overcome the current high cost differential between ownership of cICEV and LCV, by decreasing the purchase cost of the LCV or increasing running costs of cICEV. They will often take the form of taxes and subsidies, and are levied on the consumer at the point of sale or day-to-day operating costs. These are currently heavily used in many countries. Further fiscal incentives may be realised through vehicle to house/electric grid remuneration, and capital allowances of fleet vehicles. In the UK the most obvious examples of these are the annual VED for car owners, fuel duty paid at the pumps and the Plug-in Car Grant. Previously, scrappage schemes have been used to encourage the replacement of older vehicles with newer more efficient models. Other examples of *Fiscal Measures* that are being considered are road pricing charges or carbon permitting schemes. Any policy related to monetary penalty or incentive is likely to be controversial. Care must be taken to avoid mis-placed benefits and burdens. Transparency in decision-making can assist in this.

Facilitating Adoption

To encourage LCV uptake, early adopters can be compensated for the lower utility it may provide them relative to a cICEV. *Facilitating Adoption* policies implement programmes of favoured traffic management or accelerated building of complementary infrastructure (e.g. charging points). Lack of refuelling infrastructure required to run an LCV to a comparable level of convenience will prove to be a hurdle to overcome particularly due to the fundamental issue of reliance on private vehicles as a way of life. Thus investment in refuelling stations and public charging points to ensure a timely roll-out and spatially sufficient provision is a possible way forward. To further encourage uptake, LCV may take advantage of priority lanes, low emission/noise zones and free parking. Learning from demonstration schemes and market research can allow both government and developers to understand which measures may be most attractive to potential consumers. This is of particular importance regarding unfamiliar new or different methods of refuelling/recharging. Part of this may also involve the easing of planning and building regulations, and standardisation of both charging method and payment schemes to ensure interoperability. Investment may be needed for the installation of both private and public charging points. Further to this, the ease of use of electric vehicles is hindered by the range restriction, and this may be overcome by rapid charging, battery swap facilities and availability of car clubs.

Raising Awareness

Perhaps the greatest challenge in the public adopting the LCV lies in the attitude towards the LCVs attributes that differ from the cICEV that they are more acquainted with. In addition there is the role of preferences – the user may feel aesthetically the ICEV is more attractive than an EV, that they have an affinity with the ICEV, or that there is a matter of status associated with the ICEV or its particular makes and models. Such attachment to the ICEV may be more difficult to overcome when there is any degree of climate scepticism of the emission reduction potential (and other sustainability aspects) of the LCVs.

Raising Awareness introduces appeals to conscience and marketing to ensure consumers have correct and current information regarding vehicle technologies, to assess if their needs will be met, and address misconceptions of LCVs. Although it is reasonable to assume that, at least at present, not all consumers will have their needs met by an LCV, it is also not deniable that many will, though they may have the perception that they will not. Thus, information provision, through various media and increasingly importantly the internet, is required to encourage those consumers to review their stance and reassess their needs in light of the situation. This is not meant to be strictly coercive, but to make a conscience-neutral appeal to rationally address the utility an LCV may offer.

2B.5.3 Research Focus

It has been clear in this review that there is a diverse range of policies required to ensure the uptake of LCVs necessary in decarbonisation of the transport system. Some have already been proven to be more effective than others. For example, regulatory measures on manufacturers were more successful than voluntary ones. On the other hand, there is split opinion on whether softer demand side measures are effective unless they are part of a larger policy portfolio. The review revealed that there has so far been less attention paid to policies directed at manufacturers than at the public in the literature, perhaps because it is too early to gather evidence. It is not possible to explore all of these policies in depth due to time and resource constraints of this research. Therefore there needs to be a focus on those policies which may have the biggest impact, one supply side and one demand side policy.

The two policies of most interest are *Regulation* and *Fiscal Measures,*[22] as through this literature review they appeared to be the most high profile, and similar approaches are in place in many countries. However, this research is also concerned with the ethics of these policies. To focus the research, an ethical framework will be developed and evaluated in Chapter Three. These will be taken into account when developing the modelling case studies in Chapters Four and Five that will explore the impacts of policies.

[22] Throughout the rest of this thesis, the generic policies will be italicised in the text to be clear when they are being referred to.

PART C: LCV UPTAKE MODELLING

2C.1 Overview

The previous sections of this literature review presented the range of LCV fuels and technologies that are being developed, the barriers that exist to their widespread adoption, and the policies that are being employed in order to overcome these barriers. It is the objective of this thesis to understand the impact that these policies and technologies may have in the real world, in order to identify potentially sustainable pathways. To achieve this, a policy model will be employed.

Many real world systems can be modelled using mathematical formulae developed to represent relationships within that system. Such models can then be used to understand the impacts of changes within the system, or identify conditions required to meet desired targets through the manipulation of relevant elements. These have been widely employed in business, industry and government for many years to aid decision making, study new product diffusion and to inform transport planning. More recently models have been applied to the specific consideration of LCV uptake.

The type of modelling employed in this research is system dynamic modelling (see 2C.5), which incorporates numerous aspects of demand and supply within the automobile market including both diffusion models (2C.3) and discrete choice models (2C.4). System dynamic modelling was chosen not only due to the inclusion of these elements but as it also allows for the exogenous manipulation of attributes, the inclusion of wider system interactions and endogenous responses over a time period, and does not suppose an equilibrium. Following an overview of the background to transport modelling, the methodological theory behind the principal types of models relevant to this research is then presented. Findings from a review of existing LCV uptake model studies are then set out, and lead to the identification of research gaps.

2C.2 Background

The growing application of models to the realm of transport planning, which was first applied in the 1950s (Hensher and Button, 2008), is due to the necessity to predict the impact that changes in transport networks would have on network users (or vice versa), thus allowing planning of optimal policies and efficient networks (Ortuzar and Willumsen, 2011). As decisions made by policy makers using transport models will be realised into a real world situation, the accuracy of the predictions is of major concern, by both model-sceptics and model-supporters alike (Timms, 2008). Despite this, modelling remains to be seen to play an important role in ex-ante evaluations of transport policy (van Wee, 2011a).

Numerous different types of models can be employed or combined, depending on the objective of the project (including the level of precision required) and the resources available to the modeller. Most models tend to be based in econometrics and can be deterministic or stochastic, depending on the degree of randomness which is employed. The model could be static or dynamic, the latter representing changes over time. Many are based on an idea of seeking an equilibrium within the system and that actors within any system are rational and utility maximising.

Although most transport models are concerned with modal choice, trip assignments and network effects, car ownership models can be seen as precursors to LCV uptake models. In the UK, the first forecasts were made in the 1920’s (Allanson, 1982), with models being developed since the 1940s (Ortuzar and Willumsen, 2011). The ability to predict changes in, impacts on or preferences for car ownership and use is important for local planning, government policy and the automobile industry.

These studies have ranged from simple analysis of existing ownership (Tanner, 1958; Wong, 2013) and forecasting uptake (Huang, 2005; Tanner, 1978), as well as more detailed studies such as extensive vehicle characterisation (Lave and Train, 1979), behavioural understanding (Bhat and Pulugurta, 1998), location/spatial/population impacts (Clark, 2007; Fang, 2008; Ritter and Vance, 2013), income/cost effects (Dargay and Gately, 1999; de Jong et al., 2009), or usage and retention (de Lapparent and Cernicchiar, 2012). Although it is not the purpose of this work to go into the findings of these studies in detail, some findings relevant to LCV uptake from an overview study suggest that both purchase price and operating costs have significant negative impacts on vehicle choice, whereas spacious and powerful vehicles are preferred, while brand-loyalty is also important (Cao and Mokhtarian, 2004).

Several approaches were used in these studies, including extrapolation from historic trends, establishing econometric relationships to socio-demographics and applying product diffusion, random utility or discrete choice models related to vehicle attributes. Recent studies were summarised by de Jong et al., (2004) into nine types, covering demand and supply markets, vehicle stock and usage, aggregation and disaggregation, and static and dynamic. Similar methods are used to estimate LCV uptake, though all have their limitations. For example, econometric models require historical databases of variables rendering them inappropriate for the forecast of LCVs, whereas choice models require stated preference surveys to provide underlying data, which is not wholly representative of real-world actions. More recently, studies have incorporated static data into dynamic models to better realise feedbacks which exist over time (Richardson et al., 1999). A significant advance between standard car ownership models and those for LCV uptake is the inclusion of multiple car types, as de Jong et al. (2004) suggest only choice models, which can consider numerous attributes are capable of doing so to a significant extent.

To forecast the uptake of LCVs, there needs to be an understanding of car ownership and use (to allow for realistic substitution patterns), through in reality many LCV uptake models assume constant fleets and mileage. As LCVs are a new technology not yet widely available in the market, knowledge of the diffusion of innovative products and of the specific preferences which exist within and between consumers is required. The following section presents the theoretical background to the main types of models employed in studying LCV uptake. Other forms of modelling, based on equilibrium, econometrics or individual agents (see for example (Brand et al., 2012; Karplus, 2010; Zhang et al., 2011) have also been applied but are not the focus of this review.

2C.3 Diffusion Models

Diffusion of innovation theory describes the process that occurs when new ideas are invented, diffused and adopted or rejected. It has widespread application to both sociology and business. Though first discussed by social scientists at the turn of the 20th Century, it was developed in the early 1960s by Everett Rogers, who described it thus;

> *The process by which an innovation is communicated through certain channels over time among the members of a social system.* (Rogers, 2003, p.5)

The adoption process was already established as a standard S-shaped curve, and Rogers standardised adopters as five categories of innovativeness, as shown in Figure 2.14. Although not explicitly used in this research, it is the first three categories that are likely to be the focus of the model, though the remaining cohorts remain a concern in the ethical discussion.

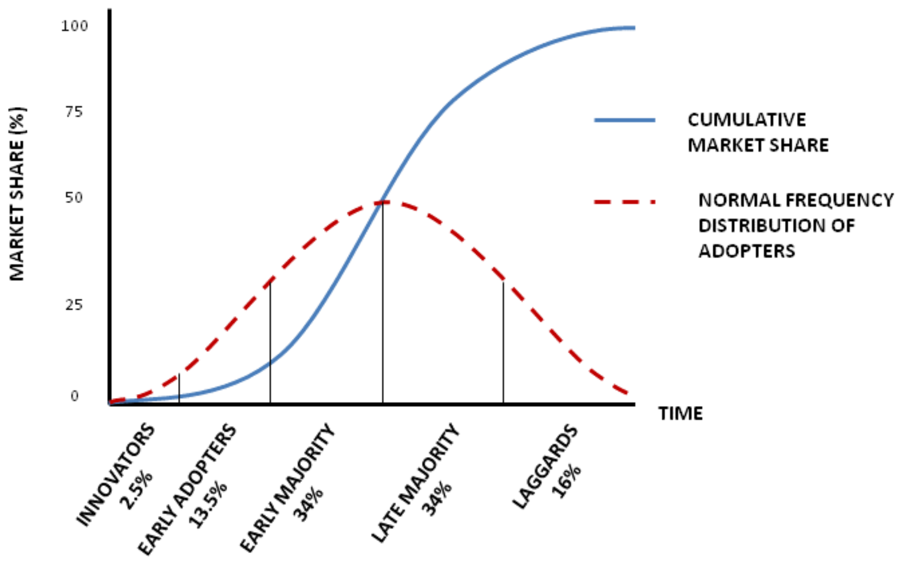

Figure 2.14: Diffusion of innovation standard S-Curve and adopters (adapted from Rogers, 2003).

This theory was first described as a product diffusion model by Bass in 1969 via Equation 2.1 and this is a highly cited work in marketing literature. This simple differential equation relates the number of sales to the number of previous buyers over a specific period of time, and can be used to calculate the rate of adoption at any given time. Integration of Equation 2.1 yields the S-shaped cumulative adopter curve of Figure 2.14.

$$S(T) = pm + (q-p)Y(T) - \frac{q}{m}[Y(T)]^2$$

Equation 2.1 (Bass, 1969)
S(T) = Sales at time T

p = coefficient of innovation (constant)

q = coefficient of imitation (constant)

m = number of initial purchases over period of interest (constant)

Y(T) = number of previous buyers at time T

t = time

The evolution of sales over time is then described by Equation 2.2. The non-cumulative adoption curve related to this is shown in Figure 2.15. In this figure, the sales above the dashed line are due to *Imitators* - those who are influenced internally by previous buyers (represented by the coefficient of imitation). Below this line are adoptions due to external influence. These *Innovators* correspond to innovators and early adopters in the Rogers classification, and are dependent on the coefficient of innovation. The maximum point of the curve in Figure 2.15 corresponds with the inflection point of the s-shaped curve in Figure 2.14. For any product and set of adopters, determining p, q and m will reveal the speed and shape of the adoption curve. The parameters p, q and m require estimation through regression analysis or, in the case of no/limited data, by market analysis.[23]

$$S(T) = m\frac{(p+q)^2}{p}\frac{e^{-(p+q)t}}{(1+\frac{q}{p}e^{-(p+q)t})^2}$$

Equation 2.2 (Bass, 1969)

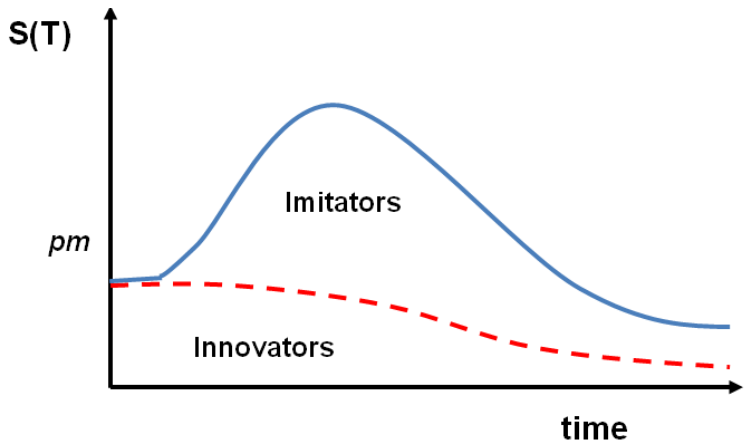

Figure 2.15: Non-cumulative adoption in the Bass Model (adapted from Mahajan et al., 1990).

[23] The most common three approaches are ordinary least squares (OLS), maximum likelihood estimation (MLE), and non-linear least square (NLS). As parameter estimation is not carried out in this research, detail on these techniques is not provided.

The basic premise is that explicit behavioural assumptions (building from theories on adoption and diffusion within a social system) can be used for long range forecasting in the growth of sales for infrequently purchased consumer durables. There are a number of assumptions and simplifications included in this, such as selecting a time period which excludes replacement sales, but the model does give good agreement with existing data (Bass, 1969). There have since been many reiterations and refinements, for example by Bass on pricing strategies (Bass and Bultez, 1982) and decision variables (Bass et al., 1994) and others, on the influence of advertising and word of mouth (Dodson and Muller, 1978), non-uniform effects (such as word-of-mouth and penetration rate timing) (Easingwold et al., 1983), introducing the concept of heterogeneity (Bemmaor and Lee, 2002; van den Bulte and Stremersch, 2004), changing attributes and cost (Schmidt and Druehl, 2005), and acceptance and rejection dynamics (Ulli-Beer et al., 2010).

Product diffusion models are relevant to LCV uptake as these technologies are examples of new, innovative products. However, most established product diffusion models are not directly transferable to the case of LCVs. Often the literature will be regarding consumer lifestyle products such as white goods, computing and mobile phones. Such goods, although increasingly becoming integrated into many people's lives, differ fundamentally from vehicles in a number of important ways. Automobiles are of a significantly higher purchase cost, leading to a longer retention of ownership – they are likely to be the most expensive item bought by an individual after a house. Also, most households in developed countries will be replacing an existing cICEV that is already an integral part of their daily life, and as such, any deviation from the utility it provides or how it operates greatly impacts on their decision.

Thus, although product diffusion needs to be a constituent part of an LCV uptake model, it would also need to take account of heterogeneity and individual decision making. Some studies that are discussed later have specifically adopted a diffusion of innovation approach to studying LCV uptake potential (Cao and Mokhtarian, 2004; Collantes, 2007; Morton, 2013), or integrated product diffusion into system dynamic models (Kohler et al., 2010; Struben and Sterman, 2008).

2C.4 Choice Models

Choice modelling is a branch of economics that was developed to account for disaggregation of individual choices within a decision set by assigning preferences. It has been in use in a number of areas, such as marketing, environmental studies and transportation, for decades (Train, 2009). Discrete Choice Modelling (DCM) has been extensively used in transport planning to understand modal choices, time savings and willingness to pay. According to Ortuzar and Willumsen (2011, p.228);

> *In general, [DCMs] postulate that the probability of individuals choosing a given option is a function of their socioeconomic characteristics and the relative attractiveness of the option.*

A DCM is based on random utility theory, assuming that individuals possess perfect information and act rationally choosing an option within a choice set which maximises their net personal utility. Within the choice set, there is a finite number of options available, each with an associated utility for the individual. This utility comprises of a measureable component based on known attributes of the choice and a random component which reflects individual tastes and unknown errors (Ortuzar and Willumsen, 2011). The decision-maker can be an individual or a distinct cohort (e.g. a household), the choice set has to be finite and exhaustive, with mutually exclusive alternatives and the decision rule is the method of calculation of the probability of choosing a variable (Train, 1993). This probability is an attempt to understand the behavioural response of an individual and in this way discrete choice modelling is highly related to individual values.

The most widely applied and basic method of calculating the choice probability is the multinomial logit model (MNL) (Bhat et al., 2008), and is given by Equation 2.3. There are three basic underlying assumptions to the MNL (Bhat et al., 2008):

1. The random components of the utilities of different alternatives are independent and identically distributed with a type I extreme-value (Gumbel) distribution;
2. It maintains homogeneity in response to attributes of alternatives across individuals (i.e. does not allow sensitivity of taste variations to an attribute due to unobserved individual characteristics);
3. The error variance-covariance structure of the alternatives is identical across individuals.

$$P_i = \frac{e^{V_i}}{\sum_{j=1}^{J} e^{V_j}}$$

Equation 2.3

P_i = probability of choosing option i,

V_i = modelled utility of alternative i out of J alternatives – a function of the attributes of alternative I and estimated parameters including constants, scaling parameters and marginal utility coefficients

V_j = utility of alternative j out of J alternatives

Other types of choice model, for example mixed or nested logit and probit, may be used to overcome some limitations of logit. Examples of such limitations are accounting for random taste variation, the independence of irrelevant alternatives and individual unobserved factors (Ortuzar and Willumsen, 2011; Train, 2009). These other models involve increasingly complex mathematics and for the purpose of this thesis only MNL will be considered, as this is the most commonly applied form of DCM in this field.

The observed data for developing DCMs is generally obtained from surveys. This would ideally be a *revealed preference* (RP) survey of actual decisions that have been made, but in reality for new products and most DCMs, *stated preference* (SP) surveys are required, that ask the decision maker to state what they think they would choose. The success of a survey is led by its design and tailoring to the question being addressed, and requires a fairly robust knowledge of likely advances and timescales in technology and infrastructure, which is usually obtained by expert/industry guidance. The outputs of this are then used to estimate the parameters of the model (coefficients for preferences or willingness to pay for example), from which likely uptake can be plotted. The model is then subjected to sensitivity testing, and where possible compared to historic data to analyse fit. There is a note of caution attached to choice modelling. Survey data is both geographically and temporally specific, and dependent upon the original survey design. SP surveys can be particularly concerning as respondents may not answer truthfully (either due to a desire to conform or in reality they do not act as intended). Additionally, in order to obtain a comprehensive and significant amount of data, the survey and its analysis can be both time consuming and costly. There is a substantial and increasing body of work concerned with the methodological, sociological and psychological aspects of choice modelling (Hess and Daly, 2010).

Furthermore, it forms the basis of the majority of studies on the uptake of LCVs, the findings of which will be discussed in 2C6.2. As a new technology, there is little available data around past decision making regarding LCVs, and as such the choice models tend to be based on SP survey data, but may take a variety of approaches to analysing the data, going beyond MNL to more advanced logit models, such as nested, crossed and mixed. However, understanding the utilities that individuals may assign vehicle attributes (that characterise different vehicle types), does not on its own assist in the identification of suitable policies to stimulate LCV uptake. In order to understand what exogenous parameters may influence decisions in a choice model, and thus determine what conditions may be required for success, it can be integrated into a larger model that accounts for a wider system, considering the product diffusion and interaction with different actors within that system.

2C.5 System Dynamic Models

Systems thinking allows integration of many interactive elements that are active in any complex dynamic systems. This approach combines non-linear dynamics, choice, diffusion, time-delays and feedback controls within many disciplines, from social science and psychology to technology and engineering. System dynamics modelling has been applied extensively within business management, led by Jay Forrester in the 1950s (Forrester, 1958), but has over the past few decades begun to be applied to other areas, including government policy, healthcare and the automobile industry (Sterman, 2000). System dynamic models with broad model boundaries that include side effects, delayed reactions, changing goals and interventions can help inform policy by establishing conditions for success, tipping points and identify otherwise unanticipated results.

Fundamentally, system dynamic models are a complex interrelated collection of simultaneous differential equations. The feedback processes within a system are modelled with *stocks* (accumulations of product) and *flows* (movement rates of product) interacting through *causal loops* over time to simulate real world processes. This allows for the understanding and analysis of impacts of endogenous and exogenous decisions and actions within a system. Causal loop diagrams represent either positive (self-reinforcing) or negative (self-correcting or balancing) feedback dependency. Reinforcing loops amplify what is happening in the system, i.e. where an increase in one parameter leads to an increase in another, and without any other interacting parameters, this increase will continue exponentially. Balancing loops are relationships that oppose change, so in such a loop an increase in one parameter leads to a decrease in another, until a dynamic equilibrium is reached. The interaction of multiple causal loops make up the wider dynamic system.

A basic example of a simple reinforcing and balancing loop in a system is shown in Figure 2.16, the causal loops which represent the interaction between eggs, chickens and road crossings. The ‘eggs and chickens’ loop is reinforcing (denoted R) (hence the “+” in Figure 2.16) as more eggs lead to more chickens, which in turn lead to more eggs. If this loop was operating on its own, both chickens and eggs would increase exponentially. On the other hand, the ‘chickens and road crossings’ loop is balancing (denoted B) – although more chickens lead to more road crossings, the increase in road crossings leads to less chickens (denoted by “-“). If this loop were operating alone, the chickens (and road crossings) would gradually decline to zero. In reality, as the loops interact, the path of eggs, chickens and road-crossings over time are dependent on the relative rates but will eventually reach a dynamic equilibrium.

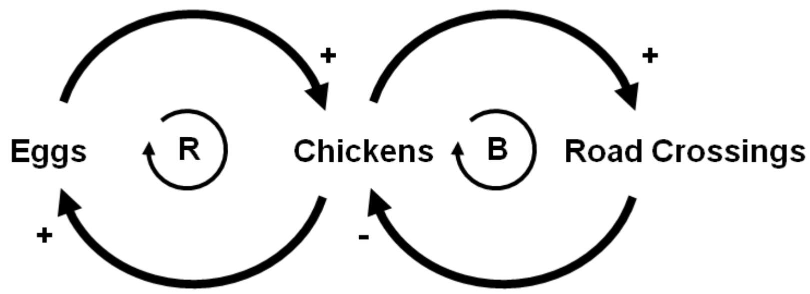

Figure 2.16: Simple causal loop diagrams (adapted from Sterman, 2000).

Stocks and flows are required in system dynamic models as in certain processes the parameters may accumulate as a stock from an inflow that declines once an outflow is permitted, similar to a bath before the plug is removed. The in and out flows may be non-linear and operate at different rates that are independently dependent on other parameters. For instance, the Bass diffusion model, as discussed in section 2C.3, was developed by Sterman (2000) to be represented as a dynamic system with feedbacks shown in Figure 2.17. Recall in Equation 2.1 and Equation 2.2 that Adoption (or Sales) is dependent on adoptions from imitation and innovation. In this diagram, innovation is represented by *“Adoption from Advertising”* and imitation is represented by “*Adoption from Word of Mouth”*, both of which are reinforcing causal loops. Adoption Rate is therefore represented in Equation 2.4.

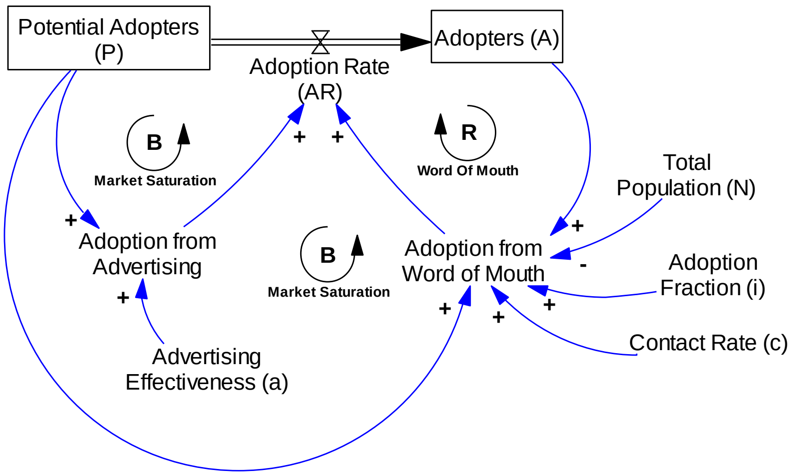

Figure 2.17: Bass diffusion model dynamics (adapted from Sterman, 2000).

$$AR = aP + \frac{ciPA}{N}$$

Equation 2.4 (Sterman, 2000)

AR is the adoption rate

a is advertising effectiveness

P is number of potential adopters

c is the contact rate

i is the adoption fractions

A is the number of adopters

N is the total population.

A substantial amount of work has been carried out using system dynamic modelling to understand the automobile industry and some more recent studies, which are discussed in the next section, have considered the demand and uptake for LCVs, incorporating diffusion models and/or choice models. The automobile industry is a complex system, combining business management, technology research and development, customer decision making and government regulation. The addition of LCVs into the system only compounds the complexity and uncertainties.

2C.6 Previous LCV Uptake Studies

There have been many academic studies on choice, diffusion and system dynamic models of LCV. A selection of these are set out in Table 2.5. It should be noted that this may not be an exhaustive review of studies, but those that were felt to be most of note within the limits of this research. The first date back to the early 1980s but have been carried out more extensively since the 1990s (Brownstone et al., 1996).

	Study	Location	Alternative Fuels and Technologies	Study Objective(s)
Diffusion	Cao and Mokhtarian (2004)	USA	NG, BF, HEV	Estimate future demand and evaluate influence of factors and policies.
	Collantes (2007)	USA	HEV, HFCV	Understand market diffusion develop estimates of market share evolution.
Choice	Ahn (2008)	S. Korea	LPG, NG, HEV	Understand impact on vehicle ownership and use.
	Batley et al. (2004)	UK	generic	Forecast demand and cost elasticities.
	Beggs et al. (1981)	USA	EV	Potential consumer demand and preference parameters for AFVs
	Brownstone et al. (1996)	USA	BF, EV, CNG	Forecast AFV demand and transactions.
	Dagsvik et al. (2002)	Norway	LPG, EV, DF	Potential demand, elasticities and willingness to pay for AFVs.
	Eggers and Eggers (2011)	Germany	BEV, HEV	Forecasting model to predict if current trends are sustainable.
	Ewing and Sarigollu (2000)	Canada	LEV, AFV, BEV	Assess consumer preferences for CFVs and identify market segments to target.
	Link et al. (2012)	Austria	EV	Gain knowledge of the needs of potential purchasers of electric cars.
	Mabit and Fosgerau (2011)	Denmark	HCFV, HEV, BF, BEV	Potential future demand of AFV under certain tax conditions.
	Potoglou and Kanaroglou (2007)	Canada	HEV, AFV	Examination of the factors and incentives that influence choice and willingness to pay.
	Train (1980)	USA	BEV, HEV, H_2, AFV	Estimate market share of non-gasoline vehicles given certain characteristics.
System Dynamic	Boksberger et al. (2012)	EU	NGV, EREV, BEV,HFCV	The interaction between supply and demand and impact of policies on diffusion of AFVs.
	Janssen et al. (2006)	Switzerland	NG	Identify difficulties and chances in market penetration process.
	Kohler et al. (2010)	Germany	HFCV	Examine Issues of infrastructure provision as part of the transition.
	Leiby and Rubin (1997)	USA	NG, LPG, BF EV	Identify necessary conditions and associated costs for successful market transition.
	Stasinopoulos et al. (2012)	Australia	BEV	Consider impacts of market competition, new materials and policy interventions on adoption.
	Struben and Sterman (2008)	USA	AFV	Feedbacks that affect consumer awareness and key processes which condition adoption.
	Walther et al. (2010)	USA	HEV, PiHEV, BEV	Examines manufacturer strategies for compliance to emission regulations.

Table 2.5: Selected LCV uptake model studies by primary model type (BF = Biofuel, DF = Dual Fuel)

2C6.1 Diffusion Models

Only two studies were identified that took a purely diffusion model approach to understanding LCV uptake, though it has been more widely applied to general automobile demand (e.g. Tanner (1978)). It would seem that a distinct problem with diffusion modelling is that each type of LCV requires a separate model, so any interactions between powertrains are not captured. Also, as new technologies, there is no historic data on which to base trends on, meaning that trends of other artefacts are be employed that may not be wholly appropriate. Thus diffusion models may poorly represent particularities of the technology and consumer preferences are not accounted for. Nonetheless, such models may play a useful role in understanding basic dynamics and the role of potential adopters.

Cao and Mokhtarian (2004) based their study on the Bass model and calibrated with existing historical data from the US Department of Energy. This approach is limited as it is based on vehicles which are already available and in use, and many LCVs of interest are not yet available, so could not be modelled. They based their study on a number of variables including sales, availability, range, refuelling availability and fuel price. Each type of LCV was modelled separately so interaction between types would not be captured, and as consumer choice was not modelled, this could lead to significant inaccuracies. The authors do recognise these limitations, alongside the failure to account for exogenous impacts and the fact that supply may not always meet demand. It was possible to carry out scenario analyses by varying the assumptions on forecasts for fuel price and model availability. Despite the model limitations, some interesting insights were determined. Firstly, their findings suggest that the only alternative fuel for ICEV which has potential to grow is biofuel (E85), though this is dependent on fuel availability. HEV however, have a great potential as they are closely related to ICEV, but is sensitive to fuel prices and customer awareness. The results of scenario tests were, however, in line with the findings on preferences in choice model studies (see later), that high purchase price, poor performance and lack of refuelling infrastructure are major obstacles, making government policy critical in successful LCV uptake.

HFCV and HEV were the focus of another diffusion model study, which considers the adoption risk of consumers, and used a stakeholder survey to predict future market penetration (Collantes, 2007). This assumes that HEV only replace ICEV and HFCV only replace HEV. The diffusion coefficients for HEV were estimated from existing sales, and the entry year for HFCV was based on survey data, which was determined to be 2014, with 5% of sales by 2033. A further assumption was made that the new technologies could capture 100% of the market, resulting in a HEV 100% market share by 2025 and HFCV by the late 2040s. Although this model can suggest a basic diffusion of these new technologies, it does not give space to examine system interaction or consumer preferences.

2C6.2 Choice Models[24]

Choice models are useful for identifying consumer preferences towards attributes related to LCVs, but do not take account for wider system interactions or the change in those preferences or attributes over time. The earliest study (Train, 1980) provided estimates for future market shares, but notably based on assumptions that vehicles would be available if demanded and that there would be no change in consumer preferences, policy regimes or fuel prices, and arbitrary forecasting of household demographic data. This static nature common to all choice models is one major disadvantage, as all of these elements (and more) may change over time, and through interaction with other system elements, to restrict the choice set. To analyse this, choice models need to be integrated into a dynamic system.

With the exception of one study (Ahn, 2008) all studies in Table 2.5 included purchase price as an attribute of vehicles in the SP survey, and the majority included vehicle range, operational costs (including fuel), fuel type and an indicator of emissions. Although not all studies are clear in how they assigned the attribute level, if they were not carried out in conjunction with automotive engineers, this could mean that the results are not realistic. For instance, Beggs et al. (1981) made no presumption if their levels of attributes were achievable. As there was a variety in fuel types and attribute levels, only general findings and notable exceptions are presented here. No studies explicitly considered the second-hand car market and preferences were related to the purchase of new vehicles.

Cost sensitivities (particularly regarding purchase price) and technical characteristics proved to be strong determinants in LCV uptake in most studies. If technical performance is of most importance, then regulations targeting

[24] The focus of this research is not developing new choice models so detail and criticism on model formulation and methodology are not provided.

manufacturers is critical, as concluded by Ewing and Sarigollu (2000). Batley et al (2004) was the first study to consider elasticises of demand related to change in LCV attributes, finding a high sensitivity to purchase price and that even with significant improvements in fuel availability and range, there is little prospect of significant LCV take-up due to high purchase prices. Conversely, a Danish study, where EVs could have a lower purchase price than cICEV due to exemption from high vehicle registration taxes, suggested great potential for EVs to capture half the market in the near term and be a market leader in the future (Mabit and Fosgerau, 2011). Findings related to the impact on fuel costs do vary somewhat. In the USA, fuel cost is such a low portion of overall costs in the absence of tax, that it was found insignificant (Ewing and Sarigollu, 2000), though a study in the UK found substantial variance in taste parameters (Batley et al., 2004). Range was found to be the most important technical characteristic in many studies (Brownstone et al., 1996; Beggs et al., 1981; Batley et al., 2004; Potoglou and Kanaroglou, 2007; Eggers and Eggers, 2011; Dagsvik et al., 2002; Ewing and Sarigollu, 2000), but refuel time was also found to be important, with one explicit exception (Brownstone et al., 1996), due to the assumption that EV recharging would take place at night so refuel time was not significant.

The earlier studies (Beggs et al., 1981; Train, 1980) do not consider the environmental attributes of the vehicle in the survey, which may indicate the lower importance or awareness of this consideration at the time the studies were carried out. Including this in the SP experiment may influence opinion, but, as noted by a number of studies, this must be approached with caution as people's actions do not always follow their preferences. However, once included strong preferences towards lower polluting vehicles were identified (Brownstone et al., 1996), particularly when fuel type is explicit, and households contain children. There is a general positive attitude towards LCVs, as some studies noted that if all else were equal they would be preferred (Ewing and Sarigollu, 2000; Mabit and Fosgerau, 2011), though Ahn (2008) found when looking solely at fuel type base utility, that gasoline was preferred to the LCV options. Although environmental impact was valued, it did not outweigh performance or price concerns (Ewing and Sarigollu, 2000).

Disaggregated studies showed large heterogeneity in LCV preferences (Brownstone et al., 1996; Mabit and Fosgerau, 2011; Dagsvik et al., 2002; Ewing and Sarigollu, 2000; Potoglou and Kanaroglou, 2007). For instance, Dagsvik et al.,

(2002) who took an approach where preferences were considered in relation to age and gender found that females are more interested in EVs than males, which was also noted by Mabit and Fosgerau (2011). Interestingly, this gender bias dates back to introduction of motorised vehicles at the turn of the 20th Century, when the EV gained a reputation of being a 'woman's' car and the ICEV being more 'manly' (Mom, 2004). Potoglou and Kanaroglou's 2007 Canadian study considered both socio-demographics and category of vehicle, and was unique in considering policy incentives within the choice set. However, the only choice set attributes of their generic LCV that differed from hybrid was fuel availability. Their findings included that the probability of choosing a LCV increased if their pollution level was more than 25% less than a conventional vehicle and long-distance commuters had a low probability of choosing an LCV. Perhaps as would be expected it was found that higher income households were willing to pay more than other households, though more surprisingly, medium-income households had the highest probability of choosing a hybrid. The most positive and only significant incentive was a tax-free purchase, as free parking and use of high-occupancy vehicle (HOV) lanes were not significant though this may be specific to the area they tested (where parking is already cheap and HOV lanes unusual).

No studies give explicit consideration to second-hand car markets, affordability of vehicle ownership, vehicle marketing or emotional attachment a customer may place on car ownership. Brownstone et al., (1996), whose research focused on vehicle transactions, noted that households with high income or currently possessing luxury vehicles are willing to pay a higher price. Ewing and Sarigollu (2000) did measure the respondent's attitude towards the environment and technology in order to segmentise the responses. This would seem to be a useful approach, particularly in terms of informing targeted policy approaches. They found that the most actively concerned about the environment are most likely to have higher preferences for LCVs and these tend to be younger and wealthier people, whereas the least concerned contain a high percentage of low income households. Eggers and Eggers (2011) allowed respondents to choose a specific brand and vehicle class to help visualise a choice, though this may bias results as it is not certain all brands will offer all models, and any influence of this was not captured. This may be an interesting aspect to explore further, as the only other study to consider vehicle size directly found a high preference for BEV in the Medium sized vehicle segment but did not follow through to other socio-demographic characteristics (Link et al., 2012). This same study took an interesting approach including modal choice to understand flexible mobility, and found those more amenable to public transport also had strong preferences for EV. Very few studies considered what the car was used for, or accounted for multiple decisions within a household, which was addressed by Ahn et al. (2007), but unfortunately, due to the static limitations of choice models, they only considered present car-owners and their patterns of car-use.

Choice models are customer-oriented so may be well placed to inform demand side policies. As the findings of the studies suggest that such measures may have less impact than those directly promoting technological improvement on the supply-side, these models present a strong argument that successful LCV uptake studies need to consider the wider system. However the findings presented here also demonstrate the importance of including a robust consumer choice model rather than basing uptake on historic trends, which may be unrealistic, as is the case for diffusion models.

2C6.3 System Dynamic Models

Finally, attention is turned to reviewing system dynamic (SD) models of LCV uptake. This method has increasingly been applied in recent years, with a specific focus on manufacturers, and appears to be favoured for the reasons identified already – that SD modelling can account for wider systems and dynamic behaviours. As an SD approach is to be taken in this research, it is important to realise any research gaps in previous work. This allows for the testing of specific scenarios and policy environments. An immediate note from Table 2.5 is that there are no existing studies which are UK based. What follows is a critical review of specific studies before some general policy-related findings.

The earliest SD study of LCV uptake identified dates back fifteen years and was built for the US Department of Energy to simulate the use and cost of LCVs over subsequent years to 2010, thought to be a transitional period for LCVs, accounting for behaviours of manufacturers, fuel retailers and consumers, and the dynamics between them (Leiby and Rubin, 1997).[25] The purpose was to understand what conditions (or policies) may be required to ensure a successful transition. It differed from previous models as SD allows for changes to be calculated endogenously.

[25] This model may not be strictly SD as it was not programmed into SD software and visualised in causal loops, but the dynamic equations and feedbacks would suggest that it can be classed as SD.

Assumptions however, still needed to be made, and so a consumer choice model for vehicle and fuel types was incorporated, from a previous model developed at the same institution (Greene, 1994). An interesting element was the inclusion of an effective cost for limiting diversity of model choice. They reported that in a base case the only fuel to achieve a significant market share by 2010 would be LPG, which would still be less than 5% of production. In a ‘no barriers’ scenario, all but electric would capture a fuel share of more than 2.5%, with LPG being almost 15%.

In reality, the 2011 data reveals that E85 vehicles are the LCV market leader and even that is less than 1% of total vehicles (Davis et al., 2013). This may be due to changes in political and economic environment over the time period, and serves to emphasis the limitations of accounting for all influences, as price curves were taken from US Government projections. The lack of success of EVs may additionally reflect the date of this study, as interest in and attributes of EV have improved since then, whereas LPG has gone somewhat out of favour. Leiby and Rubin ran two policy scenarios, regarding compulsory fleet purchase and alternative fuel tax credits, finding both options successful, but the market tends towards dominance of only one or two alternative technologies.

Janssen et al., (2006) developed an SD model to study the market penetration of NG vehicles in Switzerland. Model structure and input parameters were determined through stakeholder analysis. Within the model, consumers, fuelling stations, and import, retail and service of vehicles were all accounted for, whereas government and fuel industry were exogenous. The study then explored policy variables of subsidies (on vehicles and fuelling stations), tax reductions and advertising effectiveness, in various scenarios based on innovativeness of consumers and industry, but did not directly consider any policies aimed at manufacturers. They found that current goals (30,000 vehicles in 2010 and 300,000 in 2020) were ambitious and can only be attained in very favourable scenarios, though a sustainable market is possible. Timing of policy measures were found to have a critical, non-linear influence on market penetration. Ending fuelling station subsidies too early can stagnate vehicle sales due to lack of fuel availability and demand measures (a package including tax advantages, purchase subsidies and marketing effort) should be used in carefully timed conjunction with the fuelling station subsidy for strong and sustainable growth. Through this finding they identify a high tipping points sensitivity between success and failure that SD can be used to explore. They do not however go on to perform further sensitivity testing within the paper.

Struben and Sterman (2008) presented an SD model of LCV uptake focusing on the behavioural dynamics between consumers, which included an existing choice model and product diffusion processes based on the Bass model. Although the LCV presented were "generic AFV", the inclusion of key consumer feedbacks, and sensitivity testing of these, is a significant advance in capturing and understanding key processes. These feedbacks include "willingness to consider" and the interaction between different consumer types. The key behavioural parameters behind this were based on marketing literature for consumer goods such as microwaves, which may be inappropriate, as remarked by themselves, *"automobiles are more expensive and durable, and the purchase decision more complex and emotionally laden*" (Struben and Sterman, 2008, p.1086). They did, however, carry out sensitivity testing to these, finding that, with the exception of marketing, *"values more optimistic than the base case have relatively modest impact and exhibit strongly diminishing returns, while values less than the base case dramatically slow AFV diffusion"* (Struben and Sterman, 2008, p.1086).

Regarding utility, they found even increased AFV utility may require a long period for success, presumably due to the time needed for the willingness to consider to grow strong enough and the long lifetime (and therefore low turnover) of vehicles. As people do not necessarily keep their vehicle for its whole lifetime however, this may be misleading. They also explored the impact of increasing the installed base (rather than constant as in most models), finding that greater growth increased AFV diffusion (as would be expected perhaps), though with strongly diminishing returns.

Struben and Sterman then considered impacts outside of their initial model boundary, including vehicle performance improvement and fuelling infrastructure development. For the former, which could be taken as representative of policies aimed at manufacturers, they aggregated vehicle performance for each powertrain and allowed it to follow a standard learning curve and modelled technology learning spill-overs between platforms. They determined that whereas spill-overs from the mature ICEV industry could greatly improve AFV uptake, allowing two-way spill-over would do little to improve a stagnant baseline. In reality it is hard to see how any spill-over from AFV to ICEV could be prevented whilst the AFV market allowed to benefit from ICEV spill-over. Finally, they explored spatial co-evolution with fuelling infrastructure. Setting optimistic conditions of equal performance, universal consideration and high fuel station subsidies, AFV adoption remains limited outside urban areas, perhaps due to continued range anxiety.

The impact of infrastructure on HFCV uptake in Germany was explored by Kohler et al (2010). In addition to HFCV market penetration, the focus was also on relationships between stakeholders, and costs to the state. The model had four modules (Demand and Supply, Attractiveness, Filling Stations and Balance of Payments) but did not include manufacturer dynamics, assuming that 160,000 HFCV could be produced every year at the starting time (2013), which is highly unrealistic at present as Europe has no commercially available HFCVs. They then compared a successful penetration scenario with three policy scenarios to test sensitivity. The successful scenario achieved a 30% fleet penetration by 2040 and required very optimistic policies. These were subsidies to make the HFCV not more than €2000 than a cICEV, 500 subsidised fuelling stations, and tax-free fuel and purchase. The assumed high production rate also accelerates learning effect for cost reductions so subsidies are not necessary after 5 years. The alternative scenarios reveal that the subsidies and infrastructure provision have a significant effect, as market penetration is not possible without them. They conclude that early and strong government support is necessary, but may be cost effective and fuelling infrastructure is required before cars are available. Within this, subsidies for infrastructure will be small compared to those for vehicles. Ultimately though, the HFCV transition will take a long time and require heavy support, and as concluded by the authors:

> *Given the large uncertainties in the future costs of hydrogen vehicles and fuel, policymakers should not solely concentrate on hydrogen technology as the solution for reducing the carbon emissions of transport. It is still necessary to support a range of low-carbon transport technologies.* (Kohler, 2020, p.1046).

This acknowledgment is key, especially as the successful scenario was optimistic and assumed technology availability currently unrealistic. Additionally, they then compared the results with the EU “ASTRA” model (ASTRA, 2013), a widely used transport strategy assessment model. The HFCV market penetration rates were comparable with the optimistic scenario of Kohler et al, suggesting that ASTRA may be very optimistic.

Walther et al., (2010) incorporated the diffusion elements of the Struben and Sterman model into a wider SD model aimed at studying manufacturer strategies for meeting the Californian LEV and ZEV Regulations (see Section 2B.3.3 for details). Over a time period of 2009 to 2021, they included cICEV and pro-electric powertrains (HEV, PiHEV, BEV), which were introduced at certain times or on reaching certain range or infrastructural requirements. There were 16 models in total as each powertrain was available in extra small, small, medium or large segments (based on vehicle size and weight), though not all were available at all times. Dynamic vehicle parameters were developed alongside an automobile manufacturer, and a relevant choice model for California was included. It is not clear if it expected that segments/powertrains combinations in the model will be available in real world at the times which they are bought into the model, which could be a problem as some attributes are currently unrealistic (e.g. large BEV has a range of 240m).

The model comprised of four main modules, being Regulations, Industry, Customers and Vehicle Stock/Infrastructure. The industry was represented by an aggregated manufacturer, which means that any interactions between manufacturers, or consumer consideration of specific brands, are neglected. Walther et al. were interested in the challenges for the manufacturers in meeting the two seemingly conflicting manufacturer regulations of improving efficiencies of conventional vehicles whilst introducing less competitive LCVs. They tested various strategies in meeting the regulations. It was found that the best GHG reduction strategy made meeting ZEV requirements more difficult due to the impact of the sale of extra small conventional vehicles on the sale of BEV and hybrid in that same segment. As both of these regulations are actually in place, this is the most realistic test carried out in the paper. It is not clear whether it is intuitively valid to combine the most successful separate strategies when it has already been acknowledged how interdependent the regulations are – perhaps less successful strategies combined would reveal some interesting results. Indeed, that is the case here as it was discovered that the best GHG strategy actual results in higher overall civil penalties when combined with the ZEV strategies. As explained in the paper, this is because the extra small segment is also available in cICEV, taking some sales away of extra small ZEV and thus incurring ZEV penalties. The paper does not tell us what the resultant GHG emissions are from the strategies, which is disappointing as this is what both regulations are striving to reduce. This is surely a relevant outcome that needs to be assessed. However, if manufacturers have avoided penalties, then this is an indication of success in reducing emissions – assuming that the penalties are set at the correct level.

Two of the most recent studies also considered LCV uptake from a manufacturer point of view. Boksberger et al. (2012) analysed the interaction between supply and demand in the automobile market. The model was calibrated and validated against data from the European car industry and considered finance, R&D, production of manufacturers, and addressed a gap in research that did not consider all of these aspects together. An improvement on Walther et al was that fuel types of NG and HFCV were included and five automobile manufacturers were represented, allowing a company to go bankrupt and drop out of the market. In contrast, however, the time horizon was 100 years, which could be argued to be too long as this could bring in far too many uncertainties. Their findings include improved infrastructure and stronger penalties encourages early LCV introduction, but do not lead to market dominance of one new technology. However, high standards and penalties can lead to manufacturer bankruptcy, though policies that reward proactive manufacturers yield the greatest emission reductions. Their recommendations are aligned with other studies, and include the fact that manufacturers should be proactive and collaborate, and offer a wide range of vehicle models, but should also be aware of preventing significant increases in vehicle costs. Regarding this last point, the authors mention this in order to keep the car market sustainable rather than being concerned about impacts on people’s mobility.

Stasinopoulos et al (2012) considered the Australian car market in a wider context that also accounted for impacts of change on mode choice due to rising congestion and fuel consumption. They studied intervention by new vehicular materials and electric powertrains, allowing a previously unaccounted for interaction with down-stream supply chain. Unusually, they allow for a growing car market, though at a constant rate, and considered modal switch to public transport. As the focus of the study was more on congestion than LCV introduction, it will not be discussed in detail, though some findings are of interest. In line with other studies, they identify that petrol price may have the strongest influence on vehicle choice. They also find that electric vehicles can decrease car fleet energy consumption more than fuel efficient cICEV in the short term, but can increase transportation energy consumption in the long term as it may discourage people from shifting to public transport.

Summary of Findings from SD Models

One benefit of the dynamic feedback nature of SD models is the ability to include marketing and attitudinal changes over time. The models which included this found that influencing consumer behaviour and attitude change through marketing and education can have a strong influence on uptake (Janssen et al., 2006; Struben and Sterman, 2008; Walther et al., 2010). Of note were procurement programmes, though these could crowd out technology diversity (Leiby and Rubin, 1997). It was also a notable find that, unless they are very optimistic (Kohler et al., 2010) purchase subsidies may only work in the short term or under conditional marketing conditions (Struben and Sterman, 2008). Whilst the studies provide an analysis of high level impacts, none of the studies accounted for who in the population may be impacted by any changes in the opportunity for car ownership incurred by the policies or scenarios.

Infrastructural development has been moderately addressed, and it was found that this needs to occur rapidly. Kohler et al., (2010) suggest that for HFCV market penetration, hydrogen fuelling stations are needed before vehicle availability, and this could be achieved at relatively low cost. However, attention should be paid to the ratio of infrastructure to vehicles (Janssen et al., 2006; Boksberger et al., 2012), and home charging is required (Struben and Sterman, 2008).

Market competition and collaboration is important for technology innovation (Stasinopoulos et al., 2012; Boksberger et al., 2012), and policies aimed at manufacturers are recognised to be required for success (Walther et al., 2010; Leiby and Rubin, 1997). As such, policies to increase R&D and expand vehicle production are important (Boksberger et al., 2012). Stretching fuel economy and emission standards and technology quotas can promote R&D and drive technological improvements (Leiby and Rubin, 1997; Walther et al., 2010). As part of this, a large and early range of LCV across segments and body types is required (Janssen et al., 2006; Leiby and Rubin, 1997; Walther et al., 2010), though the costs of doing so may outweigh the benefits, and without the correct policies may lead to dominance of one technology (Leiby and Rubin, 1997).

Furthermore, feedback between different regulations needs to be considered by manufacturers (Walther et al., 2010). Similar to the choice models, none of the studies directly considered the second-hand car market, which likely accounts for a significant portion of the population. In addition, the focus of all studies seems to be on technology uptake, and while recognising the driver to be energy and emission reduction do little to actively report on this, or consider these impacts in terms of abatement costs. Although ideally placed to inform policy development, no studies contained explicit consideration or combination of policy approaches.

2C.7 Conclusion and Research Focus

Overall, the focus of the studies varies between general forecasting to more explicit considerations such as on policy development and requirements, wider system impacts (such as environmental or energy demands), infrastructural needs and manufacturers. The assumptions made regarding technological innovation, model boundaries, specific interactions and inclusion of LCV types vary somewhat. Some studies consider generic LCVs through assigned attributes (such as drive range, performance, fuel availability) whereas others may concentrate on specific technologies. Impacts that are often considered in addition to vehicle attributes are the provision of infrastructure, pricing structures and projections, and government policies. A significant share of this work is based in California, which has several state laws driving the uptake of cleaner vehicles. Few studies are concerned with wider interactions such as traffic/spatial impacts, the automobile industry, fleet considerations, public transport or second-hand purchases. There is a lower coverage of biofuels, possibly as it is already being introduced into conventional fuels, so customers do not have much choice towards them. All the above studies suggest that cICEV will continue to dominate in the immediate future due to its current strong and widespread existence and infrastructure, as well as the higher costs and deficient attributes associated with LCVs. Despite this, most studies agree that under the right conditions, a slow but successful introduction of LCVs is possible that will eventually lead to a decrease in emissions. These conditions vary, but include technological improvements, behavioural change, infrastructural provision, realising economies of scale, industry commitment and, most importantly, strong and co-ordinated political support.

2C.7.1 Model Limitations

No model is a perfect replication of the system or process it is representing. A modeller will always be bound by project restraints, whether it is in terms of resources (e.g. time, man-power, computing ability), lack of available data, or lack of knowledge (of the modeller themselves, or generally within disciplines). All models are subject to assumptions that have to be made in response to these limitations. This should be remembered when studying any model with empirical outputs or elucidated policy recommendations. The time-scale of a model could have a significant impact on reliability of results – too short and there is not enough time for policies to take effect, but too long and results may be unrealistic. Most models are based on data that is specific to the design, time and space where they were carried out. Specifically regarding LCVs there has been rapid development in both technological improvement and environmental conscience over the past decade. As people's behaviour and attitudes evolve there is need for continual updates of choice models based on SP and RP data. Furthermore there is still a gap in methodological understanding of underlying mathematics and cognitive processes. These considerations may place a significant burden on the permissibility of using modelling in policy appraisal.

2C.7.2 Difficulties in Study Comparisons

Table 2.5 presented a selection of LCV uptake model studies, but demonstrates the clear diversity that exists between studies. In addition, the underlying assumptions or boundaries within the models, are not always explicit. The variety in other model aspects, such as terminology, the timeframe considered, the policies and infrastructure accounted for and even the units used (e.g. sales, registrations, vehicle parc) all combine to make any meta-comparison extremely difficult. An example of this problem is obvious when looking at the attributes used to describe the technologies and to explain purchase behaviour. These can be roughly divided into three categories: physical characteristics, monetary implications and technical specifications and are shown in Table 2.6.

PHYSICAL	MONETARY	TECHNICAL
Body type	Purchase cost	Range
Size	Operating costs (annual or	Fuel efficiency
Class	rolling, fixed or variable):	Speed/Acceleration
Seating capacity	Maintenance	Fuel availability
Storage capacity	Fuel	Emissions
Age	Taxes	Refuel characteristics
Range of models	insurance	Engine size/power
available	Other incentives (e.g.	Safety and Reliability
Aesthetics	warranties)	Driveability (smoothness)

Table 2.6: Examples of attributes used in studies

Included attributes depend on the objective of the study, the resources available and the level of detail required. Most studies cover body type/size, purchase and operating costs (the latter may be just overall rather than the component parts), speed, range, acceleration/power, fuel availability and emissions. These are perhaps the most disparate attributes from conventional vehicles, and thus will affect uptake most significantly. Each study then includes some of the other variablesand to further complicate comparisons, there are country variations..

2C.7.3 Research Focus

It is the purpose of this thesis to develop a method that can identify the impacts of policies on different groups in society, and from this establish the acceptability of the policies. The chosen type of model in this research is System Dynamics (SD) that incorporates both a choice and diffusion model within it, allowing the study of feedbacks and changes over time. It is not the intention of the work to create a new model for this purpose, but to utilise existing, proven models. In summary of the findings from the SD studies previously presented, research gaps to be addressed are that there have been no UK based studies, the focus seems more heavily on technology take up than specifically emission reduction, impacts on individual groups or segments regarding opportunity for car ownership are not identified and none have explicitly compared or combined policies on supply and demand sides. Furthermore, the model must be one where policy scenarios reflecting the identified generic policy types (see 2B.5) may be replicated. Leading from this, this research will address three research gaps:

- Develop a UK SD model of LCV uptake by using the existing UK choice model developed by Batley et al (2004).
- Identify impacts on societal segments.
- Be able to implement combined supply and demand policy approaches within the model.

Choosing a base model for a case study is limited by availability and access to the existing models. As such, two models have been chosen for extension into case studies. A UK model was developed using Struben and Sterman (2008) as a base model. This was chosen as it is a simple model and so will allow focused exploration as skills are being developed, and due to its time-frame can be used to assess long term impacts. Walther et al (2010) forms the basis of case Study Two. It already has comprehensive coverage of the generic LCV uptake policy *Regulation*, but can be adapted to include market/society segments and calculate carbon abatement costs. As it is not possible to address all research gaps within this research, these are areas for future research. The most obvious of these would appear to be the inclusion of the second-hand car market, as this could have significant ethical implications, assuming that this overlooked portion of the automobile market constitutes not only the majority of society but also because the new car market likely consists of the most affluent.

PART D: ETHICS AND EQUITY

2D.1 Overview

Central to this thesis is a concern about fairness and responsibility. Scientific evidence would seem to support the view that climate change is likely to cause harm to both humans and the environment, and that the build up of greenhouse gases in the atmosphere originate from anthropogenic activities. This would suggest there lies a responsibility to decarbonise our society where possible, through technological and behaviour change brought about through political movement. The obligation to do so is perhaps greatest in the case of non-essential activities. This brings to mind many questions concerning what can and should be avoided, how different people will be affected by policies and technologies enforcing this and what other problems may arise from new policies or technologies.

This section is a literature review of the ethics related to low carbon vehicles (LCVs). It starts with an introduction to ethics and overview of established theories of justice that form the basis of many political structures in the Western world. Following this, the area of environmental ethics is considered, before looking specifically at the increasingly debated topic of the ethics of climate change. Finally an overview of how ethics has been applied to the area of transport is then presented.

2D.2 Introduction to Ethics

In very basic terms, ethics is the study of how to live, by understanding what is right or wrong and what our goals should be. It is a branch of philosophy, the pursuit of understanding of the nature of things. Ethics is often referred to as moral philosophy, as morals and ethics are normally taken as interchangeable within philosophy.[26]

[26] This note is made now as often (and specifically outside scholars of philosophy) a distinction does exist (implicitly or explicitly) that ethics is more of a general, accepted set of terms for a specific group of people, whereas morals are something more personal, perhaps related to one's own religious or personal beliefs. On exploring both stances, the argument for a distinction diminishes as there is no logical reason why it should be that your personal view of good and bad should depend on your situation.

There is no single unified moral theory agreed by scholars, but there are distinct groups. Arguments between the groups as to why a certain action may be right (or wrong) add to the richness and diversity of western political philosophy forming the basis of our institutions. However, these theories are often in conflict, and although one may agree with a particular theory in one instance, it may be rejected in another. Alternatively, one may have different values that are in conflict within the same theory. Moral philosophers explore such conflicts, attempting to reconcile them and develop consistent theories.

There are limits to ethical theories. A key assumption is made that the actor within a situation will act logically, and often an utopian idea of society or unrealistic scenario is in place. It can however be viewed as analogous to the scientific practise of laboratory experiments (Lawlor, 2013). Such tasks are carried out under unrealistic, non-real-world conditions, often seeking to understand the interaction or response of a particular element. In scientific theory and calculations, ideal conditions are also assumed.

There are four established approaches to studying ethics (Thompson, 1999). *Descriptive* ethics is the study of what is believed in any particular society, describing the moral choices and values. *Normative* ethics addresses the norms of how people ought to act, and asks what our moral duties should be. *Meta-ethics* considers the language, nature and justification that is employed when discussing ethics (to provide clarity on what is meant in normative ethics). Finally, *applied* ethics takes the core of established ethical theory and applies it to practical real-world situations and problems. The most developed areas of these are medical ethics, business ethics and environmental ethics.

For the purpose of this thesis, the interest lies in applied and normative ethics, seeking to establish the acceptability of certain political approaches towards the introduction of LCVs. In order to develop any claims towards this, it is necessary to understand the normative approaches that are available, which are in three broad areas (Hursthouse, 2012): *Virtue* ethics, *Deontology* and *Consequentialism.*

Virtue Ethics

The basis of modern philosophy can be dated back to the classical Greek philosophers. These thinkers, specifically Aristotle, did not distinguish between arts and sciences as we do now, but thought of life as a whole, and that it is our duty, or purpose, to flourish by pursuing "*eudaimonia"* (meaning the good life). This is achieved by behaving virtuously. However, to behave so requires us to possess practical wisdom and be both rational and reasonable in our decision making, as Aristotle defines virtue as, *"A state of character, concerned with choice, lying in a mean… between two vices"* (Aristotle, 1998, p.39). Following this, a decision is only virtuous if it is what we desire to do, not because we think it is the right thing to do or fear repercussions of doing the wrong thing. Objections to virtue ethics have arisen as it seems to be more 'agent-based' describing how a person should be, rather than 'act-based' and provide advice on what to do in a given situation, that it cannot provide guidance on conflicting dilemmas, and that it may be subject to the culture that the agent is in (Hursthouse, 2012).

Consequentialism

Consequentialism is a branch of ethics that suggests that the moral permissibility of an action is dependent upon the consequence or outcome of that act. Consequentialism has many forms, but the paradigm case is classical utilitarianism. This is also known as hedonistic act consequentialism, and dictates that the morally right action is the one which maximises the total good, and that good is measured in terms of pleasure or happiness (Kymlicka, 1990). This approach appeals to many people as it has (on the face of it) a simple, empirical approach to ethical decision making. Utilitarianism developed in the late 18th and 19th Century's through the work of Jeremy Bentham and John Stuart Mill (Darwall, 1998). There are also numerous criticisms of consequentialism, and particularly utilitarianism. These include questions around what is good or what consequences count (e.g. actual or expected), and notions that it can overlook justice and rights or that it demands too much (Sinnot-Armstrong, 2012). Two particularly notable issues are;

1. It fails to pay sufficient respect to individual persons. We may be required to perform an act conflicting with a deeply held interest, and within the calculation of 'greatest good' persons are reduced to isomorphic entities and risk losing identity and autonomy (Scheffler, 2003). For example, utilitarianism might suggest that it would be the morally correct action to kill one person to save others.[27]

[27] A classic example of this dilemma is should one healthy person be killed to provide life-saving organs needed by five ill persons.

2. It is unrealistic to be able to perform a calculation taking into account so many different parameters, some of which are not obviously empirical, and that we cannot control (Williams, 1963). This becomes more of a concern depending on how we value utility, and how we measure it, as pleasure, preference satisfaction, or an accessible proxy for this.

Deontology

In direct contrast to consequentialism, deontological ethics are based on duties or principles that tell us what we should or should not do. It is a response to the claim that we cannot be responsible for the consequences of our acts as they are not within our control – only the decisions on which we act are within our own control. Alexander and Moore (2012) claim that there are three main branches to deontology, being ‘agent-centred’ (accepting responsibility for one’s individual agency), ‘patient-centred’ (rights-based) or ‘contractarian’ (a morally right act is one that would be accepted under a social contract). There are various weaknesses to deontology (and the specific branches). Although it is not necessary to go into these in detail here, they mainly arise from *“the seeming irrationality of our having duties to make the world morally worse”* (Alexander and Moore, 2012) i.e. the duty may lead to a horrendous outcome. The most prominent philosopher in the field of deontology is Immanuel Kant, who tried to ground his theories in both logic and reason, without considering desires, happiness or consequences. Kant argued in his “Critique of Practical Reason” (1788) that there are certain principles (“maxims”) on which one must act, the strongest of which being *“categorical imperatives”* – those maxims which should be universal for any person under any conditions (for example, ‘do not kill another person’).

2D.2.2 Theories of Justice and Political Philosophy

Although ethical theories consider many aspects of justice, such as rights and fairness, and inform discussion with compelling arguments for how one should act, they may be limited in their ability to suggest how society should be structured. Political philosophy is the study of what ought to be a person’s relationship to society, and what rules and institutions should guide that (Moseley, 2005). Theories of justice inform the debate on the fair distribution of goods, and respect of individuals rights, and justice itself is thought to be “*the most political or institutional of the virtues*” (Ryan, 1993, p.1).

Particularly of interest in this work is the idea of distributional social justice brought about by political institutions. Theories of justice have evolved as humanity progresses, and still differ between individuals and cultures. Although the discussed ethical theories inform political philosophy and theories of justice, there are numerous other established theories, including egalitarianism (or liberal equality), libertarianism, Marxism, communitarianism and feminism (Kymlicka, 1990). Utilitarianism has been very influential in western politics since the time of Mill, as it can be (to a degree) empirical. Utility (depending on how it is defined) can be approximately translated in monetary terms and calculated econometrically, allowing it to be considered in policy appraisal.[28] Other ethical theories also feature strongly, such as the predominance of libertarian principles in American politics. Social justice concerns, looking towards the worst-off, or the difference between sections of society are seen as important by egalitarians. Increasingly, governments attempt to take a more balanced approach, incorporating various ethical theories and values. The most mainstream theories of contemporary political philosophy are egalitarianism (as developed by John Rawls)[29] and libertarianism (as developed by Robert Nozick), so a brief overview of each is relevant.

In 1971 John Rawls argued in his *"Theory of Justice"* that political theory at the time was inadequate, as it was caught between two extremes of utilitarianism and 'intuitivism' (Kymlicka, 1990). As discussed previously, utilitarianism is subject to numerous criticisms particularly that it did not treat people as equals or respect their individual rights. Intuitivism is the idea that rights and wrongs are intuitive, but has no developed underlying theory or explicit method for reaching judgement. Thus, Rawls attempted to find a systematic alternative to utilitarianism that structures our intuitions. At the centre of Rawls's response to this was the concept of *"justice as fairness"* – that basic social justice should be able to resolve conflicts between different individual's values and goals. In order to do this, Rawls developed a "*hypothetical contract"*, in which he proposed what would be agreed should a group of persons be setting up a new society from an "*original position"*. To imagine this, Rawls asked us to put ourselves behind a "*veil of ignorance"* where "*no one knows his place in society, his class position or social status, nor does anyone know his fortune"* (Rawls, 1999, p.11). From this position, he believed that the following principles would be agreed:

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[28] For instance, through Cost Benefit Analysis.

[29] It should be noted that some scholars in recent years have argued that Rawls' focus is not pure egalitarianism but prioritisation of the worst-off.

> 1. ***Liberty Principle:*** *Each person is to have an equal right to the most extensive total system of equal basic liberties compatible with a similar system of liberty for all.*
> 2. *Social and economic inequalities are to be arranged so that they are both:*
> *a.* ***Difference Principle:*** *To the greatest benefit of the least advantaged, and;*
> *b.* ***Fair Opportunity Principle:*** *Attached to offices and positions open to all under conditions of fair equality of opportunity* (Rawls, 1999, p.53)

Rawls was interested in the distribution of goods, which he distinguished between *social primary goods* and *natural goods.* Social primary goods can be distributed by the state and include rights, liberties, opportunities, income, wealth, as well as the social basis of self respect (Mandle, 2009). Natural goods, such as health, intelligence and talents, are those which may be affected by the state but not directly distributed (Kymlicka, 1990). Behind the veil of ignorance, Rawls argued, everyone would seek the best access to social goods as they cannot determine natural goods. In doing so they would be giving equal consideration to each person. From this, Rawls argued that without knowing your position you would not argue for utilitarianism (in case you are sacrificed for the good of others). For example, as one would not know if they are a rich white male or a poor black female, they are (unlikely) to argue in favour of any bias toward affluence, gender or race. The rational choice, Rawls argues, is to adopt a *"maximin"* strategy – you would maximise what you would get if you were in the worst-off (minimum) position. This approach would allow inequalities in society only if they benefited the worst-off (or at least don't make them worse off). In this way, Rawls was also influenced by the long established *Pareto Criterion* of economics, which dictates that the welfare of a group is at an optimum when it is not possible to make any one person better off, without making any other person worse off (Rawls, 1993).

A Theory of Justice set a new standard in political theories of justice and a significant share of work on this subject since it was published has been written in response to his arguments (Kymlicka, 1990). Criticisms include (amongst many other things) issues regarding methodology, the excessive individualism and limitation to a basic structure (Mandle, 2009), but perhaps the most notable critic is Robert Nozick who offered a libertarian argument against Rawls's work.

While Rawls focuses on fairness, Robert Nozick presents an alternative theory of distributive justice, focusing on entitlements, liberty and self-ownership, in his 1974 book, "*Anarchy, State and Utopia"*. Nozick proposes that if people are entitled to the good they possess then just distribution is whatever comes about through free exchanges. This theory leads to the idea that;

A minimal state, limited to the narrow functions of protection against force, theft, fraud, enforcement of contracts and so on is justified; any more extensive state will violate person's rights not to be forced to do certain things and is unjustified. (Nozick, 1974, p.ix)

Nozick asserts that for a holding to be just, it has to adhere to three principles. The first is that the original *acquisition* (how it became to be held from being un-owned) has to be just and the second is that the *transfer* has to be just, which includes exchange or gift. If transfer occurs by theft, fraud, enslavement or prevents an individual choice it is unjust. Finally, Nozick's third principle is that of *rectification of injustice*, which can be applied if the first two principles are transgressed. Only if all holdings in society were bound by these principles would distribution be just. This can lead to a society with significant inequalities, but Nozick argues that this is irrelevant regarding the justice of the distribution (Meadowcroft, 2011). Such an unequal society would be just, as long as the three principles described above have been adhered to.

Nozick makes a distinction between an "end-state" theory of justice, where the fairness of a situation is judged on its structure at a particular moment in time, and a "historic" theory, which is judged on how that state came about. Either of these approaches may be patterned or un-patterned, depending on if the distribution was made according to a particular pattern or not. A pattern could be: *"to each according to his moral merit, or needs, or marginal product, or how hard he tries, or the weighted sum of the foregoing, and so on*"(Nozick, 1971,p157). Nozick's theory is an un-patterned historical theory of justice, rather than a patterned end-state theory such as Rawls suggests. Nozick argues that patterned theories do not give liberty proper respect, through his well-known *"Wilt Chamberlain*"[30] example:

Suppose a distribution favoured by one of these non-entitlement conceptions is realised. Let us suppose it is your favourite one and let us call this distribution D_1; perhaps everyone has an equal share, perhaps shares vary in accordance with some dimension you treasure. Now suppose that Wilt Chamberlain is greatly in demand by basketball teams. Being a great gate attraction…. The season starts and people cheerfully attend his teams games; they buy their tickets, each time dropping a separate 5 cents of their admission price into a special box with Chamberlains name on it, They are excited to see him play; it is worth the total admission price to them…Is he entitled to the income? Is this new distribution D_2, unjust? (Nozick, 1974, p.160-2)

By Nozick's reckoning, D_2 is just, as Wilts acquisition was just. From this, we see that people's free actions would allow them to make any just transfers they wish,

[30] Wilt Chamberlain was a famous American basketball player in the 1970's.

and in doing so any pattern will be disrupted. Nozick argues that the only way to prevent this disruption to patterns is to either ban certain transactions or constantly intervene in the market to redistribute property, either of which, he argues, violates an individual's liberty. Thus he rejects the notion than any patterned or end-state theory is just (Wolff, 2006).

Critics of Nozick argue that that as he rejects the rectification of inequality, it is intuitively unacceptable and may even be self-defeating as it can undermine his own values of liberty (Kymlicka, 1990). The idea of the minimal state in itself is abhorrent to some as it grants no provisions for the most vulnerable in society, whilst allowing others to legitimately squander their resources (Wolff, 2007). Nozick did not formally address his critics, and did not pursue political philosophy after *Anarchy State and Utopia*. He reportedly accepted that libertarianism is inadequate as it did not satisfactorily account for the importance of communitarianism or collective actions (Murray, 2013).

2D.3 Environmental Ethics

There are a number of unprecedented environmental challenges which we are now facing, including mass extinctions, depletion of natural resources, exponential population growth, air, water and soil pollution, loss of habitats and climate change. Much of these are the result of well meaning decisions by previous generations with unforeseen or unanticipated outcomes. As our recognition of our impact on, and interaction with, our natural environment grew, so did our questioning of our obligations towards the environment. This was particularly during the mid 20th Century through the burgeoning environmental movement, most notably following the publication of *"Silent Spring"* by Rachel Carson in 1962.

Environmental ethics is a moral relationship between human and the natural environment. It considers the value that we put on the environment, but also the morality and social justice of allocation and distribution of environmental benefits and dangers between inter- and intra-generations, non-human life and ecosystems. There are a number of theories addressing this. Anthropogenic theories assume only humans have moral value, but there is indirect responsibility to the environment in order to preserve resources. Non-anthropogenic theories argue a direct responsibility to natural objects, which are individuals deserving respect as part of a holistic system.

Theories of environmental ethics are based on established ethics and theories of justice, which raised numerous problems as they tend to be (by their very nature) anthro-centric. Applying established ethics into new ways defines issues in standard theories. However, many environmental issues required extensions to these approaches and brought about questions, which hadn't been considered before, such as responsibility to future generations and to non-anthropogenic life. It is widely accepted that the environmental impact is proportional to population size, consumption or affluence. Therefore as our population is increasing exponentially we find that we are making a bigger environmental impact. Des Jardins (2006) suggests five distinct environmental philosophies;

- *Biocentric ethics* focuses on the inherent value of all forms of life as its own good (See Schweitzer, 1949 or Taylor, 1986).
- *Ecocentric ethics* gives consideration to non-living natural objects, so as to account for ecological wholes and the interrelationships among natural objects (See Baird-Callicott, 1989 or Leopold, 1949).
- *Deep ecology* allows environmental crises to be traced back to deep philosophical causes, thus a cure will only come with a change in philosophy – in individual and culture. Deep ecology is not a philosophy but a movement encompassing both philosophical and activist sides (See Devall and Sessions, 1985 or Naess, 1989).
- *Social Ecology and Ecofeminism* have arisen from links with theories of social justice - the distribution of benefits and burdens. Social ecology considers hierarchies, domination and balance (Bookchin, 1982) whereas ecofeminism is related to a range of female perspectives on ecological issues, linking oppression of women and oppression of the natural world (See Merchant, 1990; Plumwood, 1992 or Warren, 1987).

2D.4 Climate Change Ethics

Although politically controversial in some regions, climate scientists agree that humans are responsible for contributing towards climate change, and that it will harm a significant number of people across the world, both those alive now and future generations. However, the extent that humans can be held accountable and how to respond is a much disputed ethical debate. Climate change poses a number of philosophical challenges as it addresses responsibility, justice, rights and harms. Climate Ethics is an emerging field, leading from established ethical theories, which has gathered momentum alongside public and political interest in climate science.

A number of ethicists believe that it is the interdisciplinary complexities of climate change that proves to be the greatest obstacle. For example, Stephen Gardiner terms climate change as a *perfect moral storm* due to *"the convergence of a number of factors that threaten our ability to behave ethically"* (Gardiner, 2006, p.398). These arise in global, intergenerational and theoretical dimensions, and comprise of the dispersion of cause and effects, fragmentation of agency, institutional inadequacy and moral corruption. Others suggest that we need to develop new values and conceptions of responsibility to motivate people to respond to climate change (Jamieson, 1992), or fundamentally change certain views on morality (Attfield, 2009; Baird-Callicott, 2011). Moreover, accountability for our choices and actions are all still in much debate in the wider applied ethics community. The case for individual responsibility is explored by many authors (Butler, 2010; Cripps, 2011; Garvey, 2011; Hartzell, 2011; Hillar, 2011; Hourdequin, 2010; Nolt, 2011; Schinkel, 2011; Sinnot-Armstrong, 2005) and covers a number of arguments such as over-demandingness requiring unreasonable sacrifices, ineffectiveness of impact of individual actions, the importance of individual action and intention (virtues) and lock-in of carbon intense lifestyles and infrastructures.

Further issues within climate change ethics include the economic case for and against acting (Lomborg, 2001; Stern, 2006), the considerations of uncertainties within climate modelling predictions (McKinnon, 2009) treatment of inter-spatial and inter-generational impacts (Caney, 2009; Helm, 2011; Moellendorf, 2009; Okereke, 2011; Parks and Roberts, 2010), the difference between subsistence and luxury emissions (Odenbaugh, 2010; Shue, 1993) and our requirement to not *"do nothing"* (Garvey, 2008). Aside discussions of responsibility and obligation, there are those papers concerned more with the inadequacy of current political philosophy, particularly liberalism (Bell, 2011; Gardiner, 2011a; Hailwood, 2011). There is a specific interest around the appropriateness of carbon trading schemes, which may be risky in terms of distributional justice (Caney and Hepburn, 2011; Hyams, 2009; Page, 2011). There is also gathering work regarding the role of technology (Gardiner, 2011b; Hale and Grundy, 2009) and responsibility of engineers (Elliott, 2010) as well as specific policy approaches This literature review is not designed to be an in depth discussion of climate ethics, but accepts that majority of the gathering catalogue of work on this subject generally agrees that Western governments are morally obliged to take action to prevent or restrict carbon emissions and work towards both climate change mitigation and adaptation. This point is emphasised by the inclusion of moral philosophy in the upcoming IPCC 5th

Assessment Report, and the consequential appointment of the moral philosopher John Broome as a lead author. Alongside this there is a less established claim that individuals are obliged to reduce personal emissions but obligations lie more strongly towards ensuring that governments are successful in fulfilling their obligations to implementing climate change mitigation policies and, once in law, to follow legal policies, as described by Cripps (2011).

2D.5 Ethics and Equity in Transport

There is very little literature explicitly discussing ‘transport ethics’ as a subject of applied ethics, though themes of ethics and equity often arise within the discipline of transport studies. On the other hand, there is also little literature in the realm of transport studies regarding ethics from a philosophical perspective (van Wee, 2011a). Perhaps one of the reasons for this is that transport studies itself is a relatively new genre of academic study (Hibbs, 2000), bringing together aspects of multiple disciplines, from sociology to engineering, environmental, political and economic sciences to psychology and health. Despite transport being an integral part of life for centuries, it was not recognised as a distinct integrated political concept by UK Government until the Transport Act 1962 and the first academic journal devoted to transport, the Journal of Transport Economics and Policy, was produced in 1967 (Hibbs, 2000).

Transport is the practise of moving goods or people from one place to another. In this way, transport itself can be viewed as a good. Indeed some would argue that society has a crucial dependence on transport (Hibbs, 2000; van Wee, 2011a). It provides mobility and accessibility to individuals, which are often argued to be key elements to autonomy, itself a necessity of being human. A number of authors seek to define accessibility and mobility, identifying that although they are often used interchangeably within a transport policy context and that although there exists complex relationships between the two terms, they refer to distinctly different concepts (Gutierrez, 2002; Handy, 2002, Martens, 2012; Ross, 2000; Salomon and Mokhtarian, 1998). Mobility is the state of being capable of movement, whereas in a sociological context it is the specific movement of people (spatially or socially). Accessibility is the ability to be able to enter or reach a destination or activity. Therefore, it is perhaps more accurate to say that transport (and car ownership) is the means to these more essential goods of mobility and accessibility. As will be discussed later, Martens maintains that accessibility is more of a ’good’ than mobility as it is more related to basic needs, and many studies appear to agree with this approach by focusing on accessibility in the context of social justice (Farrington, 2007; Geurs and van Wee, 2004). On the other hand, mobility remains a critical concern, for instance as Stantchev and Meret (2010) suggest, *'increased mobility leads to increased accessibility'.* This work takes these views into account and adopts the approach that the importance of the car is primarily related to the accessibility which is provides, but mobility is not without its importance as it is part of being an autonomous being.

There are many applications for ethics within transport, and many ethically relevant questions, such as where, why and how are we moving. What seems clear is that to answer any of these questions some system of value and judgment must be devised, and in doing this, concepts of what is good or bad are employed, implicitly or explicitly. Thus, transport is a valid field for applied ethics. Though transport, mobility and accessibility are not widely discussed in ethics or philosophy, there are relevant discussions being carried out in more established areas. For instance, general debate on justice and politics can inform decision making processes for larger transport projects. Discussion on medical ethics may be relevant to the health and safety impacts of transport in our lives. Engineering ethics inform the practises of civil, mechanical and electrical engineers who develop infrastructure and vehicles. Environmental ethics requires that not all transport projects remain human centred.

There are both benefits and risks associated with transport: "*Mobility and transport sustains life and provides a necessary condition for living well. Transport also presents threats to lives and the environment."* (Mullen, 2012). Further to this, decisions about transport policy that may lead to inequalities is relevant to many ethical debates. In transport literature the major areas of discussion in relation to ethical dimensions are *"social exclusion, distribution effects as recognised in economics, and some reflection on the mobility system or the car-dependent society from a sociological perspective*." (van Wee, 2011a, p.2). More usual in transport literature, terms such as distribution, equity or fairness will be used, perhaps reflecting the sociological, rather than philosophical basis of the discussion. A significant portion of work in university transport study departments is related to policy and planning, informed by modelling of choices, networks and impacts, and by applying established analytical processes such as cost benefit analysis or multi-criteria analysis. All of these are to subject to ethical debate.

In this literature review, it is not the intention to provide an in-depth discussion of transport ethics, but to present a brief overview of works relevant to this thesis, some of which will be explored in more detail in the main body of work. There are two broad areas within this, automobility and transport policy appraisal.

2D.5.1 Automobility

It is not controversial to say the car dominants transport in the UK, where over 75% of households have a car (Lucas and Jones, 2009). This dominance has environmental, economic and social impacts, though in the literature these tend to be addressed from an anthropocentric viewpoint. Over the last century the car and society have co-evolved, embedding themselves into each other (Lucas and Jones, 2009; O'Connell, 1998). This provides many benefits to both users and society, but also many disbenefits, highlighted in Figure 2.18. Other reasons for a move away from car-dominance include safety and freedom of other road-users, the closure of local services and businesses and the decline of social cohesion (Sloman, 2006). There are those that argue that this dominance is already receding, due to recognition of the disbenefits, coupled with peaking oil supply and increased use of ICT, there is evidence to suggest that we have reached a time of ‘peak-car’ in developed countries as growth in car ownership is slowing and the youth applying for driving licences are declining (though it is noted that there is debate on why this is the case, prohibitive costs are thought to be a factor) (Goodwin, 2012).

	Benefits	Disbenefits
To users	• Freedom to travel where & when desired • Cheap travel at point of use • Access to wider range of goods and services • Ease of movement (for passengersd & goods) • Sense of power & identity	• Costs of car purchase and maintenance (if on low income) • Stress of driving • Lack of physical exercise • Chauffeuring requirements • Traffic accidents
To society	• Expands labour and customer markets • Facilities greatere diversity of skills and activities • Important manufacturing and service sector	• Conjested road networks • Contributions to local air and noise pollution • Contribution to CO_2 emissions • Car-based developments preclude non-car access

Figure 2.18: Benefits and disbenefits of car use (Lucas and Jones, 2009, p.91)

The place of the car in our society has been well discussed from a geographical and sociological viewpoint. The RAC Foundation in particular have released a number of reports relevant to discussions on automobility in the UK, including access and ownership (Cairns, 2011; Leibling, 2008), and its role in society (Lucas and Jones, 2009). The impact of automobility (as part of broader transport discussion) on social exclusion is a focus of a number of studies and may be related to age, gender, disabilities, poverty or urbanisation, amongst other concerns (Bonsall and Kelly, 2005; Farber and Pajez, 2009; Lucas, 2012; Preston and Rajac. 2007; Priya and Uteng, 2009; SDS, 2011). Social exclusion can be defined as:

> *"…a multi-dimensional concept, the process of the interplay between a number of factors, unique to the individual or group, the consequence of which is a denial of access to the opportunity to participate in the economic, political and social life of the community. The process not only results in a diminished material and non-material quality of life, but also in tempered life chances, choices and a reduced level of citizenship."* (Kenyon, 2002, pp.99-100)

It is not felt necessary to review this literature in detail for this research. It is sufficient to accept the generally accepted concern of these studies that social exclusion is a too-long overlooked aspect of transport policy, which has been strongly influenced by the increased lock-in to automobility. However, due to this lock-in, it is also recognised that social exclusion can be exasperated if transport policies result in increased disparity in the opportunity for car ownership between social groups. For example, Priya and Uteng (2009) found that the costs associated with obtaining a driving licence in Norway lead to employment and social exclusion for certain racial groups, and Bonsall and Kelly's 2005 study identified groups that would be at-risk of social exclusion if road-user charging is introduced. Indeed, a key driver for this work, which will be addressed in the development of the ethical framework, is to minimise the impact of LCV policy on the opportunity to own and use vehicles in vulnerable groups.

Within this, however, we must also acknowledge the widening interest in the car as an emotional and cultural artefact, and as such, its position in society may be much more than just a means to access and mobility, with important symbolic attributes. For example, Steg (2005, p.160) identified the significance of non-instrumental car-use in Rotterdam through a survey, concluding *"people do not only drive their car because it is necessary to do so, but also because they love driving"* and car ownership in pre-war Britain had a crucial position in signalling *"social position, taste, status and gender identity"* (O'Connell, 1998, p.221). Featherstone, Thrift et al (2005) presented a number of compelling papers regarding automobility discussing topics such as how the car has become emotionally embedded in our national identities, lives and culture, and the role of the car in social change.

There has only been a little consideration of automobility within the philosophical community, which will be discussed more fully within the development of the ethical framework. The ethics of driving was discussed by Rajan (2007), Lomasky (1997) considered the link between automobility and autonomy, Wood (2009) explored the role of the car within the rights to travel, and Duvall et al., (2002) claimed that zero emission vehicle mandate policies caused infringements of liberties.

The distributional impacts of car-related policies are being increasingly recognised in specific transport literature, though without explicit reference to ethics. Wadud et al., (2008) modelled a transport carbon permitting scheme that suggests credits spread equally between all individuals results in the greatest benefit to the poorest. The impact of the Stockholm congestion pricing was considered by Eliasson and Mattsson (2006), who reported that the richest third would lose around 2.5 times more than the poorest third. They add that if this revenue were to go on public transport, the scheme would then benefit the worst-off. A report for the DfT on the social and distributional impacts of climate change policies found that LCV uptake fiscal measures may cause an unequal distribution of impacts as they tend to favour higher income groups (Skinner et al., 2011). In contrast, Johnson et al., (2012) suggested that motoring taxes fall most heavily on medium income households. Recognising these problems, Skerlos and Winebrake (2010) suggest targeted subsidies aimed at lower income would increase PiHEV take up at lower cost and higher social benefits.

2D.5.2 Transport Policy Appraisal

Many aspects of transport studies are concerned with modelling, policy and planning. The ethics related with political decision making are widely explored outside of transport and, although they are transferable, will need expansion because of the more complex set of stakeholders, benefits and risks that transport programmes may have relative to other public projects. The philosophy and ethics of modelling (Martens and Hurvitz, 2009; Rabins and Harris, 1997; Timms, 2008) and practises such as cost benefit analysis (CBA) (Gardiner, 2011c; Kelman, 1981; Schmitdz, 2001) is an emerging field within this. One of the main criticisms appears to be the implicit utilitarian stance that such practises take and as such are subject to the concerns that are raised against utilitarianism as a political construct. Also, even though such practises may seem systematic, they are in fact "*unexamined decision-making*" (Kelman, 1981) due to implicit assumptions within them, such as the ability and acceptability of quantifying risks and benefits economically, and weighting or inclusion of certain morally relevant criteria. A number of authors are now attempting to address such criticisms, not just in transport but in other areas of public policy, particularly within health care (Harris, 1997).

One of the most prominent authors in recent years within transport ethics is Bert van Wee, who, in addition to numerous journal publications (van Wee, 2011b; van Wee and Geurs, 2011; van Wee et al., 2012; Van Wee and Molin, 2012; van Wee and Rietveld, 2013) has produced the only book known to this author that directly addresses this area (van Wee, 2011a). Van Wee is from a transport policy background, but is attempting to bring in explicit ethical theory into the deficiencies or arguments he has identified in practises such as cost benefit analysis, from an ex-ante perspective. By doing so, he believes that policy makers may overcome perceived limitations. Karel Martens approaches transport planning from the perspective of social justice, claiming that transport appraisal should be based on need rather than demand and that CBA is biased towards already highly mobile groups so should be based on accessibility rather than time-savings (Martens, 2006). Furthermore, he applies Walzer's *"Spheres of Justice"* (Walzer, 1984) to transport planning (Martens, 2012). Walzer proposes that primary goods as suggested by Rawls can be separated into distinct categories of goods, and Martens argues that transport is one such category (see Section 3A.5.3).

Attempts have been made by other authors to incorporate ethics or equity into transport appraisal by combining approaches such as multi-criteria analysis (MCA) and CBA alongside explicit consideration of equity perspective options (Litman, 2013; Thomopoulos and Grant-Muller, 2013; Thomopoulos et al., 2009). These perspectives are expressed in terms of horizontal or vertical equity, where horizontal equity is the method of distribution between groups equally and vertical equity concerns distribution relative to circumstances, needs or abilities. Khisty suggested six different principles of distributive justice that could be adopted in transport projects (Khisty, 1996):

- *Equal shares* – distribute benefits equally between relevant groups;
- *Utilitarian distribution* – seek the greatest overall utility;
- *Egalitarianism* – treat all humans equally and distribute according to need;
- Distribution based on maximising the average net benefit with a *minimum floor benefit* of X units or *benefit range constraint* of X units;
- Rawls *Maximin* strategy (see 2D.2.2).

2D.6 Conclusion and Research Focus

The field of ethics, and its many relevant branches of philosophy (justice, distribution, rights and politics), is a complex and evolving field of study. This literature review has only touched the surface of the field to prepare the context of the wider thesis. Although the sub-genres of climate and transport ethics are less developed, this does not make them any easier to approach in this work. This thesis is interdisciplinary in nature, with ethical consideration forming one of three constituent parts to the methodology. Ethical theory will be applied to develop a framework by which policies identified within the model should be assessed. This framework is to take the form of seeking a balance between climate change obligations and accessibility or mobility rights when it comes to the introduction of low carbon vehicles. These ideas will be explored further in the next Chapter where the ethical framework is developed.

There is already a well-developed body of work on ethics and theories of distributive justice that can be adopted in order to defend the framework, and development of any new or refined theory is beyond the scope of the thesis. The approach that will be taken is one that uses the status quo as a starting point and assumes that this situation is already unjust to some extent. From this starting point, the ethical framework will be developed in order to improve on this, with respect to the welfare of those who are already worst-off, by aiming to avoid (or minimise) the amplification of injustice. In this way, the work is influenced by the egalitarian theories led by Rawls.

As there is also a significant amount of work already being carried out regarding the ethics of climate change, these arguments will be incorporated into the development of the ethical framework. Although there is a reasonable amount of literature in the social sciences regarding automobility, there is very little philosophical literature on this subject and none directly addressing the introduction of LCVs (at least from the point of view of climate change), so this area will be explored more fully from an ethical viewpoint. This part of the research will be a novel contribution to much-needed development of the field of applied ethics regarding both climate change and transport. Finally, the ethics and permissibility of appraisal and modelling in policy decision-making will be considered. There is a burgeoning field of discussion on this, currently focused around CBA, so any output from this work will make a worthwhile contribution to this debate.

PART E: CHAPTER SUMMARY

This literature review was divided into four subject areas reflecting the interdisciplinarity of the thesis, and demonstrated the complex interrelation between these disciplines. The act of carrying out the review has made an important contribution to achieving the thesis objectives and has confirmed that the concerns raised are valid ones that have not been fully addressed in previous work. The remainder of this thesis explains and integrates the four strands of this literature review and in doing so this research could make a novel contribution to the advancement of understanding LCV adoption and policy appraisal. The following issues, which were established in this Chapter, form the focus of the research:

- Vehicles with electric motors may offer the greatest potential for emission reductions. Barriers of high cost and different attributes than ICEV need to be overcome to gain successful market penetration over the next decade and into the future.
- Five generic types of LCV uptake policies were determined. *Fiscal Measures* and *Regulation* are currently being given the most attention.
- No current system dynamic models are UK based or explicitly consider distributional impacts of LCV uptake policies, and few compare supply and demand side policies within the same study.
- There is a distinct research gap in the ethical consideration of LCV uptake policies in both philosophical and transport literature, and the debate on the use of modelling within transport policy appraisal is currently in its infancy.

In addressing these issues, an ethical framework for LCV uptake policies is created that will encourage consideration of distributional impacts of EV uptake in the next decade as well as addressing the permissibility of models in policy prescriptions. Modelling case studies are then developed to cover the research gaps and test policies within the framework. Following this, an approach to developing an improved modelling and appraisal framework is proposed alongside recommendations for policy.

CHAPTER THREE: THE ETHICAL FRAMEWORK

The purpose of this Chapter is to consider the ethical implications of the introduction of Low Carbon Vehicles (LCVs) and the role of modelling in policy appraisal. From this an ethical framework for LCV policies is developed in order to be implemented alongside the modelling that is also carried out in this research. There are two Parts to the Chapter. The first Part takes a philosophical approach, establishing the permissibility of modelling in policy appraisal and two claims related to LCV polices. The first claim is in defence of coercive policies due to the potential harms of climate change, and the second claim calls for the rectification of injustices that may arise from such policies. In Part B, the elements of the framework established in Part A are subjected to a pre-modelling empirical evaluation, combining quantitative and qualitative approaches. It describes a workshop and survey that was carried out to understand if there is support of the claims by experts in the field of LCVs, and also identify the potential impact of the generic polices established in Chapter 2 Part B on the average cost and utility of car ownership.

PART A: ESTABLISHING AN ETHICAL FRAMEWORK

3A.1 Introduction[31]

It is the concern of this thesis that although Low Carbon Vehicles (LCVs) are necessary to reduce carbon emissions, that policies for the uptake of LCVs may cause issues of distributional justice in society. This Chapter sets out an ethical framework that recognises the need to minimise climate change on one hand and the impact that low carbon vehicle policies may have on the other. I take a pragmatic approach to exploring the relevant moral aspects of policy-making regarding low carbon vehicles, suggesting what issues of justice should be considered in these policies and how the policy appraisal processes can be improved. By considering both of these together, this Chapter highlights an important link between parts of policy-making.

In this work, the focus is 'real-world' policy appraisal for the short-term, over the next decade. Using the 'status-quo' as a starting point (or baseline), and assuming that this situation is already unjust to some extent,[32] I am concerned that carbon reduction policies may amplify existing injustice. The aim of this Chapter is to explore ways to avoid (or at least minimise) this occurring and develop an ethical framework on that basis. The ethical framework I seek to develop in this Chapter is one that not only defines what type of policies are acceptable in the promotion of LCVs but also what exceptions, or provisions these policies may require to prevent distributional injustices. *Regulation* and *Fiscal Measures,* the two policies identified in the literature review to focus on, are both coercive policies as they force people to act in an otherwise involuntary manner. Although *Regulation* is aimed at manufacturers, the coercive effect follows through to customers as their choice or opportunity for car ownership becomes biased towards LCVs. In this ethical

[31] Although writing in the first person may be unusual in the sciences, it is the common approach in philosophy, as one is putting forward one's own views and arguing why they are legitimate. Therefore, Part A of this Chapter will retain a first person stance.

[32] By 'unjust' I mean that some people have more access to goods than others leading to an unequal society, arising from differences in wealth, opportunity and ability. I do not believe that this assumption is controversial. I am not concerned with how these differences have arisen, or the extent of the inequality simply accept that they do exisit and should be addressed. This is an 'end-state' view of justice as advocated by Rawls (see literature review). I do not in this research seek to reduce injustice or inequality to zero, but, as described in this chapter, to prevent the level of the worst off from being reduced from its current level.

framework, the focus is on the customer, though I accept that in future work, the arguments should be extended to consider manufacturers. Models used in policy evaluation tend to focus on measurement of an overarching objective without assessing the risks they may impose on an individual level and do not tend to contain explicit consideration of how the policies may impact on social justice. In this Chapter, I explore what these impacts may be and suggest how the appraisal process should be amended.

Firstly, I investigate claims of justice related to LCVs. The first claim I address argues for coercive polices that promote the introduction of LCVs due to the harms of climate change, through an appeal to a generally accepted harm principle, before drawing parallels to Garrett Hardin's 'Tragedy of the Commons' (1968). In the second claim, I concede that such coercive policies should minimise unfair burdens on the most vulnerable, considering issues of distributional justice that may arise. Within this, I explore specific claims for car ownership, drawing the conclusion that there exists a valid claim that some groups (such as the less physically able or the poor) are more sensitive to change in the opportunity for car ownership. They therefore may need special consideration within the policies allowed by the claim for coercive policies. I explore what form this may take through consideration of the work of Jonathan Wolff (2011) and Michael Walzer (1984) on market regulation, and by drawing comparison to existing policies.

My interest then turns to the crucial question of how policies in response to these claims can be assessed and chosen in practise in a policy appraisal process. I am concerned that such policies may be assessed in light of their contribution to carbon reductions but without sufficient focus on the issues of distributional justice I have identified. Key to this process is modelling, but as I seek to demonstrate, this is constrained by a number of parameters, including design, boundaries and cognition, but most notably recognition of the relevant moral considerations. Nonetheless, modelling is an important tool in policy appraisal, and has already been widely applied to the subject of low carbon vehicles. Despite this, the permissibility of modelling in policy making has had little discussion in ethical literature, unlike another tool, Cost Benefit Analysis (CBA) (Gardiner, 2011c; Harris, 1997; van Wee, 2011a). In this Chapter I suggest, through comparison to CBA, how models used to support LCV policy decisions can be developed to take account of ethical implications of policy. From this, I propose a methodology for modelling in my own work.

3A.2 Background

At the centre of this research is a concern about the harms of climate change caused by carbon emissions associated with anthropogenic activities. I believe, as many others do, that these burdens can only be mitigated through interdisciplinary collaboration. This work focuses on the transition to LCVs. My concern is that we are currently locked-in[33] to infrastructure, attitudes and lifestyles built up around car ownership, and those who are most legitimately dependent upon car ownership, are likely to already be amongst the worst-off. Thus if climate change policy reduces the opportunity for car ownership in these groups, it may not be morally permissible, requiring adjustment or compensatory measures.

Before starting the discussion I will stipulate the assumptions that frame my arguments. These include empirical and non-empirical assumptions and judgements, which I think are reasonably uncontroversial on either a scientific or ethical basis, and most have been discussed in more detail in the literature review.

- Climate change, that will result in significant harm and death to living things,[34] is occurring, is set to increase, and is due to anthropogenic carbon emissions, with a significant contribution from the road transport sector.
- Developed carbon-intense countries, such as the UK, are responsible for the majority of both historic and present carbon emissions and as such governments have a moral obligation to reduce emissions due to the harms of climate change.[35]
- Low carbon vehicles (including their production and dismantling phases and all fuels and power supplies) are a technically feasible option for decarbonising road transport.
- Other impacts on sustainability arising from the introduction of LCVs (e.g. biofuel impacts on food crops) are externalities I am not directly concerned with in this thesis, but recognize that they have potential to cause harm.

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[33] This is explored later in this chapter. I do not take 'locked-in' at its strongest interpretation, which would suggest that the users have no way out at all, but take a weaker interpretation in that it is extremely difficult, requiring many sacrifices, and removal of oneself from many aspects of society. This position is reflected in many works on individual responsibilities regarding climate change.

[34] There are many discussions about obligations to future persons, not just in regards to climate change, for a summary of these see Desjardins (2006). The moral status of animals, plants, land, resources and environment has been widely discussed (see for example, Singer (1979) or Naess (1973)).

[35] This reflects a position held by many scholars in the field of climate ethics, as discussed in the literature review, for example Gardiner et al. (2010) or Garvey (2008).

- This work is specifically limited to the case of private passenger cars[36] and does not consider wider transport systems and behavioural or modal shift. I accept that these omissions are necessary for decarbonisation, and that many groups would benefit from greater access to alternative modes, but I believe that such a discussion would detract from the central arguments presented here. Importantly, neither do I wish these arguments to be taken as an acceptance of (or support for) our continuing car dependency. This is because in the short-term (which this work considers) there is not enough time for major infrastructural or attitudinal change, and levels of car ownership are unlikely to change significantly over this time.
- When I refer to the ‘worst-off’ in this work, I have two groups in mind. First, there are those that are already most disadvantaged (compared to other people) in an unjust society (e.g. the disabled or the poor), and that the condition that disadvantages them makes them reliant on car ownership and/or very sensitive to changes in the opportunity for car ownership (in terms of cost and utility). Second, I am also concerned with those who are not in this worst-off category at present, but could become so as the result of an LCV policy. This ensures that anyone who is amongst the worst-off at any point in the timeframe of this research is considered.
- Though the majority of people who want to own a car currently do so,[37] there is a notable minority who do not. There are some groups for whom I assume car ownership is never an option (such as certain disabled or banned drivers) but I am prevented from including these groups as I do not address wider transport systems. For those who voluntarily choose not to own a car I assume that this is due to personal preference, or they have no need. As such they need no special consideration and they could choose to become a car-owner at any time. My main concern regarding non-car-owners is therefore those who do not own a car for economic reasons. These may well be *even more* worse off than the worst-off amongst the car-owners. Although I do not explicitly address this group in my work, I implicitly assume that any policy that would benefit the poorest car-owners would also help the poorest non-car-owners to become car-owners.[38]

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[36] i.e. not fleet or company cars.

[37] Recall 75% of households have a car. In this research I implicitly assume that car ownership and use are, in our current culture, largely inter-dependent and synonymous, but I fully recognise that they are separate concepts, which require decoupling from each other in the longer term

[38] This does not reflect a desire to increase car ownership *per se*, but accepts that in the current lock-in there should be equal opportunity for ownership for all.

- LCVs currently have characteristics that differ from conventional cars, which despite other advantages, form barriers to adoption.[39] These include high purchase cost, lack of fuelling infrastructure, and inferior technical attributes. Coercive policies to encourage LCVs, as described in the literature review, will overcome these barriers to an extent, but in the short term will result in a reduction in the overall opportunity for car ownership (of both conventional and low carbon vehicles) by increasing costs leading to car-poverty (being unable to afford a car) and decreasing car-utility (the accessibility and mobility a car offers). Within these policies. I do not directly consider the complete prohibition of conventional vehicles.
- Accessibility and mobility are goods that should be preserved where possible, as they are means to many ends. Car ownership is not only a form of mobility that provides accessibility, but an important one given the current infrastructural lock-in.

3A.3 Models in Policy Appraisal

Recall from the literature review that models have been used to inform transport planning for over 50 years and more recently, there has been a widening range of studies modelling the likely uptake of LCVs. The focus of the studies varies between general forecasting or understanding of preferences to more explicit considerations such as policy development and wider system impacts. They often concentrate on overall emission reduction or technology uptake, but few take a disaggregated approach that can account for preferences of, or impacts on, socio-demographic segments and none appear to voice explicit concerns about impacts on social justice. Because of this, many have recommended policies focused on achieving the objective for the study (i.e. emission reduction or market penetration), without assessing the costs they may impose on an individual level. I am concerned that the ethical issues I discuss in this Chapter regarding LCV policy are left out of these models. After I establish my claims regarding the policies, I will make a more detailed consideration of the permissibility of models in policy appraisal.

[39] Although I accept that there may also be advantages, such as lower running costs.

3A.4 Defence of Coercive LCV Policies

CLAIM 1*: In order to limit the harms of climate change, there is a strong case in favour of coercive policies that promote the introduction of LCVs – even if these policies may limit people's opportunity for car ownership.*

In my stipulations I stated that governments are obliged to reduce carbon emissions for the sake of climate change. A review of previous literature regarding the ethics of climate change was presented in the literature review of this research and so I feel this stipulation is uncontroversial enough to need no further discussion. I believe that this is also a strong enough reason to justify limiting (but not preventing) people's opportunity for car ownership compared to the present situation. In this section I defend the use of coercive policies that encourage the introduction of LCVs. These include the generic categories of polices identified in the literature review (*Regulation*, *Competition and Collaboration*, *Fiscal Measures*, *Raising Awareness* and *Facilitating Adoption*), as they may all directly or in-directly force a bias towards LCVs in the choices related to car ownership. A previous author (Duvall et al., 2002) has claimed that zero emission vehicle mandates (such as the Californian mandate discussed in the literature review) are unethical because they *"override consumer preferences and limits the choices and thereby the liberty of members of society"* (Duvall et al., 2012, p.562). I do not dispute the claim that such coercive policies infringe liberty, I very much agree that this will be the case, what I seek to argue here is that this infringement is permissible due to the harms of climate change.[40]

The Claim is defended through explaining its consistency with the harm principle as a reason for legislation and Garrett Hardin's' proposed *"mutual coercion, mutually agreed upon"* to prevent a *Tragedy of the Commons* (Hardin, 1968). I use the term 'limit' to mean that people will not have as much choice about what type of vehicle they own, or in the attributes of that vehicle, as per my earlier stipulation. I do however recognise that this claim can conflict with obligations to minimise further injustices, and this is addressed in my second claim.

[40] Duvall et al., did not consider carbon emissions in their paper, focusing instead on local pollution and disputed the environmental advantages of zero emission vehicles.

3A.4.1 The Harm Principle

Any intervention that reduces our liberty may be undesirable and instinctively considered impermissible. However, there are many instances in which having freedom of choice would allow us to make unethical decisions where our actions can adversely impact others. Regulations are in place to prevent this (e.g. smoking in enclosed public areas). Prohibition of activities that prevent harm to others is a commonly accepted and uncontroversial government policy.[41] Joel Feinberg considers a range of liberty-limiting principles of penal legislation, the first being the harm principle, characterised as;

> *It is always a good reason in support of penal legislation that it would be effective in preventing (eliminating, reducing) harm to persons other than the actor… and there is no other means that is equally effective at no greater cost to other values.* (Feinberg, 1988, p.xix)

A detailed consideration of Feinberg's work is outside the scope of this study. However, of the various principles, the harm principle is the least controversial, and is consistent with many liberal thinkers and what Gaus calls the *Fundamental Liberal Principle:*

> *Freedom is normatively basic, and so the onus of justification is on those who would limit freedom, especially through coercive means. It follows from this that political authority and law must be justified, as they limit the liberty of citizens.* (Gaus and Courtland, 2011)

As such, liberals would oppose a paternalistic law that (for example) prevented people from racing cars in controlled conditions where there is no risk to anyone but themselves. In contrast, laws preventing people from racing their cars on the streets, putting *others* in danger, is clearly not controversial. Feinberg's definition of a harm is a "*set-back to interest (non-normative) or violation of persons rights (normative)"* and acknowledges that "*requiring people to help prevent harms is sometimes as reasonable a legal policy as preventing people, by threat of punishment, from actively causing harms"* (Feinberg, 1988, p.xix). In such situations, we may not carry the act out with the intention of causing harm to others, but we are (or any informed rational adult should be) aware of the risk that our actions may pose. A policy of phasing out of conventional vehicles by biasing the public towards lower carbon options can be supported by the harm principle as it reduces carbon emissions and thus their contribution to harmful climate change impacts on others.

[41] First proposed by J.S Mill in 1859.

3.A.4.2 An Appeal to "Tragedy of the Commons"[42]

Garrett Hardin's *"Tragedy of the Commons"* (1968), discusses a notion of *"no technical solution problems"* (p.1243). These are major issues that can be only overcome by change in social behaviour, and are an important class of human problems that are often overlooked. Our current decisions relating to carbon emissions (and in the particular context of this work those associated with car ownership) fall within this category of problem.[43] The concept of *"Tragedy of the Commons"* was first mooted in the mid-19th Century (Lloyd, 1832) and is explained by Hardin thus:

> *Picture a pasture open to all. It is to be expected that each herdsman will try to keep as many cattle as possible on the commons. Such an arrangement may work reasonably satisfactorily for centuries because tribal wars, poaching, and disease keep the numbers of both man and beast well below the carrying capacity of the land. Finally, however, comes the day of reckoning, that is, the day when the long-desired goal of social stability becomes a reality. At this point, the inherent logic of the commons remorselessly generates tragedy. As a rational being, each herdsman seeks to maximize his gain. Explicitly or implicitly, more or less consciously, he asks, "What is the utility to me of adding one more animal to my herd?" This utility has one negative and one positive component.*
> *1. The positive component is a function of the increment of one animal. Since the herdsman receives all the proceeds from the sale of the additional animal, the positive utility is nearly + 1.*
> *2. The negative component is a function of the additional overgrazing created by one more animal. Since, however, the effects of overgrazing are shared by all the herdsmen, the negative utility for any particular decision-making herdsman is only a fraction of - 1.*
> *Adding together the component partial utilities, the rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another.... But this is the conclusion reached by each and every rational herdsman sharing the commons. Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit - in a world that is limited….Freedom in the commons brings ruin to all.* (p.1244)

This generic concept can be readily witnessed (and addressed) in certain cases, such as grazing land, but as the size of the commons increases or its definition blurs, the impacts are not so easily identified and the exploitation can continue unabated. This is of particular concern when the impacts are temporally or spatially separated from the exploitation itself, most notably in the case of pollution. Climate change is an extreme example of such a case, and is occurring due to the growing number of people responsible for carbon emissions at increasingly greater individual contributions.

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[42] All pages numbers given after quotes refer to Hardin, 1968.

[43] Although Hardin was particularly concerned with what he termed the "population problem".

Other authors have already appealed to Hardin's work in the study of climate change (for example, Gardiner (2001)) and I do not wish to repeat those thoughts here, but to apply it more specifically to the case of LCVs. The positive component is the utility that the vehicle ownership affords the individual, and in most cases it will be almost entirely theirs. The negative component of an extra car on the roads will be shared by all other road users due to congestion, local individuals due to safety risks and local pollution, and interspatial and intergenerational populations due to climate change. The majority of self-interested, rational individuals who could benefit from car ownership would do so,[44] allowing the unabated negative impacts of car ownership to add up and lead to "*ruin to all*" (p.1244). Hardin notes, however, that *"morality is system sensitive"* (p.1245). By this, he means that the actions of a small and steady number of people exploiting the commons, who may not recognise or cause serious or irreversible impacts, are not morally comparable to those who consciously join an already overexploited commons. This would seem to indicate that although the introduction of carbon intense technologies (such as conventional vehicles in the early 20th Century) is not wrong in itself, the choice to own and operate one today is less defensible.

Hardin considers prohibition policies that governments could employ to facilitate required changes in social behaviour, which he recognises is *"easy to legislate....though not necessarily to enforce"* (p.1245), due to agreeing a just level, monitoring issues and the risk of corruption. He rules out appealing to personal conscience as the correct mechanism, as it is not guaranteed to be successful. Besides this, Hardin suggests that such actions may be morally questionable as control of others' psyche often occurs through causing guilt and anxiety, which is *"psychologically pathogenic"* (p.1247) whether one conforms or not. With this in mind (and regardless of the morality), I believe that appeals to conscience could be even less successful today than when Hardin was writing, as there may now exist a weakened sense of community, reducing the motivation to be seen to do the right thing anyway.[45] I would additionally argue that there are further moral concerns regarding appeals to conscience to those proposed by Hardin; they may allow exploitation of virtues,[46] existence of free-riders[47] and lack respect for autonomy. [48]

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[44] This assumes that anyone who wishes to own a car can do so (see stipulations).

[45] An anecdotal opinion that may be developed in future work, but it seems to be demonstrated by increased levels of anti-social behaviour and reduced participation in community activities.

[46] Exploitation of any kind implies using persons as means to an end – a practise thought wrong in most moral theories. When it is of one's virtues, I believe that may be even worse.

Consequently, Hardin offers the possibility of *"mutual coercion mutually agreed upon"* (p.1247), carefully biased options (e.g. incremental price increases) that would lead even the conscienceless to make 'responsible' decisions in regards to the commons. To illustrate this concept, he starts with an easily understood example of the prohibition of bank-robbing, to which there is no exception. Everyone (except perhaps the bank-robber!) accepts this, as the robber is clearly taking unjustly from the commons and will be (presumably) unlikely to respond to an appeal to conscience. It seems right that we should have laws against robbery, as it would be unfortunately unrealistic to assume that no one would be tempted to rob, and without such laws we would be vulnerable to the would-be robbers. Moreover, Hardin points out that *"when men mutually agreed to pass laws against robbing, mankind become more free, not less so"* (p.1248), allowing people to make decisions on how to act based on legitimate available options.

There are, however, situations where such outright prohibition of an activity may not be accepted, but needs to be controlled. Hardin uses the case of parking, where drivers are not always temperate in their use of spaces, and so parking charges are introduced, with meters for short stays and fines for longer ones. As he points out, "*We need not actually forbid a citizen to park as long as he wants to; we need merely make it increasingly expensive for him to do so"* (p.1247). These are *"carefully biased options"* which Hardin considers as "*coercion"* rather than strictly prohibition.[49] He recognises that coercion itself is not enjoyed and can be seen as unjust (though argues that so are existing legal constructs such as inheritance), but we do (in general) accept it, as *"injustice is preferable to total ruin"* (p.1247).

When we face any paradigm shifts in social arrangements, even if the present situation is imperfect, Hardin suggests that we generally resist change to another imperfect situation and would rather wait until the perfect solution arises. However, he continues, in reality "*we can never do nothing"* (p.1247) because even if we

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[47] Free-riders are those who benefit from not responding to appeals to conscience when others do. Although disputed in some instances, "free riding on the provision of a collective good is often characterised as morally wrong" (Hardin, 2012).

[48] Over-riding one's right to self-governance is a common objection to paternalistic interventions (Christman, 2011).

[49] Though I would argue that as these options may not be available to everyone, for example those who cannot afford a fine or do not wish to be burdened with the disgrace of being fined, it effectively means some people are still prohibited. With this in mind, it is possible that Hardin's idea of coercion is closer to prohibition than he assumed, as prohibition may be a sub-set of coercion.

accept the status quo, we commit ourselves to one option and accept its imperfections without balancing its merits and consequences with the proposed reform and making a rational decision. In Hardin's discussion of the population problem, he suggests that the error is in waiting for a *"technical solution"*. We must at some point accept that it may never arrive, or at least maybe not in time to solve the problem at hand as in the case of reducing carbon emissions, accepting any restrictions on freedom that may impose, such as the opportunity for car ownership.

Hardin concludes his paper by summarising how *"as the human population has increased, the commons has had to be abandoned in one aspect after another"* (p.1248). We have progressed down a path of recognising and mutually agreeing to prevent the impacts of overexploitation, from enclosing farmland to restricting waste disposal. Each new constraint on liberty was resisted until the realisation that once one knows what is prohibited and understands how that makes things collectively better, one is freer (recall the bank-robber example). Unless motivated by altruistic, moral or environmental concerns, a driver with the choice between a conventional car, which they are acquainted with and which meets their needs, would be irrational if they then chose a more expensive LCV that provides less utility. As out-right prohibition of the conventional car is arguably unjust due to infrastructural lock-in[50] and appeals to conscience may prove ineffective and morally questionable, coercive LCV policies may be the solution. These may reduce the opportunity for car ownership, but following Hardin's above argument, this is not necessarily a bad thing.

An argument against Hardin's claim that reduced choice makes us freer may be the generally held assumption that more choice is preferable to less. Gerald Dworkin, however, argues that this assumption is not necessarily always true due to the costs that come with some choices. These costs include the time and effort in making the choice (such as acquiring the information), the social and legal pressure in making a 'responsible' or 'conforming' choice, and that additional choices may change the nature of the original options. In relation to car ownership, Dworkin highlights how the introduction of the automobile increased travel options, but as this new option was taken up, funds were diverted from mass transit creating the lock-in to automobiles as, "*What started out as an increase of the area of choice resulted in a situation in which one of the original choices was no longer available*". (Dworkin, 1982, p.54)

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[50] This position is explored in the next section.

With carefully biased policy options towards LCVs, such as *Fiscal Measures*, there is still an option (albeit limited) of owning a car whilst carbon emissions are reduced. This position recognises and accepts the restrictions that climate change and low carbon technologies impose. It will also allow us to really examine what our requirements are, rather than making decisions that may be influenced by enticing, but ultimately irrelevant attributes, that may not be available in LCVs (such as top speeds above legal limits and mileage ranges above our needs).

3A.5 Injustice from Coercive Policies

CLAIM 2: *In the short-term, many people are somewhat locked-in to car ownership for access and mobility. As such, policies should not allow additional unfair burdens on those who are already amongst the worst-off in society, or result in a different group of people being similarly disadvantaged.*

Having established that policies that may limit the opportunity for car ownership are permissible (due to the harms of climate change), attention now turns to how these limits may affect people. Although this may appear to be somewhat in conflict with Claim 1, in order to address climate change ethically, I do not believe costs should be just accepted. Rather, we should do all we can to avoid further injustices from those we currently have, so must ensure that it isn't the worst-off who are hit hardest by the coercive policies from Claim 1. In this way, Claim 2 is in fact supplementary to Claim 1 rather than in conflict with it. My concern is that some people in an unjust society,[51] and particularly some of those already amongst the worst-off, may be more affected by change in the opportunity for car ownership than others. Previously, I stipulated that this opportunity is affected by two attributes: car-poverty and car-utility, and that LCV policies will (in the short term) reduce the opportunity for car ownership by increasing car-poverty and decreasing car-utility.

Car-poverty represents being unable to, or having limited ability to, own a car that meets one's needs[52] due to the costs associated with ownership (both purchase and operating). Those who are more sensitive to changes in the cost of ownership are vulnerable to car-poverty and I believe require protection if an LCV policy imposes car-poverty upon them by increasing costs of ownership. By the very nature of this group of people being sensitive to financial changes, it is very likely

[51] Recall this work begins from the status quo of an already unjust society.

[52] Although a potentially contentious concept, I define 'one's needs' as gaining access to goods and services that are important to an individual.

that they are already amongst the worst-off in an economically driven society. I have assumed that car-poverty is increased by LCV policies as I assume that such policies make average ownership costs more expensive than today as conventional vehicles costs are increased but LCVs do not reduce significantly in price (and running costs do not counteract this).

On the other hand, car-utility relates to the access and mobility that a vehicle provides to an individual. I have assumed that LCV policies reduce the average car-utility through fewer conventional vehicles being made available and LCVs becoming more prevalent before meeting performance standards of conventional vehicles. This attribute of ownership will most greatly impact on those who have a higher reliance on car ownership than average. I am particularly concerned that this group of people contains those who already have a lower level of personal mobility (i.e. having less options for mobility, for example due to a disability or living in a rural area), and this condition itself may place them amongst the worst-off as they are already in a society that marginalises their needs.

If the coercive policies permitted by Claim 1 impact groups in such a way that they are in danger of finding themselves amongst the worst-off, or if they are already amongst the worst-off then becoming more so, I believe these groups deserve special consideration, as finding oneself in one position of injustice should not lead to another.[53] As my approach is addressing the real-world, I recognise that there is scarcity in resources,[54] and so minimising these injustices for the vulnerable may require further sacrifice from those who are not amongst the worst-off. I will argue that there is a defensible claim that, in the short-term, many people are locked-in to a certain level of reliance on car ownership for mobility and accessibility.[55] I then identify those groups that have the strongest claims for car ownership on the grounds of reliance. Once established, I consider methods to protect these groups by comparison to existing policies in the UK. More specifically I explore market regulation using the work of Jonathan Wolff (2011) and Michael Walzer (1984) then draw parallels to Disability Access Regulations, taxation and welfare benefits.

[53] See later on ‘pragmatic equality’.

[54] I use scarcity in a technical definition: “A condition where there is less of something available than at least some people would like to have if they could have them at no cost to themselves.” (Johnson, 2013). In any real world situation there will always be some form of scarcity. In this case, there are numerous relevant scarcities, notably money and the amount of carbon emissions the planet can absorb before we witness dangerous irreversible climate change (also known as ‘carbon sink’ – for more information see Garvey (2008)).

[55] Though I accept that car ownership is not inherently necessary to meet these needs.

3A.5.1 Claims for Car Ownership

Philosophical Background

Recall from the literature review that transport studies involves a complex interaction of many disciplines and transport ethics is not yet an established field.[56] There is a gathering body of work regarding automobility and transport policy appraisal, which discusses rights and fairness. This, however, has been generally carried out from a social science and humanities point of view. There has been little written in formal philosophical terms regarding car ownership directly. This is why consideration from the point of view of moral philosophy is important, and even more so in the context of climate change.

Lomasky (1997) defends automobility to its critics by an appeal to its role in our development as autonomous beings, through self direction, privacy and choice. Although some of his claims may be somewhat stronger than many would accept, the combination of these goods does seem to have provided cars with a unique position in our society, embedding it in our lifestyles, and creating our reliance upon them. He states:

> *Automobility is not just something for which people in their ingenuity or idiosyncrasy might happen to hanker…(it) is a good for people in virtue of its intrinsic features*. (Lomasky, 1997, p.8)

Similarly, Rajan's work on the ethics of driving suggests that the normative view in liberal society is a positive one as it provides freedom and well-being and can be used as a *"social equalizer"* (Rajan, 2007, p.88). However, because of this a blind-spot exists which leads to the automobile being so ordinary and accepted that its *"conceptualization as a unique theoretical subject"* is often overlooked, which *"condition(s) us to accept its importance without question",* (Rajan, 2007, pp88-89). This view is perhaps supported by Wood (2009), who distinguishes the right to travel from the right to travel by a particular form of transport:

> *The right to drive a motor vehicle on the public highway crept in almost under the radar. The use of cars by a privileged few was tolerated and became a de facto right in the early twentieth century, aided by it being a symbol of a status to which many people aspired*. (Wood, 2009, p.10)

I agree with Rajan that it is likely that car ownership (that I suppose is synonymous to driving in this work) currently holds a normative positive value to society and that the importance of this should be recognised. I am not attempting to *defend* that it is

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56 Although many recognised concepts such as risk, distributive justice and value of life can be transferred or enriched by application to transport.

right that the car holds this position, but accept it to be true, and therefore relevant to this discussion on the moral issues of the car dominant society. Further, it would seem to me that the car has indeed achieved this position *"under the radar"* as described by Wood, and this has lead to Lomasky's assertion that automobility and autonomy have become entwined with one another. These are also morally relevant factors of car dominance that deserve recognition when designing policies that may affect car ownership. I would, however, challenge that this normative positive value of the car in society should remain to be the case (as I think Rajan was implying), and furthermore suggest that it is these very views that may cause the biggest barrier to a decarbonised transport system in the long term (as it will very likely require a significant shift away from private vehicle ownership).

Historical Perspective

Although removal of a technology may not intuitively be morally different from providing access to a technology in the first place, in this case the automobile has become a means to access and mobility. When the current conventional vehicle was introduced, it was only available to the rich and privileged, but now private cars are depended on, in growing numbers. The inequality of ownership at the introduction was not unfair as there was no obligation to provide this new technology to all people. However, as our current infrastructure has evolved around the automobile (which in some cases involved replacement or neglect of other transport options and their infrastructure), removal of the automobile could increase the gap in equality between sections of society. This is another example of Hardin's proposal that morality is system sensitive, and is a reason why I only focus on a short time-scale in this research. I believe that as LCV attributes are normalised, or private car ownership is not viewed as the dominant / favoured mobility option, there will come a tipping-point, after which these arguments will no longer hold true.

The 'Locked-in'[57] Barrier

The accessibility a car provides not only adds value to our lives through enabling involvement in social and pleasure activities, but also may be a vital instrument in pursuing our deeply held projects, assuring our employment and security, and allows us a freedom of movement in many other areas important to us as individuals. The private automobile is seen as an essential part of everyday life for many citizens in the western world. To an extent, this is true regardless of socio-demographics. The widespread availability of the automobile (as a form of cheap

[57] See footnote 33.

transport that allows freer movement) is seen by Karl Popper as a massive benefit to social reform and an example of *"great revolutions… (which) cannot be foreseen by anybody"* (Popper, 1997, p.42).[58] In fact, it is most difficult for one to imagine what the world could be like if the car had not been invented. Since the first cars and roads were introduced around a hundred years ago, and the internal combustion engine dominated, our infrastructure and our culture have co-evolved. Numerous political decisions have indirectly cemented the car's place in our society (e.g. cutting rail networks and building out-of-town shopping centres),[59] to the point of creating a 'lock-in' to car ownership for many. A number of constraints may force one into requiring car ownership, and are the basis for the special claims for car ownership set out in the next section. These constraints make non-car ownership impossible or highly impractical and include limited personal mobility, distance between home and work, and lack of available or credible alternative modes to access services. The cultural and social status car ownership affords you may also be viewed a constraint for some people.[60] I would not however argue that mere *perception* is such a constraint – for instance if one could simply not imagine using other modes because one is *used* to car ownership. Due to the reasons set out in this section, I believe that for many people, it is uncontroversial to say that owning a car is seen as greatly advantageous, if not a necessity, and this is an observation made by others, such as Lomasky and Rajan, but also as;

> *"Motorized accessibility to key destinations such as employment centers, schools, or medical facilities, has become, in the words of Dworkin, a prerequisite for "a life of choice and value".* (Martens, 2006, p.7)

Some people may rely so heavily on their car ownership, that their standard of living may be unfairly reduced if it is prevented or diminished in some way, creating a general claim for the preservation in the opportunity for car ownership. This said, it does not follow that owning a car is an absolute right that must not be violated. It is not the intention to suggest that car ownership is the only option for travel, or should be preserved indefinitely. Indeed, many people do not own a car, but do still travel.

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[58] This comment was made in a critique of Marx, who Popper believed did not realise the value of revolution in 'personal services', and instead was concerned with the production of material things.

[59] Or conversely, this may have been the intention for some, as Margaret Thatcher is quoted as saying *"Nothing should be allowed to stand in the way of our great car economy"* (HoC, 2003).

[60] This is well illustrated by the anecdotal term 'poverty wagon' for public buses or Margaret Thatcher's attributed comment in the previously mentioned debate that "*A man who, beyond the age of 26, finds himself on a bus can count himself as a failure"*.

For now, the question of whether cars *should* be allowed at all is one that will be put aside, though it is acknowledged that there are many reasons why we may wish to remove all (or many) cars from our roads, from environmental and safety concerns to social inequality in the future.[61]

3A.5.2 Groups with Special Claims

There are certain segments of society that may have stronger claims than others for the preservation of car ownership as they are sensitive to car-poverty and car-utility. These groups could face unfair burdens if coercive policies biased towards LCVs reduce their opportunity for car ownership, especially as these groups are often the most disadvantaged by a car-oriented society in the first place.

Low-income

Those in the lowest income quintile are already the worst-off in our money-dominated society, and are at most risk of car-poverty. This group may not have a stronger claim than others for car ownership *per se*, but I argue can have a stronger claim for assistance in preserving it. As car ownership is already one of the highest household expenses, the poor who own a car are more likely to own a private vehicle because of necessity.[62] Indeed, motoring costs account for 24% of the total household expenditure of car owners in the lowest income quintile (Lucas et al., 2001).[63]

As it is well documented that the poor are more sensitive to fiscal changes, and as I suspect that many of these people will be restricted (in terms of affordability) to owning older, second-hand cars that are less fuel-efficient, it is this group that would feel the impact of changes in motoring costs (of conventional cars), which would come about through coercive policies, the most. Further to this, they will not be able to afford expensive new LCVs and are unlikely to be able to access private infrastructure (e.g. charge points), as housing in this group is unlikely to be self-owned or have the necessary private off-road parking and they may not be able to afford to purchase and install the infrastructure anyway. When this is set in a situation where this group generally travel less than other income quintiles (not due

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[61] A discussion on this can be found in Sloman (2006).

[62] By this, I mean that they (more so than any other group) can only justify the cost of car ownership because they are required to make journeys that are not possible (or are highly impractical) without a car, due to the constraints listed earlier. Though this does not necessarily mean that they would prefer not to be car owners.

[63] This is between 10 and 15% in other quintiles.

to a lower need or desire but because they are prevented from doing so by associated costs) (SDC, 2011), and as a result of this they are amongst the least responsible for carbon emissions, it seems intuitively even more unfair that they may experience the brunt of the coercive policies.

Disabled

Before discussing car ownership claims for this group, it is crucial to note that I assume that this is a group of people who are already likely to be facing many non-mobility related restrictions. Societal practises, culture and infrastructure are generally biased towards non-disabled people and marginalise disabled people. This situation, in addition to any specific hardships that the condition directly causes (e.g. pain, lack of autonomy or poor quality of life), makes them amongst the worst-off and most vulnerable in society. I recognise, however, that there are many forms of disability each having its own impact on mobility, so need to be dealt with separately when it comes to claims for car ownership:

- There are (primarily physical) disabilities that makes car-utility a significant factor in car ownership, as they not only reduce personal mobility but also prevent or restrict access to other modes of transport. I would argue that those who fall in this category may have the strongest claims across all society for car ownership.
- By contrast, many disabilities, such as certain physical or intellectual disabilities, visual impairments and mental health issues, may prevent people from driving entirely and are therefore not my direct concern in this work. Many of these may however, still be dependent on someone else's car ownership. Should they also have poor personal mobility and/or be prevented or restricted in accessing other transport modes, people with disabilities of this type face the most barriers in a car-oriented society, so require special consideration in wider transport, accessibility or mobility policies.
- Finally, other disabilities, such as hearing impairments, may not be relevant to car ownership positively or negatively, so may not have any strong claim for car ownership.

Rural

Those living in rural areas have a high sensitivity to car-utility as they are reliant on car ownership due to the distance from major amenities (e.g. retail, leisure, education and employment) and also suffer from the poorer provision of public transport and local services. People living in rural areas have the highest incidence of car ownership of any group as they see car ownership as a necessity, imposing extra costs to rural living (SDC, 2011). Further to this, SDC report that low-income and young people in rural areas who do not have access to a car are particularly disadvantaged both in educational and employment opportunities. The claim for car ownership may not be as strong as some other categories due to the greater element of choice regarding where one lives (and works etc), but there is certainly a widening disparity in car ownership levels between rural and other areas (Lucas and Jones, 2009) that suggests a higher level of dependence that forms the basis of this claim.

Elderly

The elderly are generally less physically mobile and poorer than other segments of society, yet more dependent on social goods and services. This can make them susceptible to both car-poverty and car-utility. Although pensioners are entitled to a free bus-pass, many still own a private vehicle and see this as their main means of transport, providing greater independence and well-being (Lucas and Jones, 2009). Limited by even the shortest distances, car ownership may be a significant factor in maintaining independence, and lack of car ownership has a correlation with social exclusion (SDS, 2011). There will be many members of this group for whom car ownership is not a possibility to begin with, as some may have never driven (particularly women)[64] or are no longer capable of doing so (due to declining physical abilities). As this may mean that this group may be a relatively small group, it is possible that they may be overlooked. Towards the end of the short time-frame of this work the group size is likely to grow as the UK has an ageing population.

Other Special Commitments

There are a number of other circumstances in which people are more sensitive to car-utility than average so may have a stronger claim for car ownership than average. These circumstances are more related to lifestyle choices,[65] and as such, they may not give rise to making people amongst the worst-off, depending on how flexible that choice is. This group is quite varied, with the strength of the claim depending very much on individual circumstances. Examples of stronger claims in this category are those with particular family commitments (e.g. having large families or young children) or those who would otherwise have impractical journeys

[64] Around a third of women over 70 hold a driving licence whereas almost 80% of men do (Lucas and Jones, 2009).

[65] It is perhaps these types of lifestyle choices that become unrealistic in a low carbon future, or when the costs of carbon are internalised, not just in transport, but also housing, energy and commodities.

to their workplace, whereas weaker claims may be related to pursuing hobbies which are inconvenient without a car (e.g. scuba diving) or requires a car (e.g. racing driver). It may even include those who have particularly strong emotive attachment to the car (e.g. classic car enthusiasts). These claims may be false as they are weakened by the arguments in Claim 1, which accepts that effort or sacrifices may need to be made. This is especially so if the coercive policies for LCVs bring about mere inconvenience rather than making these people amongst the worst-off (as I believe could occur in the case of the other special claims). Although I recognise that in certain circumstances there may be strength in these types of claims, I do not believe I can argue in favour of them to the same extent as the other groups.

3A.5.3 Comparison to Existing Public Policy

I have now established that although coercive policies, which reduce opportunity for car ownership, are permissible, there exists a legitimate claim for the preservation of a basic level of opportunity for car ownership in the short-term, and have identified a number of groups who may need protection from changes in car-poverty and car-utility. In this section I argue that there is a government responsibility to provide this assistance under the same reasoning as existing public policies such as market regulation, disability access, tax exemptions and welfare benefits, in that a responsible government recognises and attempts to ameliorate inequalities within society. I believe this claim could be made even stronger when one recognises that it is government policy itself that has given rise to lock-in and inequalities.

Market Regulation

Success of any product in a true free market is due to buyer(s) and seller(s) seeking mutually beneficial agreement, without interferences from the state. This can lead to inequalities within society, due to pre-existing inequalities of needs and resources. In the UK we have a semi-regulated market, with many prices and transactions determined by market dynamics, but also with government pursuing a fair distribution. Jonathan Wolff believes that certain goods should be fenced off as a necessary condition of living well, because *“if all goods are available only on a market basis, those who have not made an economic success of their lives will be excluded from almost everything else too”* (Wolff, 2011, p.187). He further defends the need for regulation because *“the free market cannot always be trusted to deliver outcomes that will seem to be socially acceptable”* (Wolff, 2011, p.170) citing the externalities of purchase decisions, the existence of monopolies, and the asymmetry of knowledge between buyer and seller. That said, in the long term, a freer market may be advantageous, as *"free competition (can) .... drive out poor quality goods, keep prices low and match supply to demand".* (Wolff, 2011, p.174).

Wolff is not alone in asserting that different goods should be treated separately, particularly in terms of distribution rules, as Michael Walzer's *"Spheres of Justice"* (1984) would appear to come to a similar conclusion. Within his work, Walzer proposes that the distributive criteria of any specific good is relative to the social good it provides to a specific society:

> *If we understand what it is, what it means to those for whom it is a good, we understand how, by whom, and for what reasons it ought to be distributed. All distributions are just or unjust relative to the social meanings of the goods at stake* (Walzer, 1984, pp.8-9)

This recognizes that the value of a good is relative to the meaning it forms within a society, which in turn is influenced by the factors which have formed that society. Walzer goes on to establish that everyday commodities can be distributed in a free market, but for the most important goods in a society (those with a specific social meaning), the free market is not an appropriate mechanism for distribution. Such a good deserves their own "*distributive sphere"* that should be autonomous from other spheres, though he recognises that in reality *"what happens in one distributive sphere affects what happens in the others"* (Walzer, 1984, p.10). Within such a sphere, the nature of the good itself determines the rule of its just distribution. The concept of transport as a separate sphere of justice is discussed in more depth by Karel Martens (2012), who defines the transport 'good' as accessibility rather than mobility, arguing the former is more linked to needs than the latter. [66] Although I agree with Martens that access is more linked to needs, making it a greater concern for transport policy, I do not wish to neglect mobility from my work due to its important role in autonomy. I capture this dual good of car ownership in the previously discussed term of car-utility – the access and mobility a car provides.

Leading from this, I argue that because coercive policies essentially regulate the market, and in doing so reduce consumer choice in certain goods, further supportive measures are required to protect those vulnerable to that reduction in choice (i.e. likely to unduly suffer). I believe that (in the short-term) *access and*

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[66] Martens further suggests that the distributive rule within this sphere should be one of 'maximax', that "*combines the goal of maximum average accessibility with a limit on the maximal gap allowed between the worst-off and the best-off in terms of accessibility level"* (Martens, 2012, p.1048).

mobility through car ownership is such a good that Wolff's argument is applicable and there is strong argument for it being fenced off, as exclusion in car ownership can lead to exclusion from so much more than many other goods. Likewise, car ownership could qualify for having its own distributive sphere, due to its distinct social meaning arising from 'lock-in' as discussed previously, and as it allows us to move freely, participate in society, and it increase's our life choices.

Disability Access Regulations

Under the 2010 UK Equality Act, any public venue, (e.g. a theatre) is required to provide suitable access for disabled customers. Without this, the owner may decide that the extra income he would expect to receive from providing disabled access may not cover the costs required to put it in so decides against doing so. The owner has therefore acted discriminately, but in a strict free market approach that is his choice and the disabled person has no right to complain. In the UK, owning a car, like visiting a theatre, is an opportunity currently available to most of us, so an analogous law that ensures equal opportunity of car ownership between cohorts of society may be appropriate. Government assistance in mobility for disabled persons does exist, as the disability may incur higher transport costs than otherwise. For example, there is a mobility component to the Disability Living Allowance, and this may be used to lease a new car with adaptions where necessary through the *"Motability"* scheme. Yet a poor person who cannot afford transport does not necessarily get such explicit consideration (though transport costs are factored into job seekers allowance).

A government which addresses an inequality resulting from one type of disadvantage in a different way to another may be deemed biased. Disabilities may be in many ways much less escapable than poverty but the effective life choices the condition imposes can be just as restrictive (if not more so). A societal inequity of any good (such as access or mobility) should be approached in a similar way in the first instance, though I recognise the underlying reason for the inequity may ultimately make a difference to the correct way in which to address it. In addressing inequalities brought about through disabilities, Wolff calls for *"Pragmatic Equality": "a world in which disability does not add to other sources of inequality"* (Wolff, 2011, p.154). For example, disabled people should have the same opportunities as non-disabled counterparts, everything else being equal. I believe this can be transferable to people in other positions vulnerable to injustice. Therefore, if one cohort of society is particularly dependent on car ownership for their accessibility and mobility, and if the opportunity of car ownership is reduced, then the government should ensure that this is addressed by compensatory measures.

Taxation and Welfare Benefits

Another example of a coercive policy for LCVs may be a tax related to vehicular carbon emissions. Taxation as a form of coercive policy is generally accepted in the UK, even if somewhat begrudged. In a transport context there is an annual vehicle tax, based on tailpipe carbon emissions, and operational fuel tax, partly based on environmental impact. These taxes, especially on fuel, are one of the more controversial taxes in the UK due to their role in creating some of the highest fuel prices in the world, but also are integral to our economy, so are arguably necessary. If additional vehicle taxation is permissible (under Claim 1), I believe it permissible to apply further taxes to some people to help provide government support for the worst-off, perhaps also allowing the groups with special claims to be eligible for tax reductions or exemptions. There is already in place in the UK a pilot rural fuel duty rebate scheme that offers five pence per litre discount on pump prices in the Scottish Islands and Isles of Scilly. Recently a consultation has been launched to assess if this should be extended to inland remote rural areas (HMT, 2013). This is more related to the particularly high prices in these areas than car use, but may set a precedent for targeted fuel duty exemptions.

Alternatively, an entirely different form of taxation, such as carbon or road pricing may be more appropriate. These of course, are not without their own problems when put into practise (such as unintended side-effects,[67] enforcement, corruption and exploitation), but if they can be resolved, may offer a fairer distribution of burdens as they can raise the price of carbon intense goods (e.g. fossil fuels) or activities (e.g. driving) accordingly.[68] However, if some people can no longer afford a car, and the impact on others is more of inconvenience, there is an inequality in the new situation disproportionate to the current situation, hence the need for government support. I accept that this may be at the further expense of others within society, but, bearing in mind that I am assuming conditions of scarcity (recall Footnote 54), as long as they are not amongst the worst-off I believe that this is acceptable. This is in line with my defence of coercive polices. Similarly, Duvall et

[67] E.g. as witnessed by the increase in Local NOx pollution due to an increased proportion of lower CO_2 emissions diesel vehicles in UK fleet.

[68] Although fuel duty already reflects some environmental impact it is not explicitly linked to carbon emissions.

al., in their paper on the ethical issues of zero emission vehicles, argue in favour of emissions-based taxes, as customers have *"options to reduce their tax liability"* (Duvall et al., 2002, p.572) but they also recognise (through a Rawlsian "*justice as fairness"* argument) that a graduated tax system may be required:

> *If different wages are paid to different people in proportion to the marginal value of goods and services produced (given a competitive market system), the different tax amounts ought also apply to different people in proportion to the marginal cost of decision relating to car purchasing, tampering etc.* (Duvall et al., 2002, p.573)

Inequality through taxation, which requires rectification, may be brought about in various ways. For example, regarding electric vehicles, as already established the poor are more likely to own high emitting cars, and less likely to own electric vehicles. As electric cars enter the market, if the electricity used to power them remains immune to fuel taxes, the poor may be doubly disadvantaged. Likewise, those in society with a high reliance on car ownership due to physical disabilities (whom are already amongst the worst-off regarding *mobility*) and those in specific constrained situations (e.g. the poor living in rural/inaccessible areas) are subjected to higher running costs, and the limited range of an electric vehicle may not meet their needs.

Certain sections of society are recognised already as being less able to contribute tax, and are often those who are eligible for welfare benefits as well. Perhaps following this, a tax exemption on transport costs and/or assistance in purchase for certain cohorts of society may be appropriate. Such a scheme could be comparative to fuel poverty assistance schemes in the UK, such as the Energy Conservation Act 2000, which places a duty on government to have a strategy in place to *"ensure, as far as reasonably practicable, that no person lives in fuel poverty"* (DECC, 2012).

It is not clear, however, to what extent the government would have a duty to assist people in *car ownership*, rather than *access and mobility*, though I suspect that the arguments I have made relating to the locked-in barrier and special claims would be in support of the former. I believe that car *ownership* is as important to life as home *ownership*,[69] perhaps more so due to the mobility it provides. Many people cannot afford to buy a house but the government assists in this through various schemes, such as shared ownerships and more recently the *Help to Buy* equity loan scheme, which provides interest free loans for deposits for those purchasing newly built

[69] Owning a house outright or through mortgage, not through rental.

houses. Other than the Motability scheme mentioned earlier, the government does not provide assistance to those who otherwise would not be able to purchase any type of car. The Plug-in Car Grant, to assist LCV purchase, and the previously in place scrappage scheme, to incentivise replacement of older cars, are the closest approximations to assistance in car ownership, but in both cases (and in the case of Help to Buy) it is not the poorest who benefit, as significant capital is required to be contributed by the purchaser also. Although my concern is for the worst-off, which is why I point this out, I am not arguing against these policies. It is not necessarily unfair if only richer people could afford a LCV in the short term, as innovators and early adopters are needed to germinate the market, bringing about technological progress and economies of scale that will be beneficial in the long term. I am simply emphasising that they do not assist those who are worst-off.

3A.6 The Permissibility of Models in Policy Appraisal

Now that the claims have been explored and defended, I have established an ethical framework that allows coercive policies for the introduction of LCVs, which may reduce opportunity for car ownership, but recognises that some groups need special consideration within these policies. The ethical framework will form the basis of what I seek to establish within a model in the remainder of this research. Therefore, I now turn my attention to the permissibility of models in policy appraisal. I consider this alongside another common, but controversial, tool, Cost Benefit Analysis (CBA),[70] concluding that both have limitations in their use, with moral implications. Following this, I suggest how an empirical model could incorporate the non-empirical framework identified in this Chapter.

3A.6.1 Cost Benefit Analysis

In its simplest form, CBA determines whether a policy or plan would be desirable by identification of the Benefit Cost Ratio (BCR), which should be greater than “1” (the sum of all gains/benefits should exceed the sum of all losses/costs). In addition, this can be used to compare policy options. Although it is generally agreed that CBA is a useful tool in making decisions (though is not a decision making tool by itself), and has been in use for over a century (Thomopoulos et al., 2009), its appropriateness for public policy by *itself* has been widely discussed in applied philosophy (particularly in healthcare). In these debates, it has been criticised for its

[70] Also known as Risk Benefit Analysis (RBA), but I consider these terms synonymous.

utilitarian approach, economic basis, anthrocentric focus, potentially superficial or limited application and tendency to bias.[71] Whereas critics say that CBA fails to give equal value to individual lives in its calculations because it does not identify the distributional effect, tending to favour some[72] and not preventing harm in others, advocates dispute this (Williams, 1988).

3A.6.2 Modelling

Modelling differs from CBA in that it does not directly contrast costs and benefits, but attempts to simulate changes over time, or identify conditions required to meet desired targets. Models can be used to make predictions on values of indicators subsequently used in CBA. There are many philosophical discussions already ongoing around model semantics, ontology, and epistemology (Frigg and Hartmann, 2012), but not on the ethics of modelling. It is not my intention to enter the philosophical debates here, but do wish to contribute to the under-developed conversation on the ethics of modelling in real-world policy-making. Models used in ex-ante evaluation of policies tend to focus on measurement of an overarching objective without assessing the risks they may impose on an individual level and do not tend to contain explicit consideration of how the policies may impact on social justice.

3A.6.3 Limitations

There are similar moral issues concerning the role of CBA and modelling in policy appraisal, as both focus on a chosen indicator(s), and may be blind to other morally relevant outcomes. Both methods are limited by practicalities (of time, data and resources) and implicitly laden with values and judgements made by the actor carrying it out as well as limited by their knowledge, competency, motivations and ethical mindset. Additionally, amongst policy makers there seems to be an implicit presumption of these being value-neutral, without any explicit defence of that being the case. In his consideration of ex-ante evaluation of transport policies van Wee defends CBA, “*mainly for the practical reason that it may contribute to a ‘better’ quality of decision making*”, as it is “*a systematic evaluation of pros and cons*” (van

[71] Discussions can be found in Gardiner (2011), van Wee (2011), Thomopoulos et al., (2009) and Harris (1997).

[72] For instance, in transport CBA willingness to pay indicators are often used which are biased towards richer people.

Wee, 2011a, p.18). Without such an ex-ante system in place, major inconsistencies may arise and highly debateable assumptions may not be challenged.[73]

van Wee does recommend that CBA should be used with caution and should not be used as the only basis for decision making, as there are numerous ethically relevant criticisms. These criticisms relate to cases where alternatives are not comparable, winners and losers are not relatively equal to begin with, there is large uncertainty or there are political preferences. Further to this, CBA may generate more than one favourable outcome, thus is not able to conclusively assist in the decision making. I believe that these criticisms *must* be addressed when choosing a CBA approach, to defend its permissibility. van Wee also considers models, suggesting that they are favoured as they *"provide quantitative information…(and)…perceived neutrality"* (van Wee, 2011a, p.195) (through calibration, validation, testing and frequent use), but warns that modelling has many ethically relevant dimensions. In addition to generic considerations of ex-ante policy evaluations, models may be limited to their specific situation/purpose, are vulnerable to mis-interpretation and sensitive to their complexity, boundaries and assumptions. He concludes:

> *The eclectic approach – combining multiple theories to come to a practically applicable approach – would certainly match the eclectic approaches that are often seen in studying transport and its impacts on society.'* (van Wee, 2011a, p.222)

3A.6.4 Implications

Martens has considered both CBA and modelling[74] from a social justice perspective and concludes that *"there has hardly been any explicit reflection on the distributional mechanisms that are currently built into both planning tools"* (Martens, 2006, p.3), and because of this, they "*may actually reinforce the existing differences in mobility and accessibility between various population groups"* (Martens, 2006, p.5). He suggests that, although attempts have been made to ensure environmental concerns are considered, such appraisal tools should be based on accessibility needs rather than demand, though he accepts there are many challenges in doing so:

[73] I would however argue that neither CBA nor modelling is immune to such issues, but should reduce the occurrence due to the systematic nature.

[74] Martens considers the classic 'four-step' models of transport networks, but I think his conclusions are transferable to car ownership models.

> *If … accessibility has indeed become a prerequisite for such a life, and if we posit that each citizen deserves such a life, the provision of transport facilities can hardly be based on the criterion of demand. Rather, need comes to the fore as the just principle upon which to distribute key transport facilities.… the goal of such a need-based model would be to assess to what extent the existing or future transport network is able to secure a minimal level of accessibility for all population groups. Unlike demand-based models that apply a seemingly neutral methodology, the development of a needs-based model will require an explicitly normative approach, as needs will have to be distinguished from wants and explicit accessibility standards will have to be set.* (Martens, 2006, pp.7-8)

Although I understand why demand-based models were developed, I share the concerns of Martens. Systems based on and responding to aggregate demand cannot adequately take account of the *needs* of individuals, as opposed to preferences. Due to this, demand models fail to identify those who are in danger of a reduced opportunity for morally relevant goods. Further to this, Timms suggests the following:

> *Moves should be made to adopt a communicative approach to transport modelling which views models as being tools in communicative planning processes. Models used in such processes would benefit by being subjectivist, whereby explicit recognition is made by the modeller about their (personal) level of uncertainty in the model. Furthermore, models making long term predictions should incorporate the responses of actors in the transport policy-making process (planners, politicians and the voting public) to future states of the transport system. Such changes in modelling approach would be greatly aided if transport modellers were to become more aware of formal philosophical concepts and arguments….and were to incorporate the insights from such philosophy in their writing about models.* (Timms, 2008, p.408)

In agreement with Timms, I would stress that a modeller must be aware of the wider process and philosophy of their work and that a model should not be used as the sole decision-making tool. Models can only ever capture what has been decided to be modelled, which will be specific to the question raised by the policy-maker, and therefore needs to be framed within a communicative process as implied by Timms.

As models are built to reflect real world systems, which contain many complexities, feedbacks, unknown and unpredictable events, an accurate model which replicates an entire system would be a significant, if not impossible task. Therefore the modeller is limited to restricting the parameters of the model and systems within it to a manageable size. Although this reduces the accuracy and realism of a model, so does any academic task, be it lab-based or philosophical. However, I do accept that there may be a danger in this comparison. Policy makers may have high expectations for models' outputs, and therefore must be fully briefed in the interpretation, accuracy and limitations of these outputs. As part of this, the modeller should be aware of and able to manage their accountability, and the policy-maker should be wary of making judgements based on (unwarranted) appeals to authority.

There will always be insurmountable obstacles which one encounters when attempting to seek methods that marry empirical data and non-empirical judgements. However, any policy-maker who uses models to inform their decision-making must be fully aware of the ex-ante ethical evaluation, and of the purpose, design and limitation of the model. Such pressure of understanding may be too demanding, but it is not unreasonable to argue that any policy-maker has a duty to be informed. The model may be vulnerable to misuse or corruption, but no more so than other policy appraisal tools. Like any evaluative procedures, it can only test the predicted problems and ascertaining these is itself a morally relevant activity.

3A.6.5 Application

By combining the recognised limitations of modelling with the *“eclectic”* (van Wee), needs-based (Martens) and communicative (Timms) approaches, I think modelling methodology can be improved. The overarching objective, needs and burdens (including what is ‘acceptable’) should be clearly identified by both modeller and policy-maker, through an ethical-socio-technical consideration of the policies. Where needs and burdens have been identified, compensatory or supportive measures must be considered. This allows for the identification of potential vulnerable sections of society and these tasks together form what I term ‘the ethical framework’. The modellers’ decisions on the model boundaries, inputs and output parameters, should then be guided by this framework, and outputs that are indicators of unacceptable burdens should be included. This process should be transparent and clearly communicated to the policy-maker. Finally, a model should not merely be a predictive tool for identifying the best option, but should instead compare the impacts of certain options on particular outcomes, within a specific framework, and used in conjunction with other appraisal tools.

3A.7 The Ethical Framework

In this research I am developing a model to test policies within the ethical framework established here that satisfies the claims I have argued for in this Chapter. This framework allows coercive policies for the introduction of LCVs, which may reduce opportunity for car ownership, but also recognises that some groups need special consideration within these policies.

I have sought to develop a model to test policies within the ethical framework established here, through three parameters: reduction in carbon emissions (this is empirical and already built into the model I use); impact on car-poverty (by change in purchase prices) and change in car-utility (by change in vehicle attributes). The latter two should be linked to vulnerable segments of society as they are morally significant impacts on car ownership that the introduction of low carbon cars may incur. Also, the model is for one specific concern of social justice, and therefore can only be used in consideration of that. It cannot (for example) compare the impact of changes in the opportunity for car ownership on social inclusion or public transport (though these are morally relevant questions which should be addressed elsewhere). Also, the model is based on the ethical framework I have developed – another philosopher, policy-maker or scientist may view this differently. Although I recognise that there are limits to the applicability and permissibility of models in policy making (due to design and boundaries) it does not diminish the approach I take in this research. Modelling may only answer a *specific* question within an appeal to a *specific* political philosophy of a *specific* policy maker/modeller, but nonetheless plays an important role in policy decision-making when carefully applied.

3A.8 Conclusion

At the beginning of this work I established that my objective was to suggest how we should deal with the practical, real-world issue of policy-making regarding low carbon cars. I considered philosophical questions of justice regarding climate change, car ownership and coercive policies, and made suggestions on how we should protect the most vulnerable, based on existing public policy. I established that there is an obligation to reduce carbon emissions due to the harms of climate change, and it is permissible to use coercive policies to do so, even though they may impact on the opportunity for car ownership. However, as car ownership needs vary across society, I have argued that such coercive policies should not amplify existing, or create new, injustices. This may require market regulation and public policies that preserve the opportunity for car ownership for the most vulnerable and may be at the expense of others in society. Identification of these issues was a necessary step in a policy appraisal process culminating in modelling of policies, as I was concerned that modellers in the past may not have considered sufficiently the issues of distributive justice. Following from this I argued that models are an important tool in policy appraisal, but are also limited in their application, which has morally relevant implications - though this provides no reason to discard them, merely to ensure that they are used appropriately. Finally, I have presented the ethical framework for LCV policies that has been established through the research in this Chapter that will be applied in the remainder of the research.

PART B: EVALUATING THE ETHICAL FRAMEWORK

3B.1 Introduction

The next step of the research was to carry out pre-modelling evaluations of the framework, combining quantitative and qualitative approaches. This was achieved by soliciting expert opinion through an online survey and interdisciplinary workshop. The survey data was subjected to descriptive quantitative analysis in order to assess support of the claims made in the framework and the policies chosen for research. Qualitative analysis of the workshop discussion and comments from the survey revealed further support for the framework. The work in this Chapter also formed part of a separate project from this thesis that was awarded a Youth Prestige Grant from the World Conference on Transport Research in 2013.

3B.2 Quantitative Evaluation

An online survey was designed and carried out that invited experts working with Low Carbon Vehicle (LCV) issues in the fields of ethics, policy and technology, to comment on the impact that LCVs may have on society. Screenshots of the survey are presented in Appendix A. The survey was divided into three parts and only descriptive results are used in this research. Firstly the respondents were asked to express their agreement or disagreement with a number of statements related to the impact of LCVs in society, using the terms of car-poverty and car-utility as defined in Part A of this Chapter. The second part of the survey asked respondents to assess what impact the generic policies set out in the literature review may have on the cost and utility of owning a car. The final part gathered background demographic information on respondents.

Promotion of the survey was to targeted individuals and audiences through a number of electronic media including mailing lists, newsletters, websites and social networking sites for academic and professionals working in the areas of energy, transport and philosophy. Survey participants were self-selecting, given the option to take part if they considered themselves ‘an expert’ in LCVs with a sound knowledge of both technology and policy. It is recognised that the data therefore is reliant on a level of trust in the honesty of the respondents. Additionally, this method of anonymous self-selection and self-assessment, and the limitation to on-line advertising and participation, may introduce some bias in participants. However, this work does not seek to carry out detailed statistical analysis of data, but to capture a descriptive indication of attitude and opinion. This should be borne in mind by the reader. The survey was open between July 2012 and January 2013, and had forty eight responses, eleven of which were not completed. Response rates for quantitative questions ranged between 65 and 100%. Of those who responded, the majority were from an engineering or policy background, though there were some from philosophy, and this was in line with expectations. Most respondents were male, which may be due to the heavy bias of males in both engineering and philosophy, and there was a spread of ages, with the majority of people who answered this question being between twenty and forty.

3B.2.1 Support for Claims

Part A of the survey asked respondents some general background questions on their attitude and opinion of the role of the car, the impact of LCVs and the importance of these in the context of climate change. These responses were framed by a five point Likert scale ranging from Strongly Agree to Strongly Disagree. The survey was designed whilst the ethical framework was still being developed. Therefore, although the wording of the questions presented in Part A of the survey do not entirely reflect that of the claims which form the framework, they nonetheless provide some interesting insights. The results from this part of the survey are presented in Table 3.1. As can be seen, ‘Agree’ is the strongest response in each question, and there is an over 50% agreement with all questions, apart from 1e (*it is important to limit decreases in car-utility*), though even this question had more positive support than negative. It is noted however, that it is relevant that there is notable neutrality and disagreement to the questions, particularly Questions 1d to 1f where over a quarter of respondents were neutral. This does, however, imply that the concerns of the ethical framework are not controversial. To assess this level of support in more detail, it would seem appropriate to consider Questions 1a, 1f, 1g, and 1h in terms of Claim 1, and Questions 1b to 1e in terms of Claim 2.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	TOTAL
1.a. The introduction of low carbon vehicles will change the way we view and use cars in the UK.	9 *(19%)*	**24** ***(50%)***	5 *(10%)*	9 *(19%)*	1 *(2%)*	*48*
1.b. There is a general and defensible claim that one should be able to own and run a car that meets one's needs.	8 *(17%)*	**24** ***(51%)***	5 *(11%)*	9 *(19%)*	1 *(2%)*	*47*
1.c. Certain segments of society may have a stronger claim for owning a vehicle than others.	14 *(29%)*	**24** ***(50%)***	4 *(8%)*	2 *(4%)*	4 *(8%)*	*48*
1.d. It is important to limit increases in Car-Poverty.	5 *(10%)*	**22** ***(46%)***	13 *(27%)*	7 *(15%)*	1 *(2%)*	*48*
1.e. It is important to limit decreases in Car-Utility.	3 *(6%)*	**18** ***(38%)***	14 *(29%)*	10 *(21%)*	3 *(6%)*	*48*
1.f. Limiting increases in Car-Poverty is more important than limiting decreases in Car-Utility.	7 *(15%)*	**17** ***(36%)***	13 *(28%)*	7 *(15%)*	3 *(6%)*	*47*
1.g. Some increases in Car-Poverty are permissible in the context of climate change.	4 *(8%)*	**29** ***(60%)***	9 *(19%)*	4 *(8%)*	2 *(4%)*	*48*
1.h. Some decreases in Car-Utility are permissible in the context of climate change.	8 *(17%)*	**24** ***(52%)***	8 *(17%)*	5 *(11%)*	1 *(2%)*	*46*

Table 3.1: Responses to survey Part A

Claim 1[75]

The responses to Question 1a are nearly 70% in agreement with the statement that LCVs will "change the way we view and use cars". Although view and use may not be synonymous, this positive response suggests agreement that LCV introduction (which I assume is brought about or accelerated by coercive policies) will impact on the role of the car in society. What this doesn't confirm is if this impact will be positive or negative. As previously established, opportunity for car ownership is assumed to be affected by car-poverty and car-utility. Looking at the responses to Questions 1g and 1h in Table 3.1, over two thirds of respondents agreed that some negative impact on car-poverty and car-utility is permissible in the context of climate change and this can be taken as indicative evidence of support for Claim 1. There was stronger support for 1h, which reflects the general agreement in Question 1f that limiting impact on car-poverty is more important than on car-utility.

[75] *In order to limit the harms of climate change, there is a strong case in favour of coercive policies that promote the introduction of LCVs – even if these policies may limit people's opportunity for car ownership.*

Claim 2[76]

Over two thirds of respondents to Question 1b either agreed or strongly agreed that one should be able to own and run a car that meets ones needs, which may imply that there is a form of lock-in to car ownership. Question 1c confirms that almost 80% of respondents had a positive support to the statement that certain segments of society may have a stronger claim than others for car ownership, and was the strongest agreement of all the questions in Part A of the survey. Although this response cannot be used to confirm direct support for special consideration within policies for these groups, it does imply that others agree that such groups exist. Further support could come from Questions 1d and 1e, which showed that over half of respondents believed that the negative impacts on car-poverty and car-utility should be limited. It should be noted however, that the relatively strong agreement with Question 1g may somewhat undermine support for this claim.

3B.2.2 Impact of Policies

Regulation and *Fiscal Measures* were identified in the literature review as being the most high profile policies. As a central concern of this research is the distributional impacts of such policies, then it seemed sensible to develop an understanding of the potential impacts of all the generic policy options on the opportunity for car ownership. By doing so, it was possible to determine which policies should be the focus of this research.

In Part B of the survey respondents were asked to give their opinion on what impact each generic policy type could have on the *average* cost (Question 4) or utility (Question 5) of car ownership to the consumer by 2020. In doing so they were asked to take account of a number of parameters, including likely market penetration, both running and purchase costs, progress in technical attributes and ease of use. Respondents were provided with descriptions of policies and definitions of terms to assist understanding (see survey screenshots in appendix). The impact was assessed using a seven point scale ranging from Significant Increase to Significant Decrease given arbitrary scoring functions from -3 (most negative impact) to 3 (most positive impact), with intervals between impact levels being nominally 5%, and a no impact option. When the results were collected, an

[76] *In the short-term, many people are somewhat locked-in to car ownership for access and mobility. As such, policies should not allow additional unfair burdens on those who are already amongst the worst-off in society, or result in a different group of people being similarly disadvantaged.*

average score for each policy could be calculated. An in-depth multi-criteria analysis through a participatory approach may have been preferential, but as this is part of a small study, a simple online survey was thought to be more suitable. A number of approaches were considered, as the question is rather complicated. Too much information could deter a respondent from answering at all, whereas too little information may create confusion or not provide the respondent with enough guidance to appreciate the context of the question. Eventually, it was decided to limit the survey to two questions, one each for cost and utility, but with supporting information. The survey design was further informed by standard survey development methodologies (Denscombe, 2003), and a simple descriptive technique of displaying the data using a box and whisker plot was chosen (Dytham, 2010).

In assessing the impacts on cost and utility, the respondents were asked to consider how these could change for each of three powertrains (ICEV, PiHEV and BEV) and also how their market shares could change by 2020. In order to do this, policy descriptions, concept definitions and current cost and utility for each powertrain were provided, as in Table 3.2. For these, the attributes for Ford Focus (ICEV) and Nissan Leaf (BEV) and Vauxhall Ampere (PiHEV) were provided.

	ATTRIBUTE	ICEV	PiHEV	BEV
COST	*Purchase Price (£'000)*	20	37	31
	Operating Cost (ppm)	26.3	13.1	6.8
UTILITY	*Maximum Speed (mph)*	125	100	90
	Maximum Power (kW)	102	54	80
	Maximum Full Tank Range (miles)	630	360	100
	Fuel Availability (%)	100	90	40
	Max. Refuel/Charge Time (hrs)	0.25	6	12
	Refuel/Charge Location	Service stations	Service stations, home and public charge points.	Home and public charge points.

Table 3.2: Vehicle attributes in survey Part B

C/D-segment vehicles (small family car) was chosen as the highest selling new car segment in the UK (SMMT, 2013a) and because there are currently no BEV or PiHEV available in smaller classes. In these calculations, an equal petrol/diesel market share was assumed for ICEV. Purchase price, LCV fuel costs, range and speed/power were all taken from the manufacturer websites (Ford, 2012; Nissan, 2012; Vauxhall, 2012), and fuel availability calculations were the same as used in Case Study 1 of the modelling exercise (see Chapter 4). LCV refuel times and costs were also taken from manufacturer websites and calculated using EU energy prices (EEP, 2013) with ICEV derived anecdotally from the authors experience and the Automobile Association (AA, 2012). Operation costs included tyres, service labour, replacement parts, parking/tolls and tax, with LCVs being half that of ICEVs (in line with most estimations), but omit deprecation, insurance and breakdown as these were assumed to be similar for all vehicles (AA, 2012).

Figure 3.1 presents the descriptive survey results for the impact of policies on ownership cost (including purchase and running). As the scoring functions were approximately ordinal and this is a pilot study, the mean is taken to be an adequate average estimation alongside the median and interquartile ranges. *Regulation* and *Fiscal Measures* have negative mean and median scores, and the median is low in the range. In addition, almost 90% of respondents felt that *Regulation* would increase the cost of car ownership and nearly 60% thought that *Fiscal Measures* would also do this. This supports the view that these policies should be a focus of modelling work. *Facilitating Adoption* and *Raising Awareness* both have even spreads of responses around the median, the first having an approximately even split of respondents between a positive, negative or no impact, and the latter having almost two thirds of respondents assigning no impact and the remainder equally split between positive and negative impact. *Competition and Collaboration* is the only measure where the majority of respondents believe the impact on cost will be a positive one. In summary, respondents believed that only *Regulation* and *Fiscal Measures* may have a negative impact on average cost of ownership.

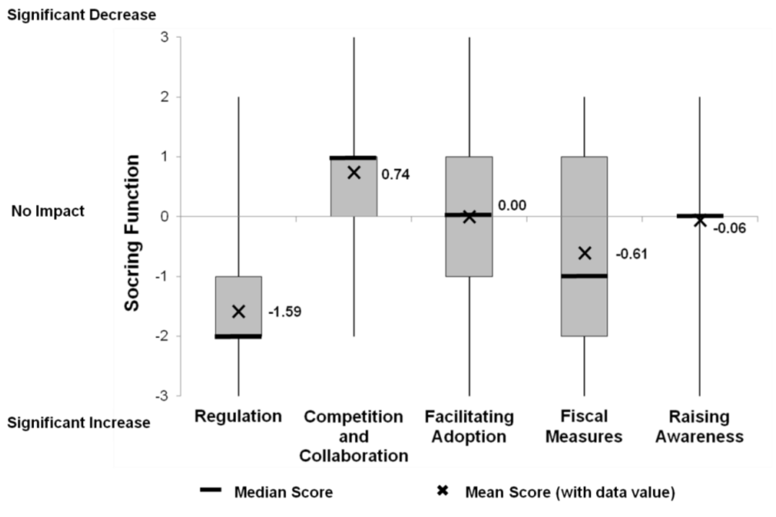

Figure 3.1: Descriptive results of survey Q.4.
Impact of policy on average cost of car ownership by 2020.

The descriptive results of the average impact of policies on utility of car ownership are shown in Figure 3.2. The findings indicate that no policies have negative mean and median scores, and only *Regulation* and *Fiscal Measures* (the policies with negative cost impacts) have an interquartile range that covers negative scores. This is a surprising result, as the hypothesis was that policies could reduce overall utility due to inferior LCV attributes. It is possible that the question or definition of car-utility was mis-interpreted by the respondents, but could also suggest that respondents thought that LCVs with a lower utility would not account for a large enough proportion of overall fleet to make a difference in overall utility, or else that they focused only on improvement in LCV utility. It is however, hard to account for how respondents interpreted the question. Looking at simply positive or negative responses, for each policy over a third of respondents believed there would be positive impact, with over half of respondents believing *Competition and Collaboration* and *Facilitating Adoption* would have a positive impact on utility. If this does occur, then policy makers may be tempted to focus on implementing them over other options. This would be a worrying strategy as there are numerous arguments for a move away from being a car-dominated society in the long-term. In summary, respondents believed that there would be very little impact from policies on average utility, and if anything, it would be positive.

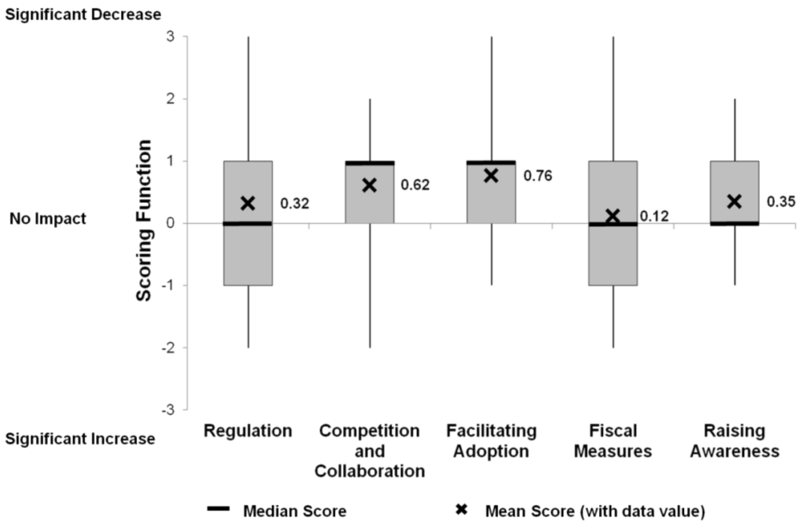

Figure 3.2: Descriptive results of survey Q.5.
Impact of policy on average utility of car ownership by 2020.

3B.3 Qualitative Evaluation

Alongside the survey, which provided opportunities to comment on each of the questions, a workshop was held. The workshop was convened to bring together professionals and academics in various fields to specifically discuss the impact of the new technologies on society. Traditionally, different disciplines rarely mix, but this subject is at the juncture of the three disciplines of engineering, transport policy and ethics. The workshop involved talks from experts in each of these fields followed by a facilitated discussion, based on the survey questions, regarding how introducing LCVs will change the way we view and use cars, claims for ownership and vulnerabilities to car-poverty and car-utility. Having both the survey and the workshop maximised the gathering of qualitative data in order to gain a greater understanding of the problems, and for the appetite for collaboration and cross discipline understanding in this area.

Figure 3.3 shows a “word cloud” representative of the workshop transcript[77] and comments captured in the online survey.

Figure 3.3: 'Word Cloud' of qualitative data

[77] This was not a verbatim transcript.

The size of each word as it appears in the image corresponds to the number of times that word appears in the text. Although no conclusions can be drawn directly from this, the illustration serves as a good visual representation of the key issues and interests arising in this work. The three most obvious words are *“people”, “need”* and *“change”.* It is recognised that these words may be biased by the wording of the questions asked, but the fact that that these three words should stand out reminds us of the concerns of the impacts of LCVs – that it affects us all (“*people”*), that there is some level of basic dependency which will be affected (*“need”*) and an acknowledgment that we cannot stand still (“*change”*).

In order to elucidate if there is any further support for the framework, a simple confirmatory analysis of the transcript and comments (Guest et al., 2012) was carried out with the intention of only identifying any evidence which was in support or denial of the claims of the ethical framework. Although this does not in itself confirm or deny any support, it does in fact highlight the many complex interactions and considerations in this area.

Claim 1[78]

For Claim 1, there was no explicit support regarding decarbonisation – but it was felt that this was not mentioned as it was perhaps taken as a given. This may reflect the interests of the people attracted to take part in the workshop and survey in the first place. Although it does not appear that any of these themes directly support Claim 1, it is not disputed either. As said by one workshop participant *“people want to do the right thing”* and *“if you can get somebody to change for a good reason it will mean something deeper to them”,* suggesting that people can only be confident in doing this if they feel they are making a fully informed choice. In the UK, many decisions are structured around ‘wants’, and the definition of how that differs from a need is not clear – such as where to draw the line between subsistence and luxury. Understanding of this can help people make better decisions. There is a declining trust in institutions from the public and people, in general, do not want to change. As another workshop attendee suggested, *“this does not mean they should be pushed, but perceptions can be challenged”.*

On the other hand, there were some comments which would appear to be against the claim. It was recognized that *“the free market is how we developed as a society”*

[78] *In order to limit the harms of climate change, there is a strong case in favour of coercive policies that promote the introduction of LCVs – even if these policies may limit people’s opportunity for car ownership.*

in the West, and that this generally allows change to happen at the right time. Indeed, a survey respondent queried, *"is it appropriate or necessary for policymakers to intervene directly in the automotive industry by introducing disruptive incentives for use of particular types of prime mover – or should this be left to market forces?"*

There would seem to be a general agreement that as an evolving society, *"a decrease in utility is not an option",* though another participant believed that *"we can deliver a low carbon fleet without having to ask people to change".* A survey respondent suggested that "*decreases in car-utility could be viewed as positive in the context of smart urban/residential and infrastructural development that reduced the need for private cars"*, though this is beyond the scope of this research to directly consider.

Claim 2[79]

Regarding Claim 2, there appeared to be a strong recognition of the lock-in to car ownership, and that this in itself may create inequalities or emphasis existing ones. It was suggested that *"mobility is a core component of how we operate as a society",* and that "*mobility is a right – but not necessarily car ownership, even though they are very much linked".* Further to this, there were some comments that strongly believed that this lock-in exists for everyone, described by one survey respondent: *"the majority of the population MUST have a car in order to get to work, shop etc and most of them will never be able to afford a new car, therefore the existing car stock is all that is available to them for many years to come*" and another believed *"that vehicle use will never decrease due to safety, movement of vehicles and the way that life is now".* One survey respondent recognised this lock-in can cause distributional issues as *"a car can be a necessity and some people who can't afford a car are at a disadvantage".*

A number of points were raised regarding whether 'ownership' itself requires preserving or if it is access to a vehicle which is more important. Ownership is restricted by purchase costs more than running costs and enforces existing inequalities. For example, one survey respondent voiced their concerns that "*a low carbon car future simply bolsters the mobility divide between those with access to*

[79] *In the short-term, many people are somewhat locked-in to car ownership for access and mobility. As such, policies should not allow additional unfair burdens on those who are already amongst the worst-off in society, or result in a different group of people being similarly disadvantaged.*

private vehicles and those who don't (have access). In fact it could increase it as the market for low carbon vehicles is immature and doesn't allow a mechanism for easy access to second-hand vehicles".

If cars had never been affordable they would not have integrated our society as they have. One respondent believed that *"individuals are entitled to cars if they can afford them",* whereas as previously mentioned, others fear such market led approaches can amplify inequalities. Car markets are already segmented and exploited by car manufacturers, but we are currently locked in to markets which may no longer be appropriate. This includes the use of GDP as a measure of success or progress, and the inadequacy of internalization of carbon (or other environmental) costs, however, one respondent suggested that *"no mechanism is too big that society could not together solve these problems"*, though it was also recognized by another participant that *"this is relatively easy to discuss at the concept level. The real issues maybe only come out when you look at individual cases".*

3B.4 Conclusion

Bringing together the findings of this Chapter, the following conclusions can be drawn which help set out an approach to modelling within the ethical framework. Firstly, from considering the responses to Part A of the survey, the arguments presented in the ethical framework seem to be supported, so there is confidence that there is validity in the claims, beyond the arguments presented in Part A of the Chapter. Secondly, the responses to Part B of the survey would suggest not only that there is general agreement that policies will impact on cost of car ownership, but also that the two policies that were suggested in the literature review to be the most high profile, are the two which come across as having potentially the greatest negative impact on costs of ownership. This further strengthens the case that these should be the focus of research. Finally, the qualitative analysis of the comments provided through the survey and workshop revealed that although some support for the claims appeared to exist, there are numerous conflicts and concerns which make LCV policies complex.

With this established, it would seem appropriate to then identify what would be required in a model in order to assess policies within this ethical framework. As the response to Part B suggests that experts do not believe that the policies will have a negative impact on utility, the focus should be on cost,[80] where the chosen policies were found to have negative impacts. This is because the concern of this research is towards reducing burdens on the worst-off.[81] Therefore, in the model, the following outputs will be required:

- *Carbon emissions* as the policies are only permissible in the context of climate change, and;
- *Changes in opportunity for car ownership*, represented by purchase cost, for societal segments defined by their vulnerability to car-poverty.

[80] The fact that the findings suggest that the policies will only have neutral/positive impacts on utility may, as mentioned, mean that the question was not understood. However, if it was taken in the way it was meant to be, and experts genuinely believe this to be the case, then it could be that these policies should be given more attention in future work.

[81] Recall the stipulations in Part A that define what is meant by the worst-off in this research.

CHAPTER FOUR: MODELLING CASE STUDY ONE

The purpose of the first case study was two-fold. Firstly to develop skills and understanding of modelling processes, and secondly to explore basic factors affecting the uptake of Low Carbon Vehicles (LCVs) in the UK. The model was developed initially for contribution to the *“Plug-in Vehicles Economics and Carbon Benefits Project”,* funded by the Energy Technologies Institute (ETI, 2010) and part of a larger government research programme for the roll out of LCVs. An aggregate version of this work was reported in Shepherd et al., (2012). This Chapter commences with a detailed description of the base model and extensions made to it for the purpose of this research, mainly in adapting it for the UK. The model calibration and development of *“Business as Usual”* (BAU) and *“Conditional Marketing”* (CM) baselines are then described. Following this, the results of model testing is presented in three sections. The first describes sensitivity testing of some key model variables, the second presents scenarios related to options for Electric Vehicle subsidies (an example of a *Fiscal Measures* policy) under both a BAU and CM scenario, and the third is an illustrative representation of a *Regulation* policy on manufacturers, based on a BAU scenario. The findings are then discussed in more detail.

4.1 Description of Base Model

The case study is based on a core model originally built by Sterman and Struben (2008) (see literature review) to study the market formation and diffusion dynamics for alternative fuel vehicles (AFVs) with a focus on the feedbacks concerning customer awareness and consideration of AFVs. This model draws on established diffusion models and discrete consumer choice models, and is a reduced-form of a more detailed model for AFV adoption that was developed in a PhD thesis of one of the authors (Struben, 2006). This case study takes the Struben and Sterman model as a base and builds upon it, in the specific case of Electric Vehicles (EVs – this includes both Plug-in Hybrid Electric Vehicles (PiHEV) and Battery Electric Vehicles (BEV)) in the UK. The most important elements are presented in Figure 4.1. Details of underlying equations and parameters are available in Appendix B. What follows is a description of the most important elements as developed by Struben and Sterman, as well as the assumptions and modifications for the UK model.

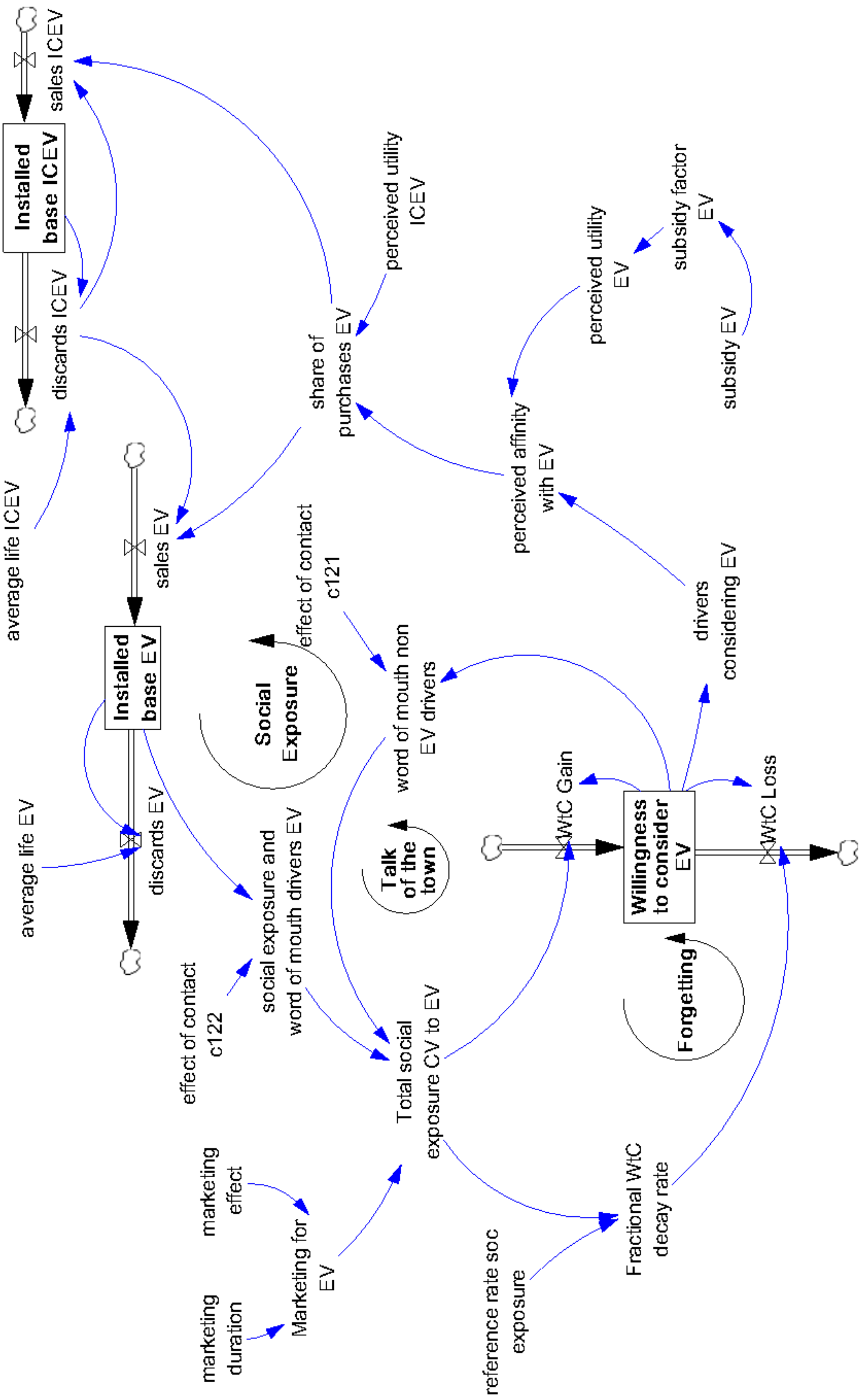

Figure 4.1: Main model of Case Study 1 (adapted from Struben and Sterman, 2008)

There are a number of interesting elements contained within this basic model. First, shown at the top of Figure 4.1, are the separate stocks of installed bases of Internal Combustion Engine Vehicles (ICEVs)[82] and EVs.[83] These are calculated in each time period from the number of sales and discards that have taken place in the previous period. Within this there is a constant installed base of 32 million vehicles so there are no new drivers entering the market, only replacement vehicle sales. As can be seen in Figure 4.1, the inflow of the installed base stock is sales and the outflow is discards. Discards are related to an average vehicle life of 14 years[84] (CfIT, 2001) and are equal to the total sales, which are then modelled in terms of the purchase share using a standard MNL choice model equation as described in the literature review, based on perceived utility to vehicle platforms. *"Share of Purchases EV"* in Figure 4.1 represents Equation 4.1, which calculates the share of sales of EVs (assuming a single platform) from those who have just discarded an ICEV. For these ICEV discarders, their perceived utility of an EV is assumed to be reduced by their lack of awareness of an EV, so the resultant *"perceived affinity"* is used in the logit model instead of the usual *"perceived utility"*. This differs from those who have just discarded an EV (which is not represented in the figure), as they are fully aware of the EV so can base their choice on the full perceived utility of an EV in the usual way.

$$\sigma_{EV} = \frac{a_{EV}^{P}}{u_{ICEV}^{P} + a_{EV}^{P}}$$

Equation 4.1

σ_{EV} is sales of EV

a_{EV}^{P} is the perceived affinity that that a drivers may have with an EV, and is dependent upon awareness of the platform and perceived platform utility.

u_{ICEV}^{P} is the perceived utility of ICEV

The key element of the base model, which was not altered in the case study, was the technology/diffusion process, which followed a standard diffusion S-curve (see Literature Review). As this is of particular importance it will now be discussed in more detail. The perceived affinity that has already been mentioned is a product of the vehicle utility and the drivers' *"Willingness to Consider"* (WtC) the platform. Each powertrain has set values of attributes, being range, fuel availability, emission

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[82] The ICEVs in the model are assumed to be produced to be conventionally fuelled but to avoid confusion they are referred to as simply ICEV.

[83] Struben and Sterman use generic Alternative Fuel Vehicle (AFV) rather than EV.

[84] Struben and Sterman used a conservative US estimate of 8 years based on their sensitivity analysis, but 14 years was found to be more appropriate for the UK.

rating, maximum speed, operating cost, and purchase price. The coefficients for each attribute were obtained from a choice model (Batley et al., 2004), and used to generate a generalised cost for each powertrain to calculate the perceived utility.

Within the diffusion process, a specific social exposure loop calculated a customer's WtC a specific vehicle platform. When a driver is unaware of a powertrain, WtC is 0, and the maximum WtC is 1, meaning that they are fully aware of the powertrain and would always consider it. For example, everyone considers a ICEV, so WtC ICEV was assumed to be constant at 1, whereas, only those drivers who have been exposed to EVs would have a WtC EV greater than 0. However, WtC represents more than just platform awareness;

> *"Willingness to consider a platform captures the cognitive, emotional, and social processes through which drivers gain enough information about, understanding of, and emotional attachment to a platform for it to enter their consideration set".* (Struben and Sterman, 2008, p.1077)

As illustrated in Figure 4.1, WtC is a product of two competing causal loops, *"Forgetting"* and *"Talk of the Town"* (TotT). The TotT causal loop consists of the effect of the total exposure to EVs from *marketing effectiveness* of EVs and *"Word of Mouth*" (WoM) contacts from both EV and non-EV drivers (that are only ICEV drivers in this case as no other powertrains are included), and assumes these interactions are positive. Total social exposure, the proportion of drivers who are aware of EVs, arises from marketing and contact between drivers, and is captured in Equation 4.2.

$$\eta_{ICEV,EV} = \alpha_{EV} + c_{ICEV,EV}\, W_{EV,EV} \frac{V_{EV}}{N} + \sum c_{ICEV,\neq EV}\, W_{ICEV,EV} \frac{V_{ICEV}}{N}$$

Equation 4.2

$\eta_{ICEV,EV}$ is the impact of total social exposure on the increase in familiarity of EV for ICEV drivers

α_{EV} is the marketing effectiveness for EVs

$c_{ICEV,EV}$ is the frequency and effectiveness of contact about EVs between ICEV drivers and EV drivers

$W_{EV,EV}$ is the willingness of an EV driver to consider an EV

V_{EV} is the installed base of EVs

N is the total installed base of vehicles

$c_{ICEV,\neq EV}$ is the frequency and effectiveness of contact about EVs between ICEV drivers and non-EV drivers

$W_{ICEV,EV}$ is the willingness of a ICEV driver to consider an EV

V_{ICEV} is the installed base of ICEVs

The first expression in Equation 4.2 relates to marketing. In the base model, the marketing effect is constant through the time period and was based on estimates from marketing literature (this is varied in the conditional marketing baseline, therefore further detail on this is provided later). The second expression in Equation 4.2 is the WoM from those with direct social exposure of seeing EVs "on the road" and talking to EV drivers, based on the frequency and effectiveness of contacts and the share of the installed base of EVs. Due to the low intial EV installed base WOM from EV drivers has little impact at the start of the time period. WoM between ICEV drivers is captured in the third expression in the same way, and dominates social exposure at the start of the time period (see Section 4.4.1 for sensitivity testing on WoM). Thus, as installed base of EV increases, this results in a positive feedback as WtC increases leading to an even higher share of EVs (the *"social exposure"* loop in Figure 4.1) and increased WoM in the TotT loop.

The TotT reinforcing loop is balanced by the Forgetting loop, which captures a rate of decay as customers 'forget' their exposure to the EV, thus decreasing their WtC. Previous work by Struben (2006) found that this awareness parameter was highly non-linear, requiring exposure to be *"sufficiently intense"* before there is no decay. The "*fractional rate of decay"* is a function of the total social exposure (Equation 4.2) and a maximum decay rate, so that when total exposure is equal to zero, then the decay rate is 1, and the rate tends to 0 as social exposure approaches ∞ as captured in the logistic function shown in Equation 4.3. Other functional forms of this were explored by Struben and Sterman in previous work (Struben, 2004), but this expression was proven to provide robust results. Further to this, they tested the sensitivity of the decay in social exposure to installed base and marketing effects, and found that in the absence of these (i.e. if all EVs were removed and un-marketed), it would take 5 years for WtC to fall from 50% to 5%. This can be slowed by including marketing, but under base case parameters EVs need only capture 5% of installed based again to increase WtC to 100%.

$$f(\eta_{ICEV,EV}) = \frac{exp[-4\varepsilon(\eta_{ICEV,EV} - \eta^*)]}{1 + exp[-4\varepsilon(\eta_{ICEV,EV} - \eta^*)]}$$

Equation 4.3

$f(\eta_{ICEV,EV})$ is the fractional rate of decay

η^* is the reference rate of social exposure at which WtC decays at half the normal rate

ε is the slope of the decay rate at the reference rate of social exposure ($1/2\eta^*$)

The base model assumes the marketing effect is constant, and is set to a time period of 40 years, nominally starting in 2010. The modifications made to the base model for this research are described in the next Section. The model was then calibrated to UK data, as detailed in Section 4.3.

4.2 Extensions to the Base Model

There are a number of notable amendments made to the Struben and Sterman base model in order to ensure that the case study was suitable for this research. These will now be described in more detail.

4.2.1 UK Choice Model

One of the most significant changes was the inclusion of a UK discrete choice model (Batley et al., 2004) to calculate the perceived utility, and as part of this, UK based vehicle attributes. This is discussed in more depth in the next section, as it was used in calibration of the model.

4.2.2 Vehicle Platforms

The inclusion of more than one vehicle platform was also an important amendment. In the Struben and Sterman base model there is only one generic AFV, whereas it was the desire of this research to consider Electric Vehicles (EV). The two EV platforms included were a Plug-in Hybrid Electric Vehicle (PiHEV) and a Battery Electric Vehicle (BEV).

4.2.3 Price-volume Effect

Purchase prices are connected to the perceived utility of customers towards EVs. There was a concern that the purchase price of EVs would not (in reality) be constant over the period of study, but would actually come down as EV take-up increased. This would occur through economies of scale in production costs and improved technology reducing battery costs. Therefore, a *"price-volume effect"* was built into the model that was a standard learning curve with the price differential being reduced to 95% of the previous value as the EV installed base doubles. Tsuchiya and Kobayashi (2003) state that the typical learning curve is described by Equation 4.4, with the exponent r calculated by Equation 4.5.

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$$Y_i = AX_i^{-r}$$

Equation 4.4

Y_i is the product cost at i^{th} production

X_i is the cumulative number of products at i^{th} production

A is a constant

$$r = \frac{\ln F}{\ln\left({^{Vt}}/{_{Vo}}\right)}$$

Equation 4.5

F is the progress ratio of production cost reduction

V_t is the EV installed base at time t

V_O is the original EV installed base

The value of 95% was taken from the report to Energy Savings Trust (2007) which states "*The typical learning rate within the automotive sector for new technologies is 95%. The learning effect is applied to the additional cost of each technology above the C/D baseline vehicle.*" Using Equation 4.5, as F is equal to 95% and V_t/V_o is 2, then r is 0.074. The price effect is demonstrated in Figure 4.2 as the relationship between purchase costs and installed base for BEVs.

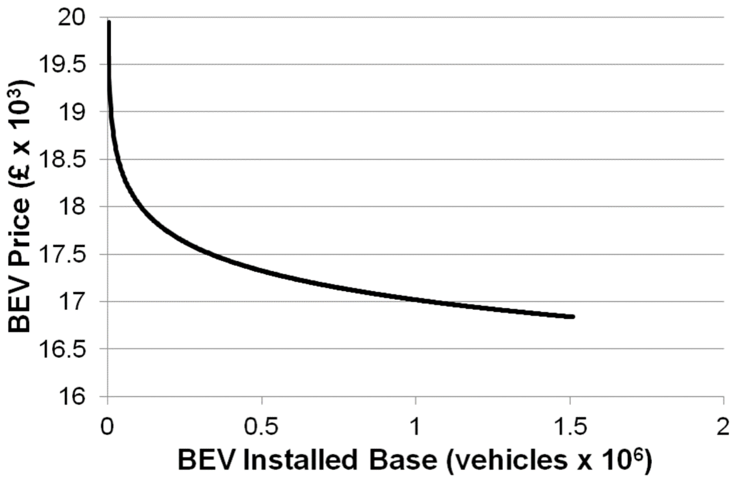

Figure 4.2: Price effect of BEV

4.2.4 Loss in Fuel Duty Revenue

One common concern about the introduction of EVs is that there will be a loss in the significant income to the UK government from duty paid on conventional fuels. A number of options to compensate for this are being considered, such as tax based on vehicle mileage. In the model a revenue preserving tax was added as a one-off annual fee within the car purchase model, so it would be felt similar to purchase price. Though inclusion within operating costs may have been equally as valid, it was felt that this approach was more representative, as it is similar to increasing VED by emissions as carried out in the UK.

To add such a tax to the model, it was first necessary to include within the model how much fuel duty revenue would be lost every year. This was taken to be the difference between the initial fuel duty revenue from a ICEV only fleet and the fuel duty revenue in the transformed fleet for each year, shown in Equation 4.6 . As the model is constant fleet and mileage, fuel duty was also assumed constant to allow a simple comparison. Though this may underestimate losses, a cautious approach was felt to be more suitable. However, as ICEVs become more fuel efficient, it could imply a relative increase in duty, which aligns with government intentions. Therefore, the initial fuel duty revenue is a product of the fuel duty (7.86p/mile),[85] installed base and ICEV mileage (15,000km / 9.375 miles (BERR/DfT, 2008)), which is £23.58b. The fuel duty in the transformed fleet comes from ICEV and PiHEV, and is the product of fuel duty, annual mileage and installed base for each of the two powertrains, with PiHEV users paying only 80% of fuel duty in line with their reduced emissions (see Section 4.2.5).

$$\begin{aligned}
&Fuel\ Duty\ Revenue\ Loss\ per\ annum\\
&\qquad = (FD \times AM_{ICEV})\\
&\qquad - [FD \times ((AM_{ICEV} \times IB_{ICEV}) + (0.8 \times AM_{PiHEV} \times IB_{PiHEV}))]
\end{aligned}$$

Equation 4.6

FD is the fuel duty (constant at 7.86p/mile)

AM_x is the average annual mileage each year for powertrain x

IB_x is the installed base each year for powertrain x

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[85] Based on 58.96p/litre and 12km/litre (HMT, 2010).

To calculate average mileage, assumptions were made that PiHEV would have similar average mileage to ICEV, whereas BEV would be slightly lower, at 80% of ICEV mileage, but could rise as range increases, equalling that of ICEV at a range of 350 miles. As this may reduce total mileage (and the model is set at a constant mileage), any loss is made up by increasing the mileage of ICEV and PiHEV user. The lost revenue could then be redistributed among all drivers based on miles driven per year (which is constant in this model), as a revenue preserving tax, shown in Equation 4.7.

$$Annual\ Revenue\ Preserver\ Tax = \frac{FD_L}{TM} \times AM_x$$

Equation 4.7

FD_L is the annual fuel duty revenue lost

TM is the total annual fleet mileage

AM_x is the average annual mileage for powertrain x

4.2.5 CO_2 Emissions

The driving focus of this work is not just the increase in market share of EVs but also what impact that has on CO_2 emissions. For this a simple aggregate approach was used. The emissions of each powertrain in each year were calculated using Equation 4.8, and then summed together for total emissions per annum. In the base case, fleet average Well- to-Wheel ICEV emissions were assumed to be 165g/km in 2010, reducing to 115g/km by 2050, PiHEV were 80% of ICEV and BEV were 106g/km down to 41 g/km. This was in line with the BERR/DfT (2008) report used to calibrate the model (see later), based on vehicles manufactured in 2030 and allowing for a lag for emissions from previous cohorts of vehicles. Ideally to fully understand impacts on CO_2, emissions from different classes of vehicles would be accounted for, but regulations are based on average fleet emissions and this approach gives a feel of the relative impact over time.

$$Annual\ CO_2\ Emissions = \sum EF_x \times AM_x \times IB_x$$

Equation 4.8

EF_x is the emission factor for powertrain x (CO_2/km x 1.6)

AM_x is the average mileage for powertrain x

IB_x is the installed base of powertrain x

4.3 Model Calibration and Baseline Development

In order to calibrate the model to a UK trajectory, it was scaled using a UK choice model and a previous sales prediction (BERR/DfT, 2008). Interestingly this calibration leads to a WtC of 1 for EVs by 2050.

4.3.1 Selection of the Coefficients

The choice coefficients came from the most recent and relevant stated preference (SP) study that used multinomial logit (MNL) and mixed logit (MXL) to model consumer demand for AFVs (Batley et al., 2004). Although technology and attitudes may have changed since 2004, it was the most recent and relevant study in the public domain at the time of the research, and it is assumed that this will not be significant. Six factors of customer choice, were considered: purchase price; operating costs; maximum speed; fuel availability; emissions; range and refuel location. It is recognised that less-emprical factors, such as affective, hedonic or symbolic attitudes towards the car do play a role in vehicle choice (Choo and Mokhtarian, 2004; Gatersleben, 2011; Peters et al., 2011; Schuitma et al. 2013; Sheller, 2004; Steg, 2005). However, such aspects are difficult to measure and a very recent study suggested that the strongest influence on choice in relation to this that can be captured is brand loyalty (Element Energy, 2013). This case study does not capture brand as an aggregrate manufacturer is represented, but would be an insightful addition to future research. Element Energy also identified that there are specific attitudinal barriers related to EVs, but these are related to technology maturity, which is captured in this model through the improving attributes, and consumer awareness, which is captured in this model through the WtC parameter as discussed.

Willingness to Pay and Willingness to Accept estimates were taken from Batley et al's MNL model, as follows:

- £665 for a 10mph increase in maximum speed;
- £1089 for a ten percentage point increase in refuelling availability;
- £986 for a 10% reduction in vehicle emissions;
- £335 for a 1p/mile increase in operating costs;
- £2225 for a reduction in vehicle range of 100 miles.

The selected base values for the attributes for each of the vehicle platforms are presented in Table 4.1. In the base case, these attributes were assumed to remain constant over time, apart from the EV purchase price, which is reduced over time as previously discussed. They are then manipulated in the sensitivity testing described in Section 4.4.1.

ATTRIBUTES	ICEV	PiHEV	BEV
Purchase Price (£'000)	12	18.5	20
Operating Costs (p/mile)	22	17	10
Maximum Speed (mph)	125	125	90
Fuel Availability (% of stations)	100	90	40
Emissions (1-10)	10	8	1
Range (miles)	350	350 + 25 electric	60

Table 4.1: Vehicle attributes

Purchase Price

A base value purchase price for ICEVs was taken from the Energy Savings Trust (EST, 2007), with an assumption of premiums on that price for PiHEV and BEV. The premiums used were the mid-points of a range of price premiums from an unpublished report by Ricardo Plc, which were £6,500 and £8,000 respectively.

Operating Costs

ICEV operating costs were taken from the Automobile Association (AA, 2012) for mid range petrol cars, and exclude depreciation, insurance and annual tax, but do include 'other running costs' related to maintenance etc. BEV operating costs were based on an assumed electricity consumption of 20kWh/100km (based on the small iMiev) and a lowest cost of 5p/kWh (typical night tariff in 2010), plus the 'other running costs' were also from the AA. PiHEV were assumed to have costs between those of ICEV and BEV. Although it may not be realistic to assume constant operating costs in the base case (considering unpredictable prices of oil and electricity), this in effect implies an offset by any increase in vehicle fuel efficiency as aggregate emissions reduce over time. Although this also may be unrealistic, because technological improvements do incur cost, as they are brought in over 40 years, an assumption is made that the impact will be minimal in order to retain the simplicity of the model.

Maximum Speed

As maximum speed is difficult to average across models, it was taken directly from Batley et al. PiHEV was assumed to be the same as ICEV and BEV was slightly higher than the original study as there had been technological progress since then.

Fuel Availability

ICEVs could be filled at any filling station. EV fuel availability is interpreted as the convenience of charging EV versus convenience of charging ICEV. It was assumed that most of PiHEV range will come from the ICE fuel tanks, which again can be filled anywhere. However, there will be some reduction in availability to account for the electric recharging, so PiHEV fuel availability is set at 90%. Based on Batley et al.'s refuel location penalty and willingness to pay for increase in fuel availability, an estimate is that BEV fuel availability is about 50 percentage points below PiHEV.

Emission Ratings

To highlight the difference between powertrains, ICEV is given the highest rating and BEV the lowest. PiHEV is given as a slightly lower emission rating than ICEV assuming that most of its use will be under ICE control.

Range

Assumptions are made based on the lower end of typically accepted ranges for the three powertrains.

4.3.2 Scaling the Predicted Share

The selected coefficients and attributes yielded a sales share in 2050 of 30.4% for PiHEV and 6.4% for BEV. However, as it is well recognised that stated preference based models may overestimate market shares, so scaling to a more recognised estimate was deemed necessary. A number of options were considered, but the most suitable was felt to be that from a 2008 BERR/DfT report *"Business as Usual"* Scenario, which suggests sales of 17.9% and 3.5% for PiHEV and BEV respectively in 2030. To do this alternate specific constants (of £3500 for PiHEV and £4000 for BEV) were added to the model. These alternate specific constants can be seen to reflect unobserved preferences.

4.3.3 Calibrating the Trajectory

The final step of calibration was to ensure that the standard S-shaped diffusion of the EV installed base is correct within the model. The BERR/DfT BAU projection was used again as a reference point that predicted 2.5m PiHEV and 0.5m BEV in 2030. The reference rate of exposure was adjusted until a similar fit was achieved, which was 2.4m PiHEV and 0.538m BEV (shown in Figure 4.3) at a reference rate of 2.5%. The difference is due to the assumption in this model of a constant car fleet whereas the BERR projection assumed growth. The growth effect was omitted to retain the simplicity of the model but also as growth is itself uncertain - if modal shift policies are successful then there could actually be a reduction in the fleet size. Although this assumption may lead to under or over-estimation of emissions, it is any relative impact that is the interest of this work.

4.3.4 BAU Baseline

Results from the model Business as Usual (BAU) baseline, following the extensions and calibration described in the previous sections, are presented in Figure 4.3. Installed base of PiHEV and BEV can be seen to increase in line with the BERR/DfT forecasts, and between them displace almost 30% of ICEV sales by year 40, though this market share has remained fairly constant for the latter half of the time period. Annual fuel duty loss has increased to almost £2b per annum by year 40 and annual emissions have been reduced by around a third since the start of the time period. Although it may be argued that perhaps EV powertrains may never realistically greatly displace ICEV or equal their market share, due to the restraints that they may have on some people, the emission reduction is disappointingly short of government targets and at great budgetary loss. These BAU results would seem to prove that interventions are required if EVs are to be a successful, cost effective method of reducing transport carbon emissions.

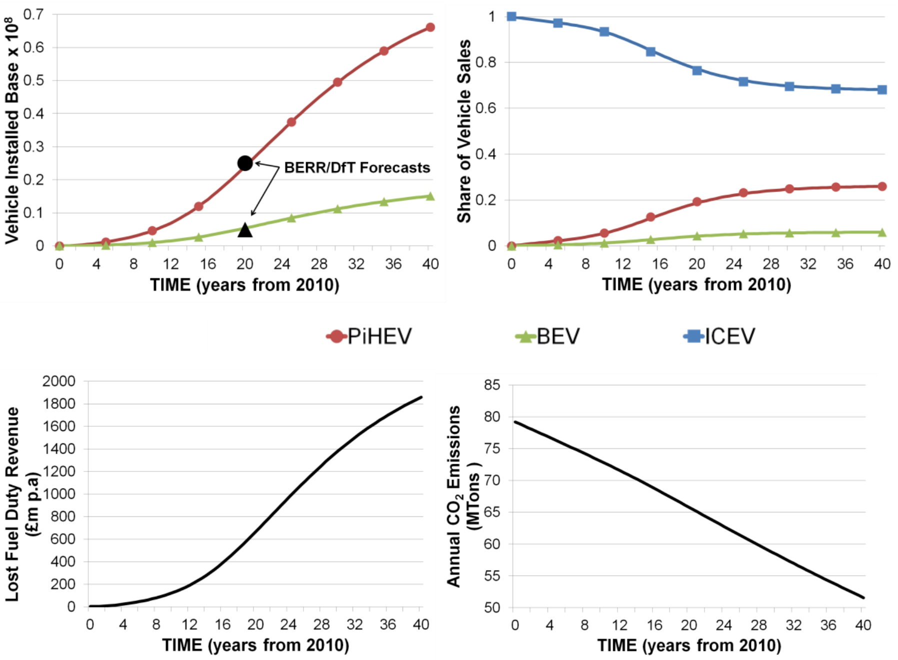

Figure 4.3: Outputs from model BAU baseline.
Installed base (top right); Sales market share (top left);
Fuel duty revenue lost (bottom left); Annual CO_2 emissions (bottom right).

4.3.5 Conditional Marketing Baseline

In the base model there is a constant marketing effect throughout the time period. This marketing effect could be assumed to come from the manufacturers themselves, through government awareness campaigns, or through a combination of the two. In the Struben and Sterman study, it was noted that the marketing duration has a significant impact on market success, as marketing was required to be in place for 20 years to sustain EV market penetration. In this model, it is assumed that the marketing comes directly from the manufacturers and that they reconsider their marketing and production after 10 years based on sales at that time. This is a reasonable assumption as continuing to fund potentially expensive marketing campaigns and vehicle development without success would be a risky business plan (though the choice of 10 years itself is fairly arbitrary).

In the BAU scenario, after 10 years the EV share of sales is 6.7%, and removal of the marketing results in market collapse, demonstrated in Figure 4.4. If marketing is retained, as in the successful case, year 11 has a share of 8%. As the marketing feeds directly into the social exposure and therefore WtC, this would seem to signal that the social exposure without the marketing is not effective enough after 10 years, so when marketing is removed there is a collapse. To recreate a failing case that could be tipped into success, a nominal threshold of 7.5% in year 10 (halfway between these shares) was chosen to create a hypothetical failure case. This represents a situation where if a 7.5% share is not attained by year 10, the manufacturer believes that the market will collapse and therefore no longer wish to invest in marketing. This mechanism was included in the model, creating a "*conditional marketing"* baseline.

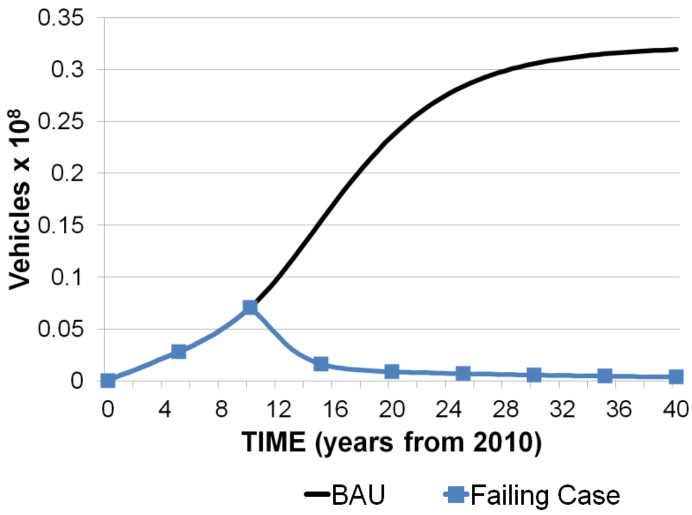

Figure 4.4: EV sales market share in BAU and failing cases

4.4 Model Testing

The purpose of this model was to build understanding of modelling processes and explore factors affecting EV uptake, specifically regarding the two specific policies relevant to this research, *Fiscal Measures* (in the form of subsidy) and fleet *Regulation*. This section describes the tests carried out.

4.4.1 Sensitivity Testing

The model BAU baseline was subjected to sensitivity testing for three of the input parameters. Firstly, the effect of *"word-of-mouth"* (WoM) within the social exposure loop on the WtC, secondly the average life of vehicles, and finally the emissions of the electricity generation.

"Word-of-Mouth" Effects

The *"Talk of the Town"* loop was described in Section 4.1. Within this, WtC is influenced by three input parameters (marketing, WoM with EV drivers and WoM with ICEV drivers), and was shown in Equation 4.2. The impact of marketing has already been discussed in the development of the failing case, which is also explored in later scenario testing. Therefore, it was felt worthwhile to consider the impact of WoM whilst keeping marketing constant, as the *"contact effectiveness"* values were taken from Struben and Sterman (2008), who themselves developed the value from another study (Easingwold et al., 1983), but they recognise them as being highly optimistic.

Figure 4.5 shows the impact of doubling and halving the WoM impacts from EV and ICEV drivers on WtC and ICEV installed base. These results clearly show that the WoM of ICEV drivers have a much greater effect than EV drivers, until the base of EV drivers builds to a significant level later in the time period. Perhaps what is of more interest is the impact on installed base of ICEV. Again the WoM of EV drivers would appear to make very little difference, but it is noticeable that halving the WoM of ICEV drivers seems to have a greater impact than doubling it does. This means that if the base case parameters of WoM were overestimated, then the predictions could be very optimistic. Clearly the results are highly sensitive to assumptions regarding WoM.

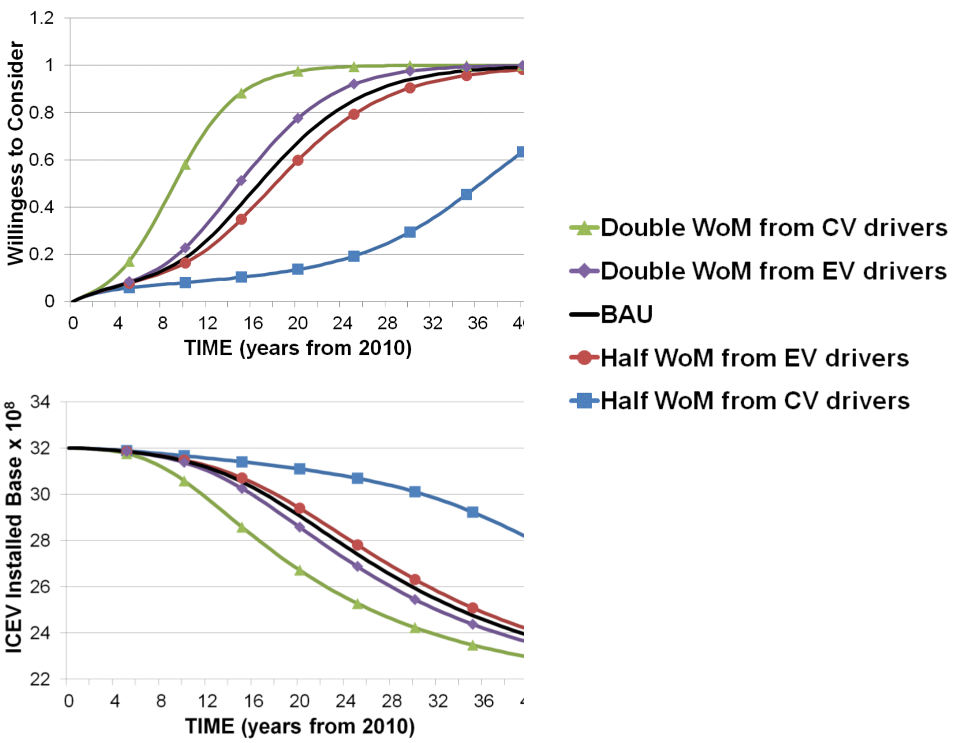

Figure 4.5: Impact of changes in WoM on WtC (top) and ICEV installed base (bottom)

Average Vehicle Life

Vehicle life is assumed constant in the BAU model. As a new technology, lifetimes for EVs are uncertain, particularly around battery life and associated expenses of replacing batteries, and so are generally expected to have a shorter life than ICEV. Also, so-called *"scrappage"* schemes could be reintroduced, that encourage the removal of older cars from a fleet by providing the owner with a discount on a newer model. To test the sensitivities regarding this, tests were carried out that reduced either the EV or ICEV life from 14 to 10 years, and the results of these on total EV installed base and annual CO_2 emissions is shown in Figure 4.6. This in effect increases the turnover of vehicles, and thus the total new vehicle requirement. When a vehicle is discarded the owner has the choice to either purchase the same type or change to another powertrain (as explained in Section 4.1). It is worth noting that vehicle life doesn't itself influence vehicle choice, though as few people will purchase a vehicle with the intent of keeping them for the whole lifetime, this may not be relevant in reality.

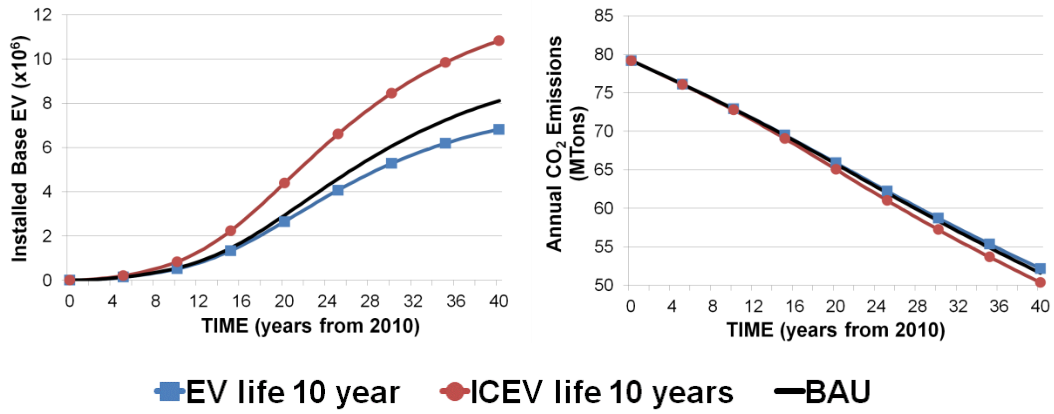

Figure 4.6: Impact of changes in vehicle life on EV installed base (left) and CO_2 (right)

When the EV life is reduced, discards are increased. Due to the low perceived utility with EV, the driver has a high probability of purchasing a ICEV to replace their vehicle. Following this, EV installed base under a reduced EV life is lower than BAU, reducing the probability of an ICEV driver replacing their vehicle with an EV. This is because the lower installed base (than BAU) leads to reduced social exposure which then impacts on willingness to consider and perceived affinity with EV (recall the social exposure loop in Figure 4.1). This is despite the fact that *total* sales are increased compared to BAU in order to maintain a constant fleet when discards are increased. EV discards therefore increase at a greater rate than sales increase as some replacement EV sales go to ICEV.

On the other hand, reducing ICEV life has a bigger impact on EV installed base than reducing EV life. This may seem counter-intuitive, but is due to the fact that the initial ICEV fleet is so much larger than the EV fleet. With the faster turnover of ICEVs (due to reduced vehicle life), there is more opportunity for an ICEV driver to become an EV driver (as they face the choice more often), increasing EV sales (with no change in EV discards). In addition, as EV installed base increases compared to BAU, WtC increases as the social exposure loop is positively reinforcing leading to a greater affinity of the ICEV driver with EV and thus a higher probability they will choose an EV. In this scenario EV installed base has nearly 3 million vehicles more than BAU, which corresponds to a 9% increase in EV market share.

Of course, there are limits to these findings as there is no second-hand car market within the model (taking an assumption that the car is retained for its whole life), but it would suggest that mandatory scrappage schemes may favour EV uptake. If some other benefit is offered to the owner for scrappage this would alter the choice and may not achieve similar results. There is not as significant an impact on CO_2 emissions through such schemes, shown in Figure 4.6, and in fact when considering cumulative emissions the difference is almost zero. The increased turnover may mean that the embodied (production and dismantling) emissions are increased across the fleet, whilst fleet average emissions are reduced by the increase in EV. While not included here, such effects should be studied in more detail if scrappage schemes are considered to be a viable option.

EV Emissions

The introduction of EVs as a solution to carbon reduction challenges is wholly dependent on decarbonisation of the electricity generation mix itself. This may be uncertain but it was felt useful to consider a scenario where the reduction was greater than assumed in the BERR/DfT report (see Section 4.2.4). To test this, the BEV emission factor was reduced by 15% to 35g/km (from 41g/km) and the PiHEV by 7.5% to 85g/km (from 92g/km). The results shown in Figure 4.7 suggest that there would be very little difference to annual emissions by 2050. This may be partly due to the fact that the emission factors were not directly linked to vehicle choice in the model, so shares would be the same as in the BAU scenario, where the EV share is only a quarter of the installed base by 2050, and mainly PiHEV. Even if the BEV emissions were set to zero and PiHEV reduced to 75g/km (highly unlikely unless considering decentralised micro-generation), the reduction from BAU is still less than 5%. It is also likely that ICEV emissions may be less than the BAU scenario, and this will be tested in the *Regulation* scenario in Section 4.4.3.

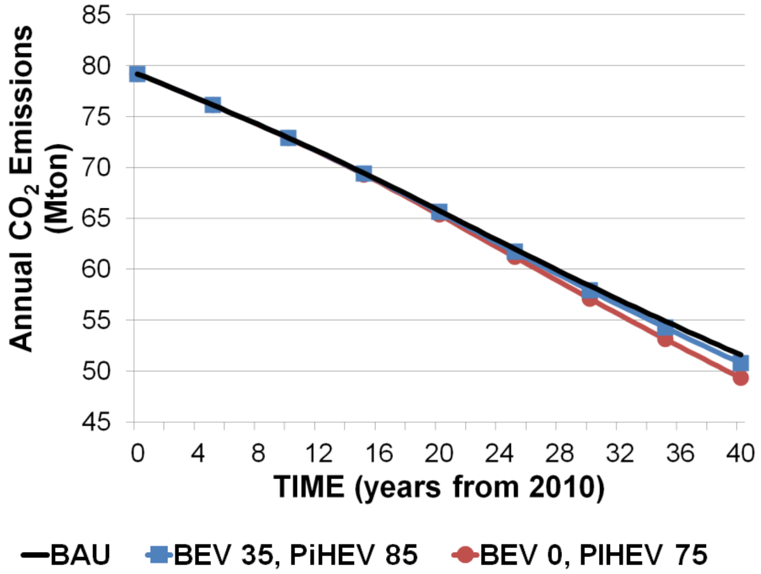

Figure 4.7: Impact of EV CO_2 reductions on total CO_2

4.4.2 Subsidy Scenario Testing

Fiscal Measures was identified in the previous Chapter as having a potentially high impact on car ownership opportunity. The model was then tested to understand the impact that subsidies on EV purchase prices may have. Subsidies were chosen as they are the most widely recognised type of *Fiscal Measure*, though future work would benefit from exploring changes in ICEV purchase costs or manipulation of operating costs. Twenty different subsidy scenario tests were carried out, twelve of which were based on the BAU scenario, and eight on the failing base with conditional marketing. Eight indicators were chosen to assess impact:

- Market share of installed base in year 10;
- Market share of installed base in year 40;
- Total sales over 40 years;
- Additional sales compared to BAU base over 40 years;
- Total subsidy over 40 years;
- Fuel duty lost over 40 years;
- Annual fleet CO_2 in year 40; and
- Total CO_2 emissions over 40 years.

4.4.2.1 Business as Usual Base

The conditions for the 12 BAU subsidy scenarios are set out in Table 4.2. These scenarios reflect a range of options that could be taken regarding subsidy-based policies for EV uptake. The subsidies are £2500 or £5000 on BEV, PiHEV or both EVs, which are in place for a fixed duration of 3 or 6 years or, in the case of SUB11 and 12, under specific budget caps of £250m and £500m.

SCENARIO	PiHEV SUBSIDY	BEV SUBSIDY	BUDGET DURATION/CAP
SUB1	£2500	0	3 years
SUB2	0	£2500	3 years
SUB3	£2500	0	6 years
SUB4	0	£2500`	6 years
SUB5	£5000	0	3 years
SUB6	0	£5000	3 years
SUB7	£5000	0	6 years
SUB8	0	£5000	6 years
SUB9	£2500	£5000	6 years
SUB10	£5000	£5000	6 years
SUB11	£5000	£5000	£250m
SUB12	£5000	£5000	£500m

Table 4.2: BAU subsidy scenarios

Table 4.3 presents the results of these scenarios. It can clearly be seen that none of the subsidy scenarios make a significant impact on installed base market shares or sales compared to the base case scenario, but the costs of the subsidy and lost fuel duty revenue is in the scale of £billions for most scenarios. SUB10, which provides £5000 for both EVs for 6 years has the most significant impact. Even this however, provides less than 2 million additional sales of EV over 40 years and around 0.13 Mtons of annual CO_2 savings in year 40 compared to BAU.

The limited reduction in CO_2 may be surprising as from the vehicle attributes (Table 4.1), a BEV could provide a 65% drop in emissions per km and a PiHEV a 20% drop. However, from BAU to SUB10 there is only a 1.2% shift from ICEV to EV and the majority of the EVs are PiHEV (81%), this leads to an emission reduction of only 0.34% (1.2 x (0.19 x 65 + 0.81 x 0.2)). Considering these marginal changes in CO_2 emissions and EV additional sales, it may then be concluded that subsidies have very little impact if they are the only policy intervention.

	INSTALLED BASE MARKET SHARE (%) 2020	2050	TOTAL SALES ($x10^6$)	ADDIT. SALES ($x10^6$)	TOTAL SUBSIDY (£M)	TOTAL LOST FUEL DUTY (£B)	ANNUAL CO_2 (Mt)	TOTAL CO_2 (Mt)
BAU Base								
ICEV	98.26	74.62	73.71					
PIHEV	1.43	20.66	14.44	n/a	n/a	12.75	51.58	2690.14
BEV	0.32	4.72	3.28					
SUB1								
ICEV	98.11	74.50	73.50	-0.20				
PIHEV	1.56	20.76	14.62	0.17	260	+0.24	51.56	-1.10
BEV	0.33	4.74	3.31	0.03				
SUB2								
ICEV	98.22	74.59	73.66	-0.05				
PIHEV	1.44	20.68	14.47	0.03		+0.10	51.57	-0.30
BEV	0.34	4.73	3.30	0.02	57			
SUB3								
ICEV	97.77	74.30	73.14	-0.57				
PIHEV	1.89	20.93	14.94	0.50	873	+0.65	51.53	-3.06
BEV	0.34	4.77	3.35	0.07				
SUB4								
ICEV	98.15	74.54	73.58	-0.13				
PIHEV	1.45	20.71	14.51	0.07		+0.29	51.57	-0.89
BEV	0.40	4.74	3.34	0.06	188			
SUB5								
ICEV	97.85	74.31	73.17	-0.53				
PIHEV	1.80	20.92	14.90	0.46	925	+0.64	51.54	-2.94
BEV	0.34	4.77	3.35	0.07				
SUB6								
ICEV	98.17	74.55	73.58	-0.12				
PIHEV	1.45	20.71	14.52	0.07		+0.26	51.57	-0.82
BEV	0.38	4.74	3.33	0.05	204			
SUB7								
ICEV	96.91	73.83	72.25	-1.45				
PIHEV	2.71	21.33	15.72	1.28	3196	+1.69	51.47	-7.91
BEV	0.38	4.84	3.45	0.17				
SUB8								
ICEV	97.96	73.35	73.35	-0.35				
PIHEV	1.49	20.80	14.64	0.19		+0.80	51.54	-2.42
BEV	0.55	4.79	3.44	0.16	684			
SUB9								
ICEV	97.47	74.13	72.81	-0.89				
PIHEV	1.95	21.04	15.11	0.66	1759	+1.43	51.50	-5.34
BEV	0.58	4.83	3.51	0.23	693			
SUB10								
ICEV	96.61	73.69	71.97	-1.74				
PIHEV	2.77	21.41	15.85	1.41	3210	+2.43	51.45	-9.99
BEV	0.62	4.89	3.60	0.32	704			
SUB11								
ICEV	98.11	74.50	73.50	-0.21				
PIHEV	1.55	20.76	14.61	0.17	205	+0.29	51.56	-1.21
BEV	0.34	4.74	3.32	0.04	45			
SUB12								
ICEV	97.95	74.38	73.29	-0.41				
PIHEV	1.67	20.86	14.78	0.33	410	+0.57	51.54	-2.36
BEV	0.37	4.76	3.36	0.08	90			

Table 4.3: BAU subsidy scenario results
Lost fuel duty and total CO_2 emissions for SUB1-12 in relation to BAU Base, costs discounted to NPV at a rate of 3.5% years 1-30 and 3% years 31-40 (HMCO, 2013).

There are noticeable reinforcing effects that the uptake of the two EVs have on each other. For example, SUB8 (£5000 for BEV only) achieves around 160,000 additional sales of BEV compared to BAU, yet SUB10, which offers the same plus £5000 for PiHEV achieves 320,000 additional BEV sales to BAU. This effect appears to work both ways, as in SUB7, which offers £5000 only for PiHEV, there are 1.28m PiHEV sales additional to BAU, whereas SUB10, the same scenario with a £5000 BEV subsidy, achieves 1.41m additional PiHEV sales. Though, looking at these numbers it would appear that BEV gain more by PiHEV subsidies than the other way around, presumably due to the higher installed base of PiHEV. This phenomenon is due to the increased number of EV drivers and thus increased WoM effects, which depend on total EVs.

As annual emissions were 79.2 Mtons CO_2 at the start of the time period, the BAU base represents a 30% reduction in emissions, which is far off government targets of 80%. When looking at the cumulated CO_2 emission savings, the results look more impressive, as the most successful scenario, SUB10, may save almost 10 Mtons of CO_2 over the 40 year period, but this is still less than 0.4% from the BAU Base total emissions. Furthermore, this is at a cost of nearly £4b in subsidies and £2.4b from fuel duty revenue loss (in addition to base), which works out at £2255 per vehicle from subsidies alone or £3652 if including fuel duty loss.

When considering carbon abatement costs (£/tCO_2), a simple calculation can be carried out that describes the cost the government would pay for each ton of CO_2 removed relative to the baseline at the end of the 40 year time period. Although other approaches can be applied this is the preferred approach for estimating carbon abatement costs by at least two governments (DCCEE, 2011; Atkins, 2009). Carbon abatement costs can give an indication of cost effectiveness, but should be viewed with caution as costs may be uncertain and should account for all social cost and benefits (Anable, 2008). Using Equation 4.9, the abatement costs (just considering subsidy) are between 190 (SUB2) and 459 (SUB9) £/tCO_2. The lower end of this is in line with carbon abatement costs in the EC GHG TransPoRD project (Schade et al., 2011), which reports a feebate abatement cost from an Authority Perspective of 199 €/tCO_2 (approximately 170 £/tCO_2), though it is noted that this project was a much more in-depth study and feebates differ slightly from subsidies. Note however, that the UK shadow price of non-traded carbon is 29 - 86 £/tCO_2 (DECC, 2011c).

$$Carbon\ Abatement\ Cost\ = \frac{TC_{NPV,Scenario,}}{TE_{BAU} - TE_{Scenario}}$$

Equation 4.9

$TC_{NPV,\ Scenario}$ is the total incurred government cost (due to subsidies and/or loss of fuel duty revenue) by year 40 of the policy scenario compared to BAU at net present value[86] (£)

TE_X is the total emissions of CO_2 over the 40 year period in Scenario x (tons)

Budget caps, as in SUB11 and 12, are more likely than the government dedicating up to £4b to subsidies. In these scenarios, the available money is used up in less than 3 years. The impact in the short term, during the subsidy and not long after is more promising, but the drop in sales when the subsidy ends is quite clearly seen in Figure 4.8, which shows EV sales, by the 'kink' in the uptake trajectory. At this point, the removal of the subsidy effectively creates a £5000 increase in EV purchase price, as the learning effect price reduction is not yet strong enough to bring down purchase price as much as the subsidy had done. This affects PiHEV more strongly, halving sales the year after the subsidy is removed.

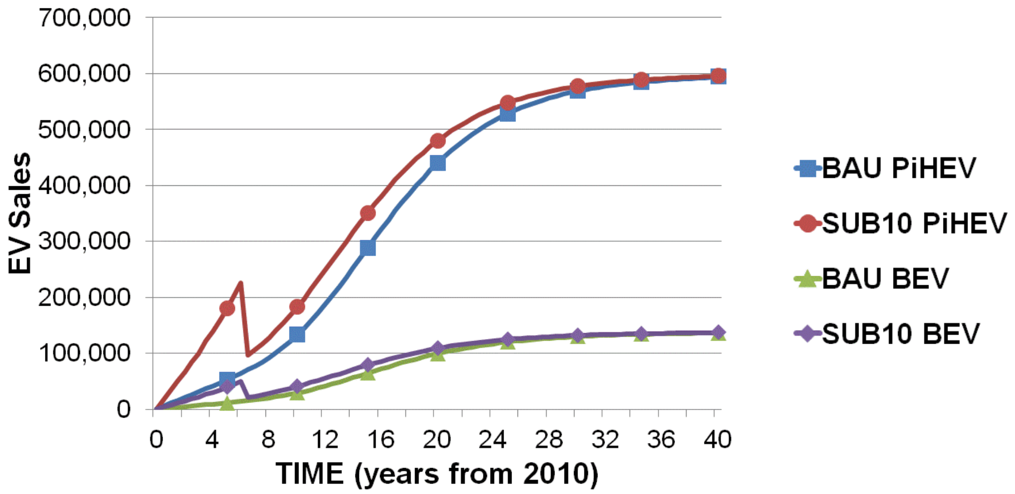

Figure 4.8: BAU vs SUB10 EV sales

4.4.2.2 Conditional Marketing Base

Although it would seem that under BAU conditions, subsidies may not have a great impact, model testing then moved on to assess if subsidies could make any difference to the failing market baseline outlined in Section 4.3.5. Recall that this involved a conditional marketing regime of the manufacturers, such that if a sales threshold of 7.5% by end of year 10 were not achieved, marketing was removed

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[86] Discounted at 3.5% p.a. up to year 30 and 3.0% from year 31 to 40 as per UK government guidelines (HMCO, 2013).

(implying production would scale back also). Eight Scenarios, as presented in Table 4.4, were designed that resulted in a successful market as they succeeded in exceeding the sales threshold of 7.5% in year 10. The only intervention for CMSUB1-4 were subsidies, similar to those in the BAU subsidy tests, and these were based around the duration of subsidies required to achieve success, and demonstrate the sensitivity to the market to this (also proven by Struben and Sterman (2008) in their study). CMST1-4 were themed, combining subsidies with changes in vehicle attributes over the time-period. To design these, it was necessary to understand what sort of change would bring about success. Therefore, each vehicle attribute was tested individually (with all else constant), identifying the following requirements:

- 6.8% increase in ICEV operating costs;
- 10.6% decrease in PiHEV operating costs;
- 66% decrease in BEV operating costs;
- 160 mile range for BEV;
- 130mph max speed for BEV;
- Fuel availability increase from 40 to 55% for BEV (with associated PiHEV increase).
-

SCENARIO	PiHEV SUBSIDY	BEV SUBSIDY	BUDGET DURATION /CAP	OTHER
CMSUB1	£5000	0	4 years	n/a
CMSUB2	0	£5000	10 years	n/a
CMSUB3	£5000	£5000	3 years	n/a
CMSUB4	£3000	£5000	4 years	n/a
CMST1	£5000	£5000	5 years	ICEV op. cost -5% by year 10
CMST2	£5000	£5000	3 years	BEV range 200m by year 20 BEV fuel availability 70% by year 40 BEV max speed 100mph by year 20 PiHEV op. cost -10% by year 40 BEV op. cost -10% by year 40
CMST3	0	£5000	£500m	BEV range 300m by year 20 BEV and PiHEV fuel availability 100% by year 40 BEV max speed 120mph by year 20 PiHEV op. cost -10% by year 40 BEV op. cost -20% by year 40 ICEV op cost +10% by year 40
CMST4	0	£5000	£500m	As CMST3 Revenue Preserving Tax in place

Table 4.4: Conditional marketing with subsidy scenarios

It seemed clearly unrealistic that PiHEV or BEV could have such high decreases in operating costs over the next ten years, nor that there would be the technical advances in BEV for the increases to average range and speed. However it was interesting that only a relatively small increase in ICEV costs could tip the market. As it was felt plausible that oil prices may drop over the coming decade (as the oil market is extremely volatile), ICEV operating costs and fuel efficiency could actually decrease, so CMST1 is a scenario that considers what a 5% drop in ICEV operating costs would mean for subsidy duration. It should be remembered that the sales threshold figure was somewhat arbitrary when viewing the results. Had it been set slightly lower, success would have been achieved at lower costs. CMST2-4 were designed to have relatively realistic improvements to the EV technical attributes over the time period, though in CMST3 and 4, by year 20, BEVs have a higher perceived utility than ICEVs and PiHEVs so this is an optimistic case. This is likely due to the fuel availability, maximum speed, purchase price and range becoming more in line with those of ICEV and PiHEV whereas emission factor and operating cost remain significantly lower. In CMST4 the revenue preserving tax, as described in Section 4.2.4, is added to CMST3.

The results of all the Conditional Marketing scenarios are presented in Table 4.5, which also include the BAU and CM baselines for further comparison. As can be seen, there is only a marginal installed base of EV in the failed market scenario, CM base, though even this has resulted in a £2b loss in fuel duty revenue. The result is 3.5Mt more annual CO_2 emissions than under the BAU base, and an extra 56Mt over the time period. The subsidy scenarios result in market shares as successful as BAU base but not as successful as the best case subsidy scenarios under BAU. The three optimistic themed scenarios offer the greatest potential for any of the scenarios tested so far.

	INSTALLED BASE MARKET SHARE (%) 2020	2050	TOTAL SALES ($x10^6$)	ADDIT. SALES ($x10^6$)	TOTAL SUBSIDY (£M)	TOTAL LOST FUEL DUTY (£B)	ANNUAL CO_2 (Mt)	TOTAL CO_2 (Mt)
BAU Base								
ICEV	98.26	74.62	73.71					
PIHEV	1.43	20.66	14.44	n/a	n/a	12.75	51.58	2690.14
BEV	0.32	4.72	3.28					
CM Base								
ICEV	98.26	99.14	89.91					
PIHEV	1.43	0.70	1.25	n/a	n/a	2.09	55.08	2746.63
BEV	0.32	0.16	0.27					
CMSUB1								
ICEV	97.60	74.15	72.88					
PIHEV	2.05	21.05	15.16	13.92	1533	+11.65	51.51	-61.03
BEV	0.36	4.79	3.39	3.12				
CMSUB2								
ICEV	97.46	74.24	73.01					
PIHEV	1.48	20.87	14.73	13.49		+12.45	51.51	-61.68
BEV	1.06	4.89	3.69	3.41	1833			
CMSUB3								
ICEV	97.77	74.25	73.06					
PIHEV	1.83	20.96	14.97	13.72	923	+11.56	51.53	-60.18
BEV	0.41	4.79	3.40	3.13	201			
CMSUB4								
ICEV	97.80	74.29	73.12					
PIHEV	1.76	20.92	14.89	13.65	575	+11.55	51.53	-59.90
BEV	0.44	4.79	3.41	3.14	335			
CMST1								
ICEV	97.21	75.29	73.42					
PIHEV	2.28	20.11	14.67	13.43	2228	+11.70	51.68	-60.02
BEV	0.51	4.59	3.33	3.06	488			
CMST2								
ICEV	97.33	60.47	63.51					
PIHEV	1.95	20.19	14.74	13.49	941	+31.38	46.81	-133.47
BEV	0.71	19.33	13.18	12.91	243			
CMST3								
ICEV	97.40	42.54	52.56					
PIHEV	1.57	11.81	9.63	8.38		+61.43	38.24	-241.55
BEV	1.03	45.65	29.24	28.96	500			
CMST4								
ICEV	97.40	42.49	52.54					
PIHEV	1.57	11.79	9.62	8.37		+61.48	38.22	-241.74
BEV	1.03	45.72	29.27	29.00	500			

Table 4.5: Conditional marketing with subsidy scenario results
Lost fuel duty and total CO_2 emissions for CMSUB1-4 and CMST1-4 are presented in relation to CM Base.

Comparing CMSUB1 and CMSUB2, supporting BEVs only would require subsidies for almost twice as long as supporting PiHEVs only for market success. As such, this would cost twice as much for similar emission savings. CMSUB3 and 4 would appear to suggest that supporting both platforms can achieve market success at lower cost (both in terms of subsidies and fuel duty loss), with little difference in emission reductions. CMST1, which also considered the decrease in ICEV costs, showed that an extra 2 years of subsidies would be required to overcome this set-back, during which time an extra £1.8b in subsidies are incurred. Even if PiHEV operating costs also decreased (not shown in table) with oil prices (by 4% assuming 80% of driving is powered by petrol as in the emissions rating), an extra year of subsidies is needed to tip the market, costing £0.7b. In all, these scenarios would suggest that, in the failing case demonstrated here, subsidies are pivotal in making EVs attractive enough to tip the market into success. This is not the case in the BAU scenario where subsidies could benefit those who would purchase an EV anyway, but it is difficult to predict which of these will be the case.

CMST2-4 have the greatest impacts on shares of any of the scenarios, and CMST 3 and 4 can result in EVs capturing over half the market by year 40. For CMST3, this is at a significant cumulated loss in fuel duty of nearly £61b. Shown in Figure 4.9, this appears to increase exponentially over time (with EV uptake), and is in the region of £3.4b per annum by year 40. This is a 46% decrease in annual revenue, or 70% over the 40 year period. A method of applying revenue preserving tax to recoup this loss was described in Section 4.2.4, specifically Equation 4.7. For CMST3, this (undiscounted) annual tax would be around £330 per vehicle for BEV and £352 per vehicle for ICEV/PiHEV in year 40, also shown in Figure 4.9. Recall CMST4 is simply CMST3 with that tax applied. We see in Table 4.5 that this revenue preserving tax makes very little difference to total sales and market shares of vehicles, with a slight favouring being towards the BEV, suggesting little impact on purchase behaviour. However, if this were only applied to ICEV/PiHEV as an increased fuel duty (not included in table), it would be in the region of £671 a vehicle by year 40, which could increase BEV share by 2%. The acceptability of a vehicle miles travelled (VMT) tax is however, under much debate. An increase in VED (as replicated here, albeit based on mileage), or mechanism to tax electricity as a fuel may be more appropriate.

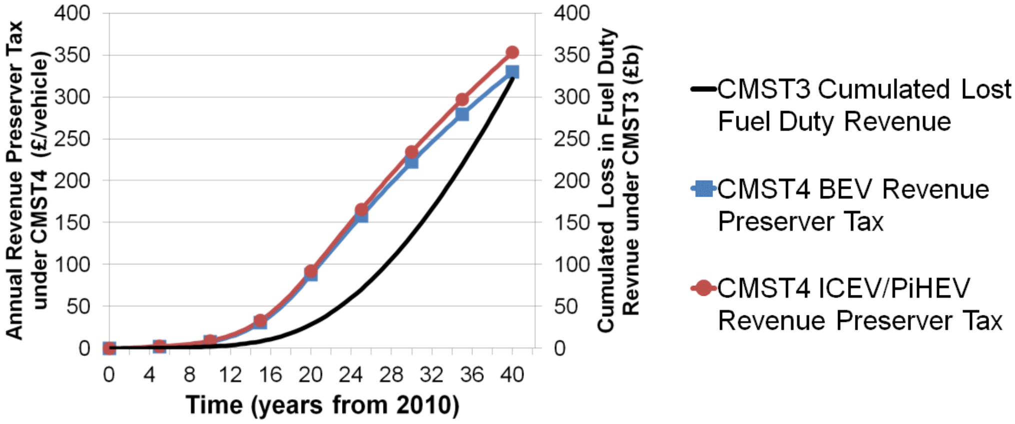

Figure 4.9: Lost fuel duty revenue (CMST3) and revenue preserver taxes (CMST4)

Despite the successful market shares obtained in CMST2-4, there is only a reduction in annual CO_2 emissions (compared to the failing case) of 15% (CMST2) and 30% (CMST3 and 4) by year 40, which is again, far off the government target of decarbonisation of the fleet. It is however similar to findings in another study that predicted a 50% shift to AFVs would lead to a 23% reduction in emissions (Kwon, 2005). In fact, when looking at cumulated emissions, there is only a reduction of 4.9 and 8.8% compared to the failing case baseline. To put this into context, it should be recalled that there is a constant fleet and vehicle WTW emissions in the model, so the maximum reduction would be 65% with 100% BEV installed base. These findings are optimistic when compared to IEA Energy Technology Perspectives 2^{o}C Scenario (2DS)[87] (IEA, 2012a). In this, the IEA report the need for global sales shares of 2% BEV and 4% PiHEV by 2020, and 22% BEV and 34% PiHEV by 2040. Sales shares in the model under CMST3/4 are 4.7% BEV and 6.2% PiHEV in 2020 and 65.0% BEV and 11.4% PiHEV in 2050. However, these cases are not wholly comparable as this case study is only concerned with the UK fleet and does not include HFCVs whereas the 2DS requires a 17% HFCV market share in 2050 with mass deployment beginning in the 2020's.

Recall that the CM base scenario (which was illustrated against the BAU in Figure 4.4), lead to complete market collapse of EVs by year 40. As ICEV then accounts for over 99% of the installed base of vehicles, annual emissions are higher than the BAU case. However, in each of the subsidy scenarios, the EV market has been recaptured and in each case there are emission savings compared to CM base in the region of the BAU subsidy scenarios. Looking at abatement costs, due to the market failure in the failing case, cost per vehicle is much more reasonable than the best case in the BAU scenarios (SUB10), as there are more CO_2 emissions in the CM base than the BAU base. Even in the most costly un-themed case, CMSUB2, using again Equation 4.9, abatement costs due to subsidies are £108 per vehicle and £30 per tonne CO_2, which were £1256 and £190 for SUB2, the least costly scenario under BAU. If fuel duty loss is included within the abatement costs, for the cost per vehicle is in the region of £753 (around 20% that of SUB10) and £211 per tonne CO_2 (around a third of SUB10). The subsidy abatement costs are even lower

[87] "The 2DS describes an energy system consistent with an emissions trajectory that recent climate science research indicates would give an 80% chance of limiting average global temperature increase to 2°C. It sets the target of cutting energy-related CO_2 emissions by more than half in 2050 (compared with 2009) and ensuring that they continue to fall thereafter. Importantly, the 2DS acknowledges that transforming the energy sector is vital, but not the sole solution: the goal can only be achieved provided that CO_2 and GHG emissions in non-energy sectors are also reduced" (IEA, 2013b).

for CMST2-4 due to the great success in EV uptake and emission reduction, being as low as £13 per vehicle and £2 per tonne CO_2 under CMST3. However, when including the fuel duty it is more in line with the abatement costs of SUB10, being £1658 per vehicle and £256 per tonne CO_2. As CMST4 has a revenue preserving tax in place however, that fuel duty loss has been recouped, making it a much more attractive option.

In summary, the conditional marketing tests, when compared to the BAU tests, highlight the importance of the baseline. The BAU tests would suggest that subsidies are an expensive method of increasing EV uptake by only a small amount, perhaps only subsidising many people who would have purchased EV anyway. Under a failing case however, when marketing would be removed if a sales threshold was not reached, subsidies are required to tip the market into success. In many ways, it may be more realistic that manufacturers would withdraw expensive marketing campaigns if they are not providing suitable returns. This could suggest that subsidies are a necessary *Fiscal Measure* if government wishes to ensure a sustainable EV market. Further to this, the final tests have demonstrated the sensitivity to vehicle attributes, and although progress in these is notoriously difficult to predict accurately, even with moderate advances, significant EV market shares could be obtained with capped subsidy budgets. However, these shares come at the considerable loss of fuel duty revenue, and the government would need to consider ways of addressing this potentially major impact on public money.

4.4.3 *Regulation* Scenario Testing

The final model exploration to be carried out involved replication of a *Regulation* scenario. The manufacturer *Regulations* that are of interest to this study are the mandated reduction of fleet average tailpipe CO_2 and technology quota of LCVs (particularly EVs). As this model was specifically focused on the demand side of the EV market, there were no direct factors relating to manufacturers decisions built within it, and as such it was not possible within this simple model to constrain availability of EVs and ICEVs: both options were always available for the customer to choose between them. The fact that EVs are available means that there is an implicit regulatory effect in the BAU baseline forcing manufacturer to produce (and market) the vehicles, and recall from Section 4.2.5 that some emission reductions over the time period were assumed. Further to this, replication of *Regulation* being in place could be approximated by altering the CO_2 emissions and the EV marketing effect in a manner that would be expected should a manufacturer be responding to *Regulations*. For this, further assumptions were required, as it is equally unlikely that no technological improvements would be made over the 40 year timeframe. Although these are essentially sensitivity tests, they can be approximated to policy scenarios for the purpose of this research.

The scenarios designed to test the impact of *Regulation*, based on the BAU baseline, are presented in Table 4.6. Scenarios REG1 and 2 reflect a reduction in the emission factor of ICEVs from 115g/km to 105g/km or 95g/km (9% or 18%) at the end of the time period. These reflect emission reduction targets. In this case, no technology quota is assumed. It should be noted here, as mentioned in Section 4.4.1 where sensitivity to EV emissions were explored, that these changes in emissions are not connected to vehicle choice in the model, nor do they alter any vehicle attributes such as costs or fuel efficiency. Due to this, REG1 and 2 are the same as BAU base, and the interest is in seeing the impact of the enforced manufacturer emission reductions may have on overall carbon emissions.

Although within the model it is not possible to enforce technology quotas as such, as it is assumed that all vehicles are available throughout the period, the EV marketing effect was doubled to represent an increased effort from manufacturers to promote EV in meeting such quotas. Although it is recognised that this is essentially arbitrary, and technology quotas tend to be based on vehicle production rather than sales, it was felt that this will give some indication of the impact of *Regulation*. To represent this, REG3 represents the BAU base scenario but with imposed marketing for EV. Both emission reduction and marketing are applied in REG4 and 5, the only difference being that REG5 also had subsidies in place, taken from the most optimistic BAU scenario (SUB10).

SCENARIO	ICEV 2050 Emissions (g/km)	EV Marketing Effect (year^{-1})	Subsidies
BAU	115	0.025	n/a
REG1	105	0.025	n/a
REG2	95	0.025	n/a
REG3	115	0.05	n/a
REG4	105	0.05	n/a
REG5	105	0.05	£5000 for both PiHEV and BEV

Table 4.6: Regulation scenarios

Table 4.7 presents the results from these scenarios. It can be seen that greater emission reductions have been achieved than under the BAU Subsidy scenarios, but no REG scenario is as successful as the most optimistic themed subsidy scenarios under conditional marketing.

	INSTALLED BASE MARKET SHARE (%) 2020	INSTALLED BASE MARKET SHARE (%) 2050	TOTAL SALES ($x10^6$)	ADDIT. SALES ($x10^6$)	TOTAL LOST FUEL DUTY (£B)	ANNUAL CO_2 (Mt)	TOTAL CO_2 (Mt)
BAU Base							
ICEV	98.26	74.62	73.71				
PIHEV	1.43	20.66	14.44	n/a	12.75	51.58	2690
BEV	0.32	4.72	3.28				
REG1							
ICEV	98.26	74.62	73.71				
PIHEV	1.43	20.66	14.44	n/a	n/a	47.96	-83.41
BEV	0.32	4.72	3.28				
REG2							
ICEV	98.26	74.62	73.71				
PIHEV	1.43	20.66	14.44	n/a	n/a	44.34	-166.83
BEV	0.32	4.72	3.28				
REG3							
ICEV	94.07	71.65	68.40	-5.30			
PIHEV	4.85	23.07	18.75	4.31	+6.96	51.15	-29.93
BEV	1.08	5.28	4.27	0.99			
REG4							
ICEV	94.07	71.65	68.40	-5.30			
PIHEV	4.85	23.07	18.75	4.31	+6.96	47.67	-108.32
BEV	1.08	5.28	4.27	0.99			
REG5							
ICEV	90.60	71.10	66.58	-7.13			
PIHEV	7.67	23.51	20.23	5.79	+18.18	46.69	-133.34
BEV	1.72	5.39	4.61	1.33			

Table 4.7: Regulation scenario results
Lost fuel duty and total CO_2 for REG1-5 are presented in relation to BAU base.

REG1 and 2 achieved a 7 and 14% (resp.) reduction in annual total CO_2 emissions from BAU. When comparing this to the reductions of EV emissions (Section 4.4.1), where even in the most favourable scenario the reduction was less than 5%, this would imply that *Regulation*, focusing on fleet emissions of ICEV, may be more successful than introducing EVs if the goal is reducing emissions. Obviously this is reflective of the low share of EVs in the BAU case as they are not affected by specific changes in emissions. The reduction in the conservative case is similar to SUB6, which came at much higher cost for both subsidies and fuel duty – however this model does not capture what the cost to industry would be to make the efficiencies. The impact of EV marketing on BAU, as shown in REG3 increased shares moderately, but made very little difference to annual CO_2 emissions. This perhaps further reinforces the suggestion that reductions in ICEV efficiencies have a greater impact than the introduction of EVs on emissions. However, it must not be forgotten that these emissions are dependent on the assumptions in the model, and the EV shares (particularly BEV) are still very low. The only difference between REG3 and REG4 is the impact on emissions, and again a significant contribution (compared to REG3) from ICEV efficiencies is observed, as an 8% reduction in annual emissions. Finally, when subsidies are also included in REG5, there is a marginal increase in EV share, and a 2% decrease in annual emissions compared to REG4. On top of this, although REG 5 seems to make quite an impact on market share in the short term compared to REG4, by 2050, the difference is very small, and the lost fuel duty has increased by over a quarter.

Although it should be remembered that these tests have been merely illustrative of *Regulation*, and that without manufacturer feedback the results should not be read as definitive, they do however highlight the importance of targeted efforts to decrease ICEV emissions, and that *Fiscal Measures* (in the form of subsidies) applied early on may have initial success alongside manufacturer *Regulation*.

4.5 Discussion and Conclusions

The development and exploration of this case study has contributed to the detailed understanding of some key processes in the uptake of Electric Vehicles within a simple model. The case study built upon an existing base model (Struben and Sterman, 2008) with an important socio-technical diffusion process by transferring it into a UK context.This was achieved through introduction of a suitable customer choice model, relevant vehicle attributes and calibration to predicted BAU trajectory. Further improvements were the inclusion of specific EV platforms of BEV and PiHEV, accounting for price-volume effect, and by calculating new outputs of loss in fuel duty revenue and reduction in annual CO_2 emission. Of additional benefit to the understanding of the conditions required for EV uptake, a conditional marketing scenario was designed. The model was then explored through two broad lines of testing, sensitivity to key parameters, and policy and technology scenarios. There was a specific focus on the impact of *Fiscal Measures* (in the form of subsidies) and manufacturer *Regulation*, which have been identified as the policies of most interest in this research.

Once a BAU baseline had been determined it was subjected to sensitivity tests of key input parameters into the model. As there was confidence in the suitability of many of the attributes this narrowed the field down to three areas of focus. Knowing the importance of the social exposure loop, Word-of Mouth was tested. It would appear that due to the higher incidence of non-EV drivers in the early years, the results are highly sensitive to the magnitude of the *“contact effectiveness”* with these people and exerts a significant influence on all drivers *Willingness to Consider* an EV. This was also indentified by Struben and Sterman who noted its influence on tipping points, and other studies that drew attention to the impact of consumer attitude on uptake (Janssen et al., 2006; Walther et al., 2010). Although it may seem obvious, a policy implication is that any marketing or awareness campaigns need to be specifically focused at non-EV drivers. Although there are numerous studies that are designed to identify and attract first adopter groups to be subjected to niche marketing for EVs (Morton, 2013; Schuitema et al., 2013; Tran et al., 2013), this finding may highlight the importance of general awareness as a supporting mechanism to *Willingness to Consider*. This finding would also imply that the experts surveyed in Chapter 3B may underestimate the impact of “Raising Awareness” policies on market penetration (if they did indeed take this into account in their assessments).

Further sensitivity testing involved concerns about the average life of vehicles. The findings suggested that mandatory scrappage schemes of ICEVs may favour uptake of EVs, as reduced ICEV life could increase installed base of EV by over one third. Conversely if EV life is shorter, then preferences would be reduced, though this was not as strong as an impact as reduced ICEV life. However, without a fully operational model of a second-hand car market and understanding of embedded emissions, it is uncertain if this would favour overall emission reductions. Indeed, as noted by other studies, scrappage schemes may increase vehicle miles (as travelling costs are reduced) and potentially increase emissions (Brand et al., 2013). Additionally, although the impact of reducing EV life was slight, being able to ensure (or give confidence in) a lengthy battery life of EVs may be necessary if a successful transition is to occur.

The final sensitivity test did not involve EV uptake but considered what impact a wider energy policy of decarbonisation of the electricity mix would have. With a small BEV market share in 2050 in the BAU baseline tested here, even in the case of fully emission free electricity there would be less than a 5% reduction of CO_2 emissions (though recall that this is with a relatively low BEV installed base). As BEV have more emissions in their life cycle phase than ICEV (as detailed in the literature review), it would appear to be the case that BEVs are required to achieve a significant market share alongside decarbonisation of electricity in order to realise significant CO_2 reductions. In future work, testing pathways leading to larger shares may be required to test the contribution of EVs to carbon reduction targets.

Under the BAU baseline there seemed to be limited evidence that subsidies would be a useful policy tool for accelerating the uptake of EVs in the long term and reducing carbon emissions. The most optimistic scenario would have an annual saving of less than a fifth of a Mton of CO_2 in year 40, at an abatement cost of £190/tCO_2. Though this was in line with other reports of abatement cost, the actual amount is disappointing. However, these tests did highlight how important the interrelation between PiHEV and BEV take up is, as they are mutually reinforcing. The case for subsidies was much stronger under conditional marketing scenarios where carefully timed subsidies could tip a failing market into a successful one. This concurs with findings in the literature review that suggested that timing of subsidies is important (JTRC, 2010; Janssen et al., 2006), and may only work under optimistic scenarios (Kohler et al., 2010), or under specific conditions (Struben and Sterman, 2008).

This is however, in contrast to the finding of another study that reported that feebates on purchase taxes greatly accelerated low carbon vehicle uptake (Brand et al., 2013).[88] The reference scenario in Brand et al, resulted in a lower EV uptake by 2050 to the BAU baseline (approx 13%), and their "medium" feebate resulted in an approximate 30% EV market share by 2050, more similar to the BAU described here. Their most ambitious scenario, offering a higher level of rebate, led to a 50% market share by 2050, and in both cases the vast majority of EVs were BEV. This result is more in line with the results of the themed scenarios, which also resulted in similar emission reductions over the same period. A comparison with Brand et al.'s model may not be wholly appropriate, as in the first instance such feebates (and particularly the ambitious, longer-term and detailed schemes designed by Brand et al.) are not quite the same as the purchase subsidies considered here, and

[88] The model used in this study is the UK Transport Carbon Model (UKTCM). This is not a system dynamic model, but is instead database driven. It covers the whole transport system, and independently models transport demand, vehicle stock, and impacts on energy, emissions and the environment. There are over 600 vehicle technologies considered within the model. Scenario and policy variables, based on socio-economic and political developments are input exogenously (Brand, 2010). While it is more detailed in some respects, the model studied in this Chapter contains social diffusion processes and willingness to consider effects, models the changes within the model itself and the choice model is more detailed in terms of attributes. The medium feebate was in place over the full time period for all vehicles and imposed a top tax of £4000 on high emitters and rebate of £2000 to low emitters, effectively resulting in a similar subsidy to this study, but also an electric fuel duty on top.

secondly the model had different background assumptions. It would, however, appear that the BAU here is more optimistic than Brand et al.'s reference scenario, which was more comparable to the failing market in this study than the BAU, where subsidies did make a significant impact. Other changes in attributes that would tip the market into success were generally unrealistic or subject to volatile oil price assumptions. A possible exception to this is of the achievement of 15% BEV fuel availability, should there be the accelerated deployment of public 'fast charge' stations, but this may still be insufficient for those without access to home charging.

As the BAU baseline is likely unrealistic in its current marketing assumptions (manufacturers will not wish to market EVs indefinitely), a failure is more likely, which could be a strong case for subsidy support. In these cases, when a subsidy is brought in it can tip an otherwise failing market into success, though at extra cost of subsidies and loss in fuel duty revenues. There is a danger that if a market was not going to fail, then subsidies may be provided to those who would have bought EVs anyway, which was also concluded by an earlier study, based in Canada (Chandra et al., 2010). A recent UK report suggested that a significant amount spent on the Plug-in Vehicle Program has only benefited a *"handful"* of motorists (HoCTC, 2012). Further to this, the Chief Executive of Jaguar Land Rover has also recently spoken out against subsidies that are *"only for the rich"* (Neate, 2013), as the high up-front payment and access to off-street parking are required to purchase an EV. It is however, (as already stated) very difficult to predict which would be the case in actuality. Making an assumption that these people are likely to be more affluent (as they can afford higher BAU purchase prices), this could have important ethical implications regarding appropriate spending of public money, as the marginal impacts on uptake and emissions does not suggest the poorer have benefited or carbon reduction has been successful.

When considered in conjunction with an (optimistic) improvement in technical attributes (CMST2-4), EVs may be able to secure over half of the market by year 40, though at the loss of over £3b p.a. of fuel duty revenue. This is a similar finding to a recent report commissioned by the RAC Foundation and Institute for Fiscal Studies, that suggested a £3b annual loss in fuel duty revenue by 2030 (Johnson et al., 2012).[89] Recall from the literature review, that the ICCT warned that governments need to be mindful of such impacts (Kodjak et al., 2011). In addition,

[89] The reported value was £9bn undiscounted and assumes LCV penetration and ICEV efficiency targets are met.

Brand et al., (2013) also recognised the challenge that this may create. At this point, should a revenue preserving tax be brought in, in the region of £350/vehicle there is little difference in sales and BEV is marginally favoured. As previously implied if this is based on average mileage, it may be politically unacceptable, and should it be applied as form of carbon tax (just on ICEV and PiHEV) even more so. One reason for this is that drivers on low incomes tend to drive less so would be unfairly penalised. Despite this, questions should be raised regarding the acceptability of introducing such a tax on EVs, as this would increase the operating costs. Low operating costs are one of the (current) advantages of an EV and to alter this after encouraging purchase may be unfair, particularly if the decision to purchase an EV was made on economic grounds related to overall ownership costs. The government should look at other methods of recouping these losses, such as distance based charging, justifying that the revenue is necessary and it is an appropriate cost for car owners (as opposed to the general population).

The final stage of testing was an attempt to replicate *Regulation* of the vehicle industry. As this model does not include manufacturer response, these tests can therefore only be taken as indicative. Reduction of fleet average tailpipe emissions could result in greater CO_2 reductions than even the most optimistic BAU subsidy scenario. Increasing the promotion of EVs (as a proxy for technology quotas) appeared to make little difference in the future, but at a higher cost, though this may be related to a low BAU EV market share, as sensitivity tests suggested that social exposure would have a greater influence. Combining a subsidy scheme with *Regulation* would appear to make a greater impact than subsidies alone in the BAU, but the extra benefits were not significant compared to the impact of *Regulation* alone. This may be a case for investing in ultra fuel efficient ICEV, but as these tests did not account for full manufacturer dynamics, such a strong conclusion may not be drawn.

From the above discussion, the key findings of this Chapter can be summarised:

- Social exposure of EVs to ICEV drivers may exert a strong influence on EV uptake, so *Raising Awareness* Policies may be integral to creating a successful EV market.
- Subsidies do not help under BAU baseline tested here, and lead to high carbon abatement costs – but bearing in mind that this assumed constant marketing, it may be that the conditional marketing scenario is more realistic, where subsidies were important in making a difference. Despite this, they are

still not effective enough without advancement in technology that should be brought about by supply side policies and infrastructural provision.

- In most of the scenarios tested here, there was only a small market share of EV, and this meant that there were only marginal impacts on emissions, even if electricity was zero carbon. This may suggest that a tipping point, beyond which EVs make a suitable impact, is yet to be identified. If it is not realistic, then this may be a case against the introduction of EVs. It is not clear if such a task would be possible, as great care would be needed to ensure that this was not essentially arbitrary, especially bearing in mind the complexities of accounting for life cycle emissions as discussed in the literature review. *Regulation* of manufacturers was not fully tested in this model, but there was an indication that reducing ICEV emissions may make a greater impact on overall carbon emission than EV introduction – though this finding is sensitive to the low EV market share in that scenario and further tests within a more robust model which includes manufacturer dynamics would be required to explore this.
- Even with a low EV uptake, there could be a high loss in revenue from fuel duty, which could have grave consequences to the UK economy. Assuming that this duty is set at an appropriate level that represents the externalities of the fuel use, then some other method of taxation may be required, but this should be proportional and the government should consider the impact of such changes on the worst-off. If the income is a revenue for the government, the case to find a new source from car ownership is however less strong, and may require review of other taxes in society.

In closing, comment would now seem appropriate on weighing up the suitability of this model and its findings, as this should inform or identify requirements for a second case study. Firstly, this was a deliberately simple model, focused on the demand side of EV uptake and long term impact on government costs. Due to the simplicity, there were many assumptions that had to be made, both about present and future factors. As this model was over a relatively long timescale of 40 years, these assumptions may well be vulnerable to criticism. During testing it was clear that there is a great deal of sensitivity to all of these assumptions, therefore confidence and defence of chosen values is important in model understanding and interpretation of findings. Again, as this was a simple model, many factors were exogenous, and so perhaps important feedback processes were not included.

Being aware that this is the case is perhaps more important than including these factors, as it allowed the specific focus on those processes that were included. Not included in this model were processes of the automobile manufacturer, including endogenous pricing effects of the vehicles and response to *Regulation*. To address this research gap, this is a key feature in the second case study. In addition, this study did not address the ethical framework developed in Chapter Three. Although CO_2 reduction can be identified, the simplicity of the model prevented identification of any specific sections of society, so identification of impacts or inequalities was not possible. In the second case study the automobile market can be disaggregated between segments of vehicle size with separate attributes, in order that the distributional impacts may be identified.

CHAPTER FIVE: MODELLING CASE STUDY TWO

Whereas the first case study in the previous Chapter was an exercise of exploration and understanding, Case Study Two (CS2) of this research builds on the findings of the first and incorporates the ethical framework developed in Chapter Three. An existing model was adapted to suit the research needs, as identified in the literature review (Walther et al., 2010). This is a much more in-depth and complex model than that used in Case Study One (CS1), with a number of advantageous features. It builds on a similar social diffusion process as CS1, and demand-side policies may be simulated through a consumer choice model (in this study, subsidies as an example of *Fiscal Measures* are again the focus). In addition, the reaction of the automobile manufacturer to the supply-side policy of *Regulation* is modelled. Furthermore, the Walther et al., model has the possibility of including multiple LCV platforms and segments of vehicle market with associated endogenous attributes to allow for study of distributional impacts and thus assessment of policies within the ethical framework. The key outputs of this model that need to be identified and understood in order for the tested policies to satisfy the established ethical framework are GHG emission reductions, vehicle market shares and vehicle ownership costs.

This case study is set out in a slightly different way than the previous one. Although this Chapter also commences with a description of the base model, as the model is much more complex than the one in CS1, a high level overview is provided and only the most important elements are described in detail. Due to the model complexity, this model has not been adapted to the UK, therefore no calibration has been carried out. Also there is no sensitivity testing. Therefore, following the detail of the base model, baseline and scenario development are explained. CS1 was mainly concerned with sensitivity testing whereas the focus of this case study is to assess and compare policies within the ethical framework that has been developed and evaluated in Chapter Three of the thesis. Due to this, findings are presented in terms of the outputs of interest to the ethical framework. The final Section presents a discussion and conclusion, focusing on the model limitations, comparison to CS1 and finally assessment of the policies within the ethical framework.

5.1 Description of Base Model

The base model selected for this case study considers the policy *Regulation*, over a short time-scale of 2010 to 2020. It was presented in a 2010 journal paper (Walther et al., 2010), and was initially developed by one of the paper authors for their PhD thesis (Wansart, 2012). It is a detailed and complex system dynamic model of the Californian Low Emission Vehicle (LEV) and Zero Emission Vehicle (ZEV) Regulations aimed at manufacturers. These were explained in the literature review (Section 2B.3.3) and require a reduction in average fleet GHG emissions of new vehicles and the introduction of ZEVs as a certain percentage of their fleet. To avoid confusion between LEV and ZEV, from here on the LEV Regulations will be referred to as the GHG Regulations. They are of interest to this work as they are similar to the European Fleet Average Emission Regulation.

The complexity of the model is partly due to the nature of the *Regulations*, in particular the ZEV classification and credit accounting system, which includes some feedbacks between the make-to-stock production supply chain and manufacturer behaviour when motivated by regulatory penalties.[90] Further to this, sixteen different vehicle models are offered through four powertrain options (ICEV[91], HEV, PiHEV and BEV) and four segments based on vehicle weight and size (extra small (XS), small (S), medium (M) and large (L)). In the model, ZEV refers to HEV, PiHEV and BEV due to their classification in the ZEV regulations (which is explained later). It should be noted that ZEV and LCV are not interchangeable, as LCV can include low carbon ICEV.

On the demand side, the model links together a diffusion model with the same social diffusion process as CS1 (Struben and Sterman 2008) including interaction with drivers of all 16 vehicle types, and discrete choice theory, utilising an established detailed customer choice model by Brownstone and Train (1998).

A key reason in choosing this model as a case study, in addition to the focus on the manufacturer, is because the level of detail within the vehicle market allows for identification of potential GHG emissions reductions and the deduction of impacts on segments of society desired in order to incorporate the proposed ethical

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[90] It should be noted that the model assumes an aggregate manufacturer response so that individual manufacturer responses are not included.

[91] As with the previous case study these are assumed to be conventionally fuelled (in this case Walther et al., specify gasoline, but for simplicity are referred to as ICEV).

framework. Recall that the focus of concern is to prevent unfair burdens on the worst-off (as defined in Chapter Three). As the vehicle segments are directly related to purchase price, it is assumed that they can be used as proxy indictors for segments within society, through making a broad assumption that the less well off purchase smaller vehicles due to price constraints related to both purchase and running costs. Although no literature was identified that confirmed that low-income households bought smaller cars, there was evidence to suggest that high-income households favoured larger cars (Baltas and Saridakis, 2013; Choo and Mokhtarian, 2004), though there was some evidence that medium sized cars are seen as a value-for-money alternative (Baltas and Saridakis, 2013). However, many studies do suggest that those most sensitive to costs have the lowest willingness to pay towards vehicle ownership (Brownstone et al., 2006; Potoglou and Kanaroglou, 2007, Santini and Vyas, 2005).

It is accepted that this assumption is a simplification, and in reality vehicle size is not a direct indicator of income, as people have specific needs or tastes towards vehicle size that are unrelated to income. In addition, many of the less well off may purchase a vehicle on credit rather than in one upfront sum or will be in the second-hand car market. This is if indeed they can afford a car at all as more than a third of lowest income quintile households in California do not own a vehicle, compared to less than 5% of the two highest quintile households (BLS, 2013). Much literature considering low-income car use focuses on the cultural/infrastructural constraints that induces forced car ownership, rather than the type of vehicle purchased (Currie and Delbosc, 2011; Lucas, 2011). As this ownership is forced, and specific needs vary widely so are difficult to capture, it is felt that it is not unfeasible to assume that the greatest influence on choice will be cost for the low-income. However, this is just a proxy indicator in the absence of the availability of a more detailed model which can capture these effects, so this approach is defended as a starting point that could be built upon in future work.

An important note is the purpose of the base model, as it has been adapted and applied for a slightly different purpose for this case study. Walther et al. were interested in the challenges for the manufacturers in meeting the two seemingly conflicting GHG and ZEV Regulations of improving efficiencies of conventional vehicles whilst introducing less competitive (e.g. higher purchase price, shorter range, lack of charging infrastructure) alternatives. There is a high interdependence between these, as pointed out by Walther et al. (2010, pp.242-243):

> *On the one hand, the reduction of fuel consumption of conventional vehicles in order to meet GHG requirements leads to a higher attractiveness of conventional vehicles in contrast to ZEVs. Thus it becomes more challenging to meet ZEV requirements. On the other hand, the more ZEVs are introduced and sold, the less GHG emissions of conventional vehicles have to be reduced. Furthermore, ZEV regulations comprise an important feedback loop that determines future ZEV requirements: mandatory ZEV sales depend on total sales of conventional new vehicles that were sold 4, 5 and 6 years ago. Thus higher sales of conventional vehicles due to decreased fuel consumption leads to higher mandatory ZEV sales, making fulfilment of ZEV regulations even more challenging. Conversely, higher ZEV sales will result in lower sales of conventional vehicles and thus lower future ZEV requirements.*

Complicating this challenge further are the significant uncertainties regarding consumer acceptance and technological development, and the balancing of both short and long term objectives. A further challenge in developing a model that accounts for all of these interacting elements is ensuring that feedbacks between supply and demand dynamics are sufficiently captured. Although there are civil penalties in place for non-compliance with the targets set by the regulations, the manufacturers do have some freedom in the strategy they choose to adopt in order to meet the targets.

With the focus on the manufacturer, Walther et al., assess various strategies in meeting these regulations, in an attempt to identify the option with minimal penalties incurred. In doing this, a pragmatic approach, based on outcomes, is adopted that considers only one aggregate manufacturer covering the state. Profit levels and returns are set at typical rates to avoid the unrealistic dynamics of a monopoly. Despite this, the interaction between manufacturers may be relevant as each will adopt their own approach (based on their individual wider business plans and desired market) and if manufacturers all acted identically the competition dynamics, which drive the free market, may be hindered and as such innovation would stall. This model limitation should be recalled when interpreting any results.

Walther et al., establish three broad options for manufacturers to meet regulatory requirements, which are:

- *Improvement of current ICEV efficiencies*. This is a continuation of much of current R&D, that has led to historic efficiency improvements and engine downsizing;
- *Introducing a new "Extra-Small" vehicle segment.* Such an approach may be novel in the States, where the "sub-compact" is not widely available and larger vehicles are generally favoured (Auto Alliance, 2013), as opposed to

Europe where small vehicles are favoured and vehicle downsizing is already occurring (ACEA, 2012), and;

- *Switching to low carbon fuels and powertrains.* This option also will aid with meeting ZEV Regulations. In designing the focus of the overall strategy, manufacturers must also make decisions on the attributes of any new platforms, and the timing of their introduction.

As this model is much more complex than CS1, it will be described in terms of four high level modules as identified by Walther et al. These modules are not equal in their complexity, but represent four specific areas of interest. Where appropriate, further detail will be provided on processes specific to this research. The model, illustrated in Figure 5.1, comprises of four modules and a number of exogenous parameters.

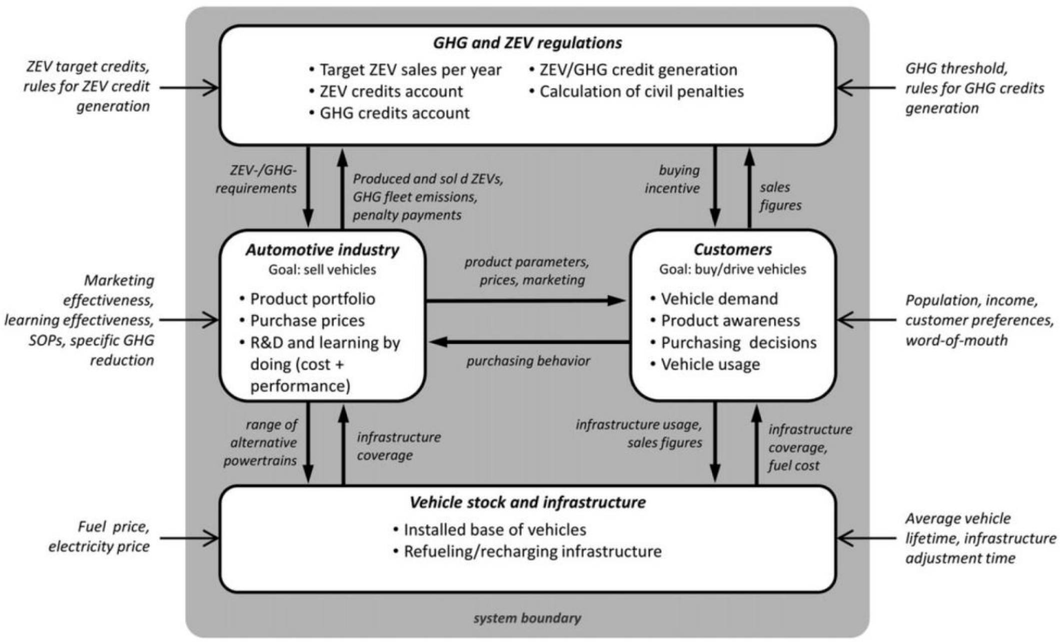

Figure 5.1: Structure of the model (Walther et al., 2010, p.244)

The *Regulations* module is designed to calculate credits and civil penalties through sales (from the *Customer* module) and emissions (from the Industry module). These outputs feed in to the *Industry* module and combine with purchaser behaviour (from the *Customer* module) to predict adjustments in vehicle purchase prices, fuel consumption and emissions, taking into account learning through experience. ZEV adjustment impacts are also calculated in this module, taking into account targets, actual sales, vehicle range, and costs of new technologies. Vehicle demand is calculated in the *Customer* module, as a function of population and income, with a purchase probability based on customer awareness (through marketing and word of mouth) and vehicle availability and utility, feeding into the choice model. Both the *Customer* and *Industry* modules feed into the *Infrastructure* module, which models the interdependence of market share and network effects.

The structure and dynamics of the four modules, as developed and described by Walther et al., are presented in the following Sections. Due to the complexity and commercial sensitivity of the model, it was not appropriate to comprehensively describe the model in more detail. These descriptions are interpretations of Walther et als., work, based on the paper and through experience of using the model. Any assumptions detailed in this Section come from Walther et al., but where sources are available they are provided. Vehicle attributes were determined by Walther et al., in conjunction with Volkswagen. Unless otherwise stated, module, group and parameter titles are those used by Walther et al.

5.1.1 Industry Module

At the heart of the model is the reaction of the manufacturer to the regulations, which requires adjustment of vehicle characteristics. These are demonstrated in Walther et al.'s diagrams[92] presented in Figure 5.2 for the GHG Regulations and Figure 5.3 for the ZEV Regulations. Within this, there are five aspects to this module which will be described in detail:

- Vehicle Attributes;
- Production Costs;
- Pricing and Cash-flow;
- Battery Costs and Capacity, and;
- Production and Sales.

[92] These are simplified illustrations of the larger model.

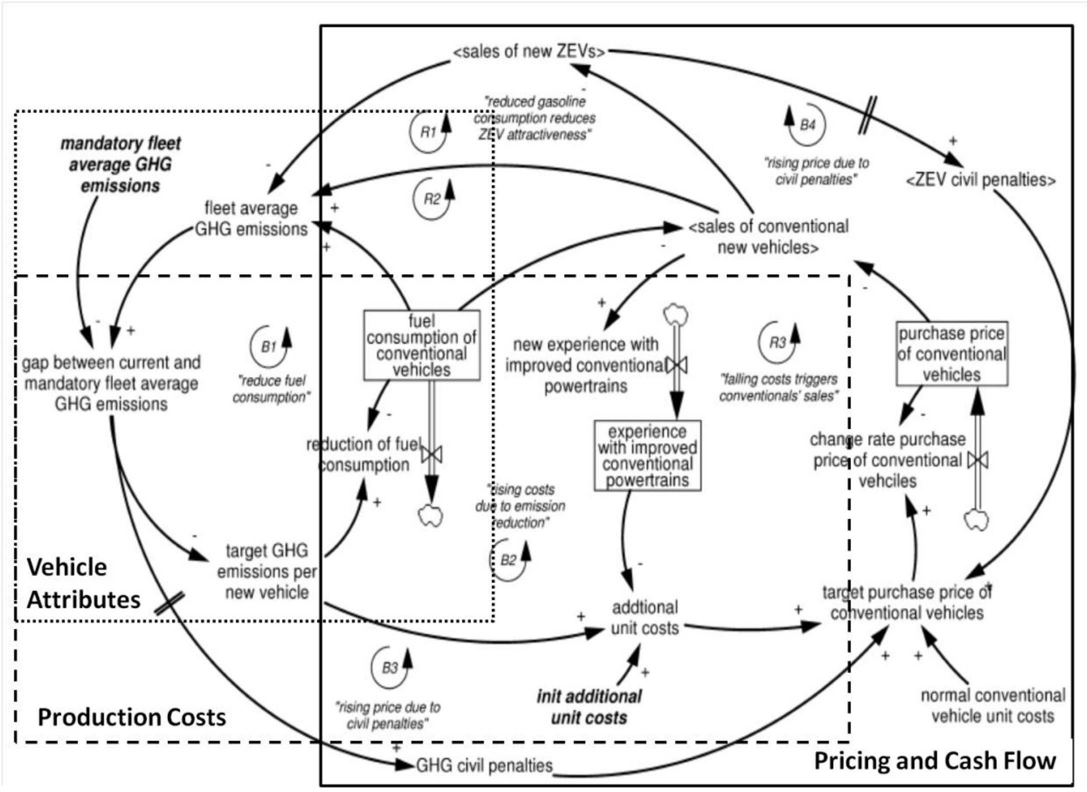

Figure 5.2: Adjustment of ICEV (conventional vehicles) to GHG Regulations (adapted from Walther et al., p.246)

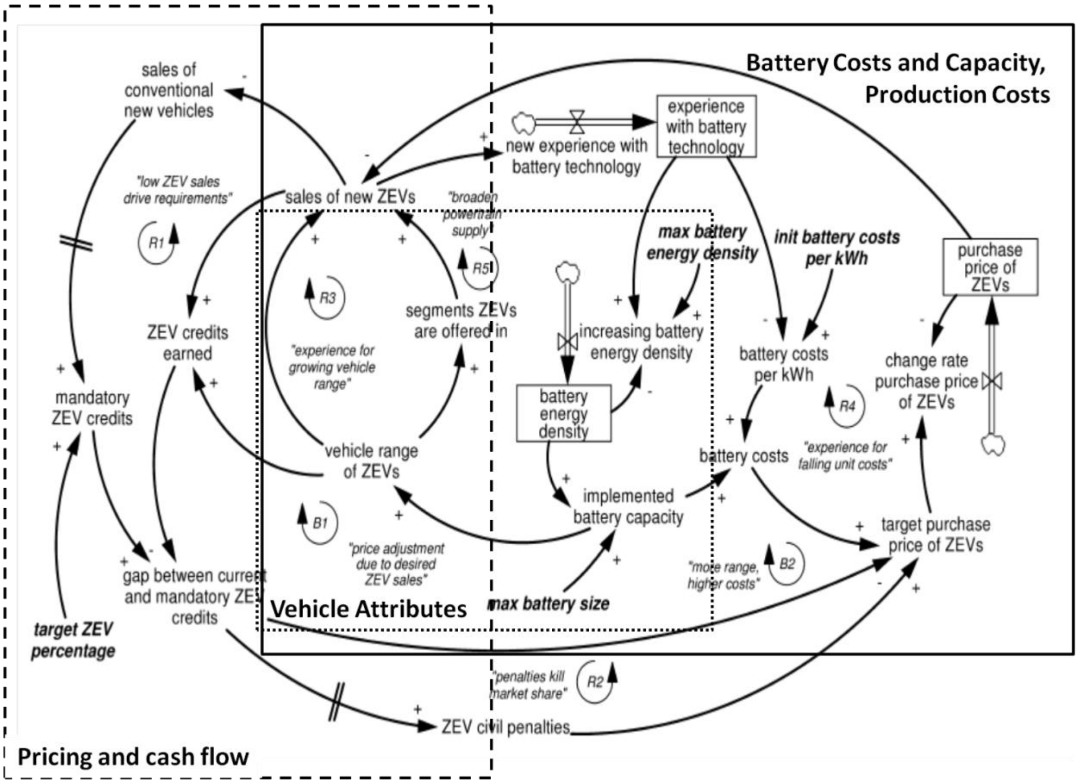

Figure 5.3: Adjustment to ZEV Regulations (adapted from Walther et al., p.247)

Production Costs

Unit production costs consist of fixed and variable costs, which are accounted for in loops B2 in Figure 5.2 and R4 in Figure 5.3. The *fixed production cost* is $5000 per vehicle for all segments. The *variable production cost* is the *variable unit production cost* plus the *battery cost per vehicle* for each vehicle. The initial variable production cost is shown in Table 5.1. The cost increases due to a *GHG adjustment cost* and decreases at a fractional rate of 3% per year (suggested by industry experts), representing economies of scale and improvements in production efficiency. Battery costs are discussed later under *Battery Costs and Capacity*.

		PRODUCTION COSTS ($)			
		XS	**S**	**M**	**L**
UNIT	*ICEV*	3,500	6,500	11,000	20,000
	HEV, PiHEV, BEV	8,000	10,000	15,000	20,000
BATTERY	*HEV*	900	1,200	1,500	1,500
	PiHEV	2,100	2,700	3,600	4,500
	BEV	3,000	4,500	9,000	21,000

Table 5.1: Initial variable production costs

The *GHG adjustment cost* is the cost to the manufacturer to reduce the fuel consumption in order to meet targets, but decreases with experience (R1, R2 and R3 in Figure 5.2). The equation for *GHG adjustment* is shown in Equation 5.1. The parameters included here were based on regression analysis data from the EU Joint Research Centre who carried out an extensive economic study on different technical concepts to reduce ICEV GHG emissions (Smokers et al., 2006). Production costs influence both purchase price and manufacturer costs, and is reflected in loop B2 in Figure 5.2 (See also: *Pricing and Cashflow*). In the model, only XS vehicles incur additional unit production costs as this is a new segment in the market.

$$GHG\ adjustment\ cost_i = \alpha_x ER_{\mathrm{i}}^3 + \beta_x ER_{\mathrm{i}}^2 + \gamma_x ER_{\mathrm{i}}$$

Equation 5.1

ER_i is the target emission reduction of vehicle i

α_x is a regression parameter for segment x: 0.007, 0.007, 0.0055, 0.0025 (XS,S,M,L)

β_x is a regression parameter for segment x: -0.1, -0.1, -0.11, -0.027 (XS,S,M,L)

γ_x is a regression parameter for segment x: 22, 22, 18, 18 (XS,S,M,L)

Pricing and Cashflow

Industry profit is the difference between revenue and costs discounted to Net Present Value. *Total costs* to the industry come from production, marketing and retail store costs, and civil penalties incurred from the GHG and ZEV Regulations (loops B3 and B4 in Figure 5.2). *Unit production costs* have already been discussed, and marketing and retail store costs are fixed costs influenced by vehicle availability and production rate and civil penalties are discussed in the *Regulation* module. *Marketing costs* are $1M for each 0.01 of *marketing effectiveness* and *retail store costs* are set at $1000 per unit in stock. *Revenue* comes from *vehicle sales*, so is dependent upon purchase price. *Purchase price*, shown in Figure 5.4, is influenced by production costs, a desired overall profit margin of 0.1 and the desired ZEV market share to meet ZEV requirements, with adjustments occurring via anchoring and adjustment (thereby biased to previous price).

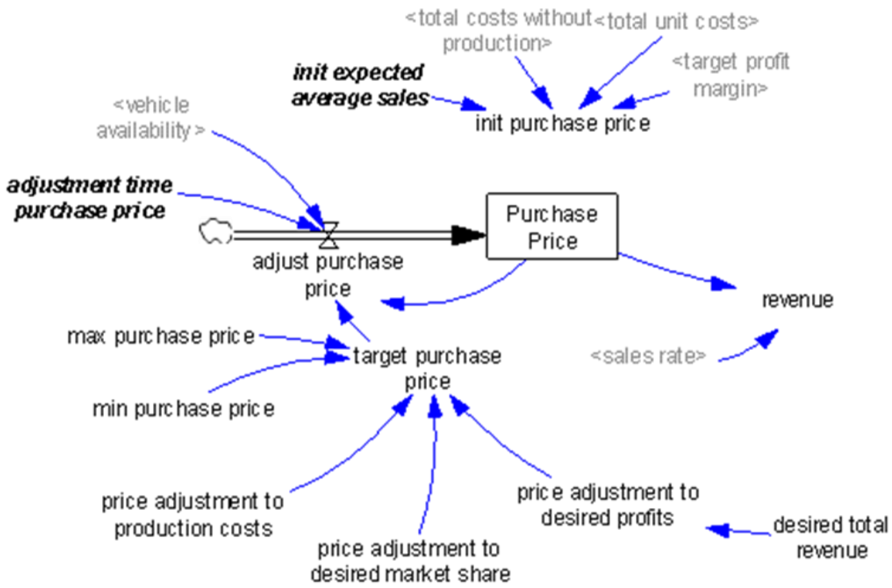

Figure 5.4: Influences on purchase price (adapted from model)

Purchase price is calculated by an *initial purchase price* (Equation 5.2) that is then adjusted (Equation 5.3) to meet a *target purchase price*. The target purchase price is the product of purchase price and the *price adjustment* to *production costs, desired profits and desired market share*, calculated using Equation 5.4, Equation 5.5 and Equation 5.6. Note that the profit weighting favours new technologies, the market share weighting favours BEV and the production costs weighting favours non-BEVs. The target purchase price is bound by a range between a maximum (which is five times the initial purchase price) and minimum (80% of the current purchase price). The purchase price for each vehicle (powertrain/model) in each time period is then multiplied by the *sales rate* to calculate the total revenue to the manufacturer. The desired market share is influenced by desire to avoid ZEV penalties, as if a ZEV target is not met an increased market share can lead to a decrease in purchase price (loops R1, R2 and B1 in Figure 5.3).

$$Initial\ Purchase\ Price = \mathrm{PM} \times \left(UC + \frac{NPC}{\mathrm{AS}}\right)$$

Equation 5.2

PM is the target profit margin (1.1)

UC is total unit production cost per vehicle.

NPC is the non-production cost: unit costs without production (marketing, retail store and penalties shared between expected unit sales).

AS is the initial expected average sales (1.4 x 10^6)

$$Purchase\ Price\ Adjustment\ per\ year = \frac{PP_{target} - \mathrm{PP}}{t_{adjust}}$$

Equation 5.3

PP_{target} is the target purchase price

PP is the purchase price

t_{adjust} is the adjustment time (0.5 years)

$$Desired\ profit\ price\ adjustment = 1 + w_p \times \left(\frac{R_d}{R} - 1\right)$$

Equation 5.4

W_p is the weighting for profit margin (ICEV: 1, HEV, PiHEV, BEV: 0.1)

R_d is the desired total revenue

R is the total revenue

$$Desired\ \ Market\ Share\ adjustment = 1 + ZEV_G \times w_m \times \left(\frac{M}{M_R} - 1\right)$$

Equation 5.5

ZEV_G is if vehicle is a Gold ZEV (ICEV, HEV, PiHEV: 0, BEV: 1)

W_m is the weighing for market share (0.1)

M is the market share

M_R is the market share requirement (For BEV: 2009-11: 0.11; 2012-2014: 0.12; 2014-17: 0.14; 2018-20: 0.16)

$$Production\ cost\ adjustment = 1 + w_c \times \left(\frac{1.1 \times UC}{PP} - 1\right)$$

Equation 5.6

W_c is the weighting for production costs (ICEV, HEV, PiHEV: 0.5, BEV: 1)

UC is the total unit cost per vehicle

PP is the purchase price

Vehicle Attributes

Vehicle attributes that are of interest are the ICEV, PiHEV and HEV fuel consumption, as they lead to unit GHG emissions, and the BEV vehicle range, as that determines availability, partial utility and ZEV classification. Loop B1 in Figure 5.2 represents the reduction in fuel consumption to meet GHG emission targets, and this is shown in more detail in Figure 5.5. The unit emissions are based on a 55:45 split of City:Highway emissions from the fuel consumption under those conditions and emission per gallon of gasoline, as shown in Equation 5.7.

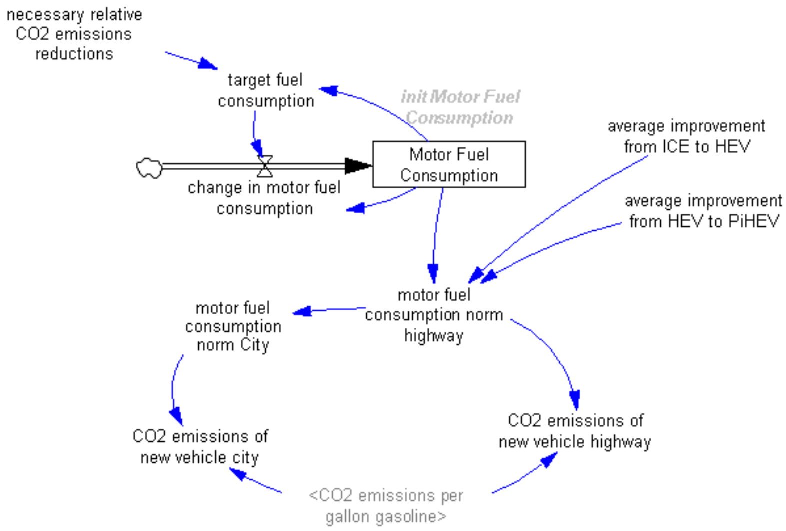

Figure 5.5: Calculation of motor fuel consumption for ICE-based vehicles (adapted from model)

$$Vehicle\ GHG\ emissions\ (g/mile) = 0.55\ \times ((MFC_{CITY}\ \times EF_{CITY}) +\ CF) + 0.45\ \times\ (MFC_{HWAY}\ \times EF_{HWAY}) +\ CF)$$

Equation 5.7

MFC is the motor fuel consumption for city or highway in gallon/mile

EF is the CO_2 gasoline emission factor for city or highway in g/gallon

CF is the conversion factor from CO_2 to CO_2 equivalent (1.176)

It is the *motor fuel consumption* that is responsible for the emissions, and this is adjusted by the manufacturer to meet the regulatory targets, based on the *necessary relative CO_2 emissions reductions* (see *Regulations* module for further detail on this). So, in the model the *change in motor fuel consumption* is influenced by the *target fuel consumption*, itself the product of *motor fuel consumption* and *necessary relative CO_2 emissions reductions. Initial motor fuel consumption* is 0.018, 0.028, 0.029, 0.036 gallons/mile for XS, S, M and L respectively. The *motor fuel consumption* is taken as the highway consumption and the city consumption is assumed to be 25% higher than highway. There is also an assumed improvement in consumption from ICEV to HEV and HEV to PiHEV of 0.005 gallon/mile.

The BEV has a constant CO_2 equivalent (based on electricity generation) assumed by the authors to be 130g/mile. The BEV range is calculated using Equation 5.8. It is determined by the battery capacity, making the assumption that the energy consumption of the electric motor is constant (see *Battery Costs and Capacity*). The maximum battery weight in vehicle and energy consumption are both constant and endogenous, taken from a 2010 report on electric powertrains (Kromer and Heywood, 2007). The 0.8 term refers to the fraction of usable battery capacity.

$$BEV\ range = \frac{ED\ \times W_{MAX}\ \times 0.8}{EC}$$

Equation 5.8
ED is the battery energy density (kWh/kg)
W_{MAX} is the maximum battery weight in a vehicle (kg) (const.)
EC is the energy consumption of electric motor (kWh/mile) (const.)

Battery Costs and Capacity

Battery costs are influenced by *battery production* and *capacity*, as shown in Figure 5.6. They are assumed to develop by reducing unit cost per kWh, which follows a standard experience curve (R4 in Figure 5.3), and increasing energy density (loop R3 in Figure 5.3). Energy density follows an S-shaped technology development curve with a maximum of 0.22 kWh/kg (the theoretical maximum for Li-ion batteries). The increase in battery capacity over time influences the range of an EV, which in turn impacts on availability, desirability and purchase price, captured by loop R5 in Figure 5.3.

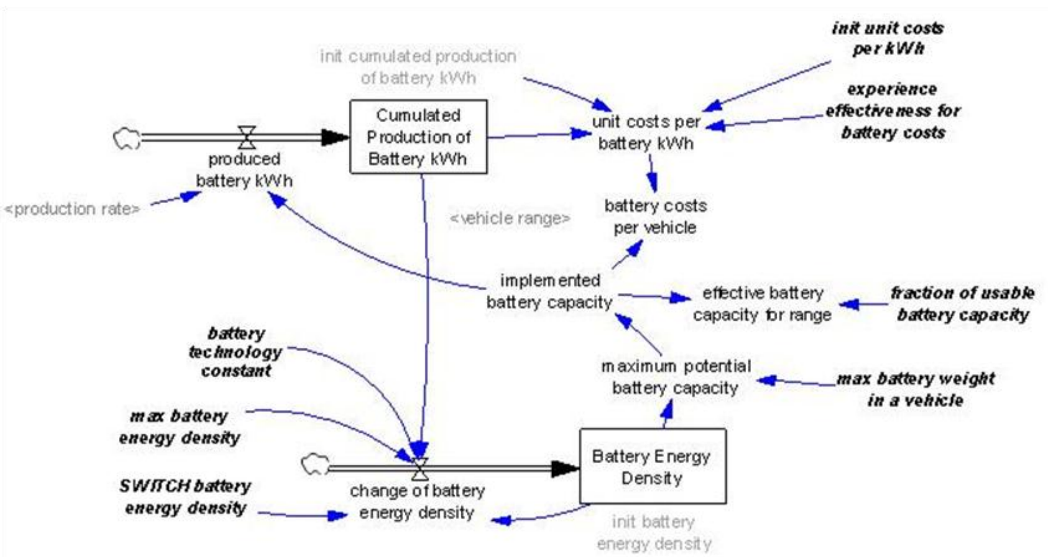

Figure 5.6: Battery Costs and Capacity (adapted from model)

The battery costs per vehicle, calculated using Equation 5.9 are dependent on *unit costs* and *battery capacity*, itself a product of *energy density* and the *maximum battery weight*.

$$Battery\ Cost\ =\ (ED\ \times\ W_{MAX})\ \times \left(BUC_{init}\ \times \left(\frac{E_{cum}}{E_{cum,init}} \right)^{-0.1} \right)$$

Equation 5.9

ED is the battery energy density (kWh/kg)

W_{MAX} is the maximum battery weight in a vehicle (kg) (const.)

BUC_{init} is the initial battery unit costs (250 $/kWh)

E_{cum} is the cumulated production of battery energy (kWh)

$E_{cum,init}$ is the initial cumulated production of battery energy (1×10^6kWh)

Production and Sales

The supply chain of the automobile industry is modelled as make-to-stock, as it is usual in the U.S. to buy direct from a dealer (not shown in Figure 5.2 and Figure 5.3). Within this the *production capacity*, *order backlog* and *retail stock* are included and *waiting customers* are also modelled, so that if a demanded vehicle is not in stock, they will wait a time (one month on average) before making a new decision. This in effect captures supply and demand dynamics with a realistic time lag, allowing for disequilibrium between sales and demand so a manufacturer can push towards a minimum production rate of 150,000 PiHEV and HEV and 50,000 BEV vehicles a year. *Total demand* is then calculated using Equation 5.10. Further detail on this is not directly relevant to this case study so for details see Walther et al.

$$Total\ Demand = \sum \frac{WC_i}{WT_a} +\ FD$$

Equation 5.10

WC is the number of waiting customers for vehicle i

WT_a is the average time until waiting customers cancel first choice (0.083)

FD is the fixed demand for vehicles (140,000)

5.1.2 Regulations Module

The GHG and ZEV Regulation module can be seen as comprising of the two separate, but interacting systems for the two regulations, as shown in Figure 5.7.

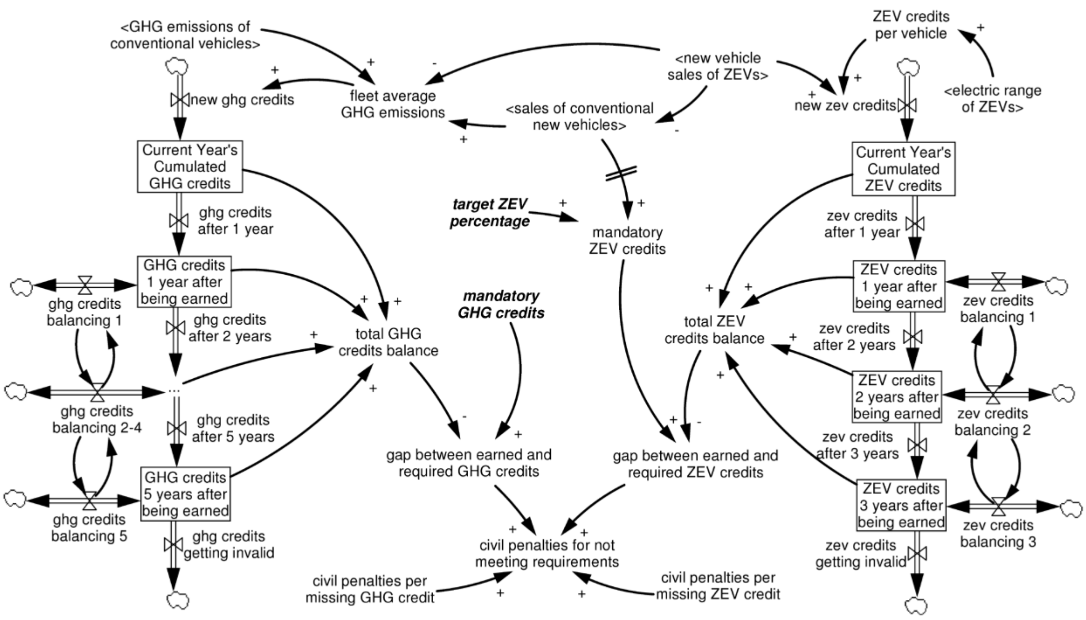

Figure 5.7: GHG and ZEV Regulation requirements (Walther et al., 2010, p.245)

GHG Regulations

The accounting structure for the GHG Regulations is implemented as an ageing chain (as the stocks and flows of credits are age-dependent – recall they are valid for five years). Credits (measured in g/mile) are calculated for a time period from the difference between the *fleet average emission* and the exogenous *target emission* (as shown in Table 5.2), multiplied by the number of new vehicles. *Fleet average emissions* are calculated from the *unit GHG emissions* (see *Industry* module) for each powertrain/model combination and the number of each of those vehicles sold in the time period (see C*ustomers* module). GHG credits (which may be positive or negative depending on whether or not targets are met) are cumulated over each year and then get older, and after five years penalties are calculated at $5000 for every negative g/mile. These penalties then feed into the pricing and cashflow of the manufacturer (see *Industry* module).

Year	Fleet Average Emission Target (g/mile)
2009	323
2010	301
2011	267
2012	233
2013	227
2014	222
2015	213
2016	205

Table 5.2: Fleet average emission targets (CARB, 2012)

ZEV Regulations[93]

Within the ZEV Regulations, there are four categories of ZEV (Gold, Silver, Silver Plus and Bronze) depending on their degree of zero emission, which are eligible for different proportions of credits, shown in Table 5.3. Target ZEV credits are calculated on the average of the preceding three-year Gold (fully zero emission) ZEV sales multiplied by a general percentage requirement (2009-11: 0.11; 2012-2014: 0.12; 2014-17: 0.14; 2018-20: 0.16) and minimum percentage requirement for Large Volume Manufacturers (LVM) for each ZEV type.

ZEV Classification	Description	Powertrain	ZEV Credits per vehicle sold
Gold	Fully Zero Emission Vehicle (ZEV)	Fuel Cell or Battery Electric Vehicle	See Table 5.4
Silver Plus	Electric Advanced Technology Partial ZEV	Plug-in Hybrid Electric Vehicle	2009: 0.92, 2010: 0.87, 2015: 0.77
Silver	Advanced Technology Partial ZEV	Conventional Hybrids Electric Vehicle	2009: 0.4, 2012: 0.35, 2015: 0.3
Bronze	Partial ZEVs	Super Ultra Low Emission ICEV[94]	0.2

Table 5.3: ZEV credits for main classifications (CARB, 2009)

Actual ZEV credits are based on new vehicles produced and sold, with specific credit allowances for different classes of ZEVs (from the industry module) that are based on powertrain and range, shown in and Table 5.4.

Gold ZEV type	Definition	Credits per produced ZEV	Additional credits per sold ZEV	
			2009-2017	from 2018
Type V	EV with 300 or more mile range of fast refuelling capacity	1	6	2
Type IV	EV with 200 or more mile range and fast refuelling	1	4	2
Type III	EV with 100 or more mile range and fast refuelling or 200 mile BEV	1	3	2
Type II	EV with 100-200 mile range	1	2	2
Type I.5	EV with 75-100 miles range	1	1.5	1.5
Type I	EV with 50 to 75 miles range	1	1	1
Type 0	EV with less than 50 mile range	0	1	1
NEV	Neighbourhood Electric Vehicle: Low speed vehicle certified as ZEV	0	0.3	0.3

Table 5.4: ZEV credits for Gold ZEVs (adapted from Walther et al., 2010)

[93] The European Average Fleet Emission Regulations have similar provisions in that manufacturers are awarded GHG credits for LCVs that are sold, though LCV production is not mandated.

[94] 90% cleaner than average new ICEV – not included in this model.

ZEV credits are modelled using an aging chain (as with GHG credits), with civil penalties calculated after 3 years of $5000 per deficit credit between target and submitted credits. Any deficit in credits may be made up through extra allowances from excess partial ZEV Credits from previous years, based on their zero emission vehicle miles travelled (VMT) and a fleet average Non-Methane Organic Gas (NMOG) requirement. From this, g/mile ZEV credits can count towards overall credits, and are delayed by 2 years. Accounting for this, ZEV penalties can be calculated using the (simplified) Equation 5.11.

$$Annual\ ZEV\ Penalities = 5000\ \times \left[\frac{\left((C_T - C_{ZEV})\ \times NMOG\right) - (C_{GM\ PZEV})}{NMOG}\right]$$

Equation 5.11

C_T is the total required credits for that year (based on previous sales and ZEV requirement)

C_{ZEV} is the total credits from ZEVs from ZEV sold and produced that year

NMOG is the fleet average NMOG requirement in each year

$C_{GM\ PZEV}$ is the amount of credits in g/miles from partial ZEV credits which were excess in previous year but can contribute allowances relative to the NMOG requirement.

5.1.3 Customers Module

The Customer module determines demand by considering total demand and probability of purchase. This probability is based on awareness and a choice set. Purchases are made relative to the probability of choice on the available sets of vehicles. Choice sets are determined through homogenous purchase decisions for each powertrain. It is based on a mean household income, and so different segments of society are not accounted for. There are three aspects which combine to create the customers module. These are choice set generation, utility of automobiles and vehicle market share, which are shown in the simplified diagram Figure 5.8.

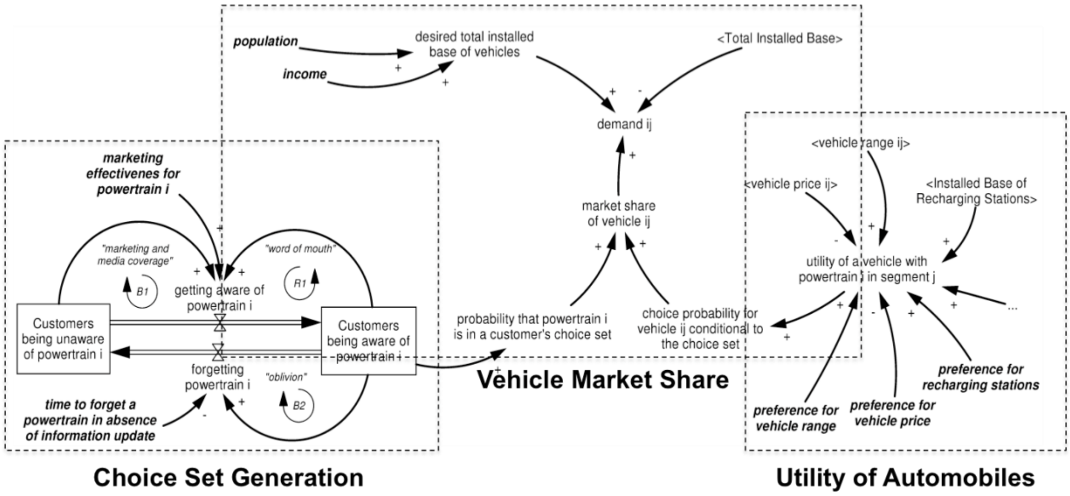

Figure 5.8: Customer demand for new vehicles (adapted from Walther et al., 2010, p.248)

Choice Set Generation

Customer awareness of a powertrain is based on the same Struben and Sterman (2008) model as CS1, influenced by marketing effectiveness of a powertrain (loop B1 in Figure 5.8), word of mouth with other drivers (R1) (EV and non-EV) and forgetting the powertrain (B2). Marketing effectiveness is dependent upon vehicle availability, and once each new model is introduced it has a marketing effect[95] of 0.03 that persists throughout the time period. ICEV has a constant marketing effectiveness of 0.01. The contact effectiveness between drivers varies as in Table 5.5.

Current Powertrain	Contact effectiveness of being aware of other powertrain on others			
	ICEV	HEV	PiHEV	BEV
ICEV	1	0.3	0.3	0.2
HEV	0.9	1	0.5	0.3
PiHEV	0.9	0.3	1	0.3
BEV	1	0.5	0.5	1

Table 5.5: Contact effectiveness between drivers

Utility of Automobiles

The utility of each vehicle is based upon preference parameters from a standard MNL model (Brownstone and Train, 1998) and vehicle characteristics (developed with the automobile manufacturer Volkswagen), as displayed in Table 5.6. There are a number of variable attributes that are responsible for the change in utility of each vehicle over time, which differ between policy scenarios:

[95] The Bass model external influence coefficient, relating to the population becoming aware of the powertrain from marketing and based on estimates from previous studies.

- *Purchase price* was described in the *Industry* module Section;
- *Range* is static for conventional vehicles and progressive with battery capacity for electric motors (also described under *Industry* module);
- *Fuel or energy consumption* is also linked to battery capacity;
- *Fuel station availability*, which is described in the *Infrastructure* module Section and for EV increases with installed base and vehicle range; and
- Other attributes were chosen to be fixed by model developers.

		P	R	A	V	RP	C	FS	EV
ICEV	*XS*	10	250	1.9	90	1	0.03	1	0
	S	14	300	2.3	100	1	0.04	1	0
	M	19	350	2.8	110	1	0.045	1	0
	L	30	400	3.5	130	1	0.05	1	0
HEV	*XS*	16	250	1.9	90	0.7	0.025	1	0
	S	19	300	2.3	100	0.7	0.035	1	0
	M	25	400	2.8	110	0.7	0.04	1	0
	L	31	450	3.5	130	0.7	0.045	1	0
PiHEV	*XS*	18	250	1.9	90	0.6	0.02	1/0	1
	S	20	300	2.3	100	0.6	0.03	1/0	1
	M	28	400	2.8	110	0.6	0.035	1/0	1
	L	35	450	3.5	130	0.6	0.04	1/0	1
BEV	*XS*	19	48	2.8	80	0	0.18	0	1
	S	23	65	3.0	100	0	0.2	0	1
	M	33	120	3.2	110	0	0.24	0	1
	L	49	240	3.5	130	0	0.28	0	1
Preference Parameter		-0.185	0.35	-0.716	0.261	-0.444	-0.768	0.413	-0.719

Table 5.6: Initial vehicle attributes and preference parameters
P: Price[96] (10^3\$), R: Range (miles), A: Acceleration (ms^{-2}), V: Velocity (mph), RP: Relative Pollution (dimensionless), C: Fuel or Energy Consumption[97] (gal/mile, kWh/mile), FS: Fuel Station Availability (dimensionless), EV: Electric Vehicle (binary).

Vehicle Market Share

The vehicle market share is determined from a choice probability for every vehicle available when a choice is made, based on the vehicles available at that time. The conditional choice probability is based on the *vehicle utility* and *perceived vehicle availability*, as shown in Equation 5.12. These have been calculated in the model for every possible vehicle combination. The probability of the possible choice set being the customers is calculated separately, based upon the fractional awareness of the powertrain, again for every possible combination. The vehicle market share is then the sum of all possible combinations of conditional choice probability multiplied by the choice set probability. By linking the fractional awareness and vehicle utility,

96 Preference parameter is for Price/Income. Partial utility is for the purchase price divided by average household income which is given as $51,563 from the 2005 US Census.

97 Preference parameter is for operating cost. Operating cost is determined by fuel consumption multiplied by fuel price.

diffusion and discrete choice theory may be linked mathematically. Once calculated the vehicle market share then feeds into vehicle demand in the industry module.

$$Probability\ of\ choosing\ vehicle\ i = \frac{VA_{p,i}\ \times\ e^{U_i}}{\sum\left(VA_{p,i}\ \times\ e^{U_i}\right)}$$

Equation 5.12

$VA_{p,i}$ is the perceived vehicle availability of vehicle i

U_i is the utility of vehicle i

5.1.4 Vehicle Stock and Infrastructure Module

The vehicle stock and infrastructure module, shown in Figure 5.9, captures the network effects (loop R1) between installed base of alternative powertrains and the refuelling/recharging infrastructure. This module captures a commonly acknowledged 'chicken and egg' problem. As recharging infrastructure increases, EV become more attractive, increasing the installed base and thus demand for recharging infrastructure. This can continue until saturation, through loop B1, which itself is dependent on range and recharging with respect to refuelling time

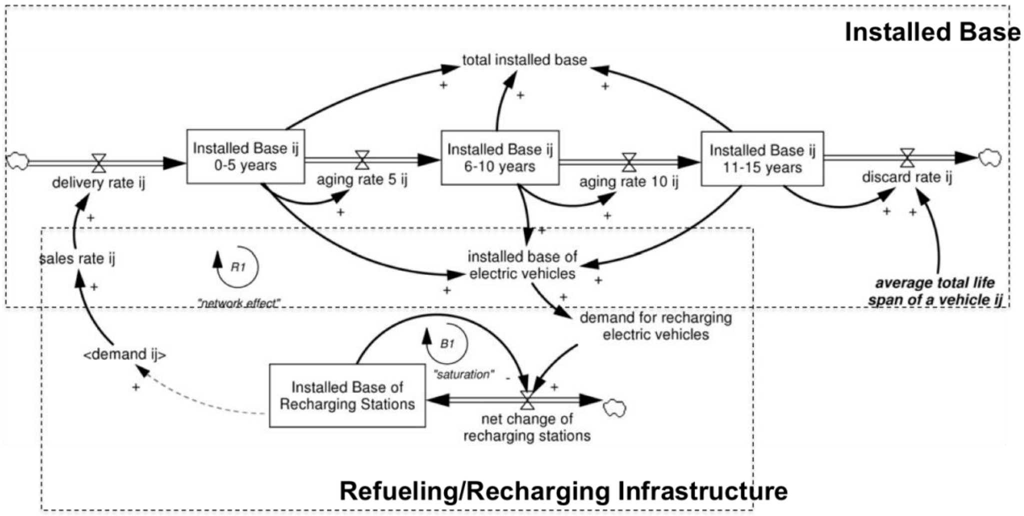

Figure 5.9: Infrastructure module (adapted from Walther et al., p.249)

Installed Base

Installed base is modelled as a standard ageing chain, with an average life span of 11 years. A certain portion of vehicles are discarded from each age stock up to the rest age, based on survival probability of 97% for 0-5 years and 87% for 6-10 years. Thus, *total discard rate* is calculated using Equation 5.13, which then feeds into the *total demand*, as described under *Production and Sales* in the *Industry* module.

$$Discard\ Rate = (IB_{0-5} \times 0.03) + (IB_{6-10} \times 0.13) + \left(\frac{IB_{11-15}}{11}\right)$$

Equation 5.13
IB is the installed base of each age stock of vehicles

Refuelling/Recharging Infrastructure

Availability of refuelling and recharging contributes to the utility of each vehicle and to range dependent availability of BEV. In the model this is based on recharging at a recharge station similar to a ICEV fuelling station. Fractional availability refers to the availability of EV recharging station compared to gasoline refuelling stations (which have a constant availability of 1). The target number of recharging stations is then determined by Equation 5.14, for which the only variables are installed base and vehicle range.

$$Target\ Recharge\ Stations = \frac{\sum IB_i \times \left(\frac{DVMT \times RT_i}{R_i \times DHR_i}\right)}{RU_s}$$

Equation 5.14

IB_i is the installed base of each EV model

DVMT is the daily average vehicle miles travelled (100 miles)

RT_i is the recharge time (PiHEV = 0.1 hrs, BEV = 0.5 hrs)

R_i is the range of each EV model

DHR_i is the daily total hours required for recharging (12 hours)

RU_s is the recharging units per station (4)

5.1.5 Initial Model Scenarios

Walther et al., use their model to understand the impacts of strategies for meeting the GHG and ZEV Regulations separately, and then on meeting them together. Although it is not necessary to discuss their findings for this case study (this has already been presented in the literature review), the strategies employed in their study were used to develop the baseline scenario in this case study.

There were three GHG strategies, as presented in Table 5.7. It was found that only the combined strategy (GHG3) met requirements for every year. GHG1 meets them only in some years but does not incur civil penalties (due to the five year accumulation period – see Section 5.1.2), and GHG2 only meets the requirements in the first year, incurring large civil penalties overall. This suggests that customer behaviour may have a high impact, as GHG3 reduces customer choice the most.

Strategy	Description
GHG1: *Vehicle adjustment*	Gradual reduction of CO_2 in each model.[98]
GHG2: *Fleet adjustment*	Change in fleet by introducing XS segment vehicles.
GHG3: *Combined adjustments*	Implementing GHG1 and GHG2 together.

Table 5.7: GHG strategies (Walther et al., 2010)

Four strategies were tested against the ZEV regulations, as in Table 5.8. Each strategy phased in HEV and PiHEV in the years given in the table, with or without BEV, which was dependent on minimum range and/or infrastructural requirements.

Powertrain	Segment	ZEV1: *Conservative without BEV*	ZEV2: *Conservative with BEV*	ZEV3: *Aggressive without BEV*	ZEV4: *Aggressive with BEV*
HEV	*XS*	2014	2014	2012	2012
	S	2012	2012	2011	2011
	M	2009	2009	2009	2009
	L	2010	2010	2010	2010
PiHEV	*XS*	n/a	n/a	2016	2016
	S	n/a	n/a	2015	2015
	M	R_e>60 miles	R_e>60 miles	2012	2012
	L	R_e>75 miles	R_e>75 miles	2013	2013
BEV	*XS*	n/a	I>50%	n/a	R>50 miles
	S		I>60%		R>70 miles
	M		R>200 miles		R>150 miles
	L		R>400 miles		R>300 miles

Table 5.8: ZEV strategies (Walther et al., 2010)
(R_e = Electric Range, I = Infrastructure coverage, R = Total Range)

All of these strategies resulted in high civil penalties, with only ZEV4 being close (and in the final year exceeding) the ZEV requirements. This would suggest that the accelerated introduction of both full and plug-in hybrids in as many segments of possible and early introduction of BEV are key to success. This is to overcome market inertia from customer low awareness of new technologies and to help build the infrastructure required for BEV. This would make sense intuitively as it will create awareness and be more likely to meet needs of customers, but is also likely to be most costly. Finally, compliance with both GHG and ZEV regulations and interactions between strategies is investigated through applying GHG1 with ZEV4 and GHG3 with ZEV4. It was found that the best GHG strategy made meeting ZEV requirements more difficult due to the impact of the sale of extra small (XS) ICEV on the sale of ZEVs in that same segment. Thus joint compliance would need a reduction of all ICEV emissions *and* to establish a new XS ZEV vehicle segment.

[98] Fractional reduction is equal across all vehicles (i.e. larger vehicles require absolute emissions reducing to a larger extent than smaller vehicles).

5.2 Extensions to the Base Model

In general the model as it was (‘off the shelf’) was a close fit to the requirements of the case study. Although, ideally, a UK based model would have been preferred, it was not realistic to calibrate the model to the UK and European regulations as the complex detail of the model was very specific to the California regulations. The two sets of regulations are, however, broadly similar and California and the UK have similar population demographics and car ownership, with California being about two-thirds of the size of the UK. Culturally, both states value civil liberties, recognise anthropogenic climate change and have comparable relationships with the automobile. One major difference is the price of fuel, which will affect any payback period for an LCV, as discussed later. Due to these similarities, the findings in terms of ethics and policy are assumed to be transferable. However, a few small amendments were made to the model in order to retrieve the information required for the investigation and to allow the introduction of subsidies as an alternative policy.

Firstly, it was made possible that the GHG and ZEV penalties were able to be “turned off” in order to create a “no penalty” baseline, representative of a ‘Business as Usual’ scenario without *Regulation* in place, as Walther et al. did not consider this scenario. Recall, in the ‘*Pricing and Cash-flow’* part of the model, the civil penalties incurred by any regulatory credits that are not met feedback into the total costs of the manufacturers. As the manufacturer has a target profit margin of 0.1, a desired total revenue is based on total costs in line with this target profit margin. The desired revenue then feeds into a price adjustment to meet the desired profits, and also on a weighted profit margin for each powertrain. This then feeds into the target purchase prices. A “no regulation switch” simply prevented any incurred penalties from feeding into total cost and thus affecting purchase prices. This assumes that the manufacturer is purely motivated by maximisation of profits. Within the baseline, new ZEV models are brought in (see later), and vehicle adjustment of ICEV emissions (Walther et al.’s GHG1) is not carried out. However XS segment ICEV are included without Regulation (GHG2), as they are already available and gaining market momentum in California (Krisher and Durbin, 2013; Lloyd, 2011).

Secondly, a reduction of BEV and PiHEV purchase cost at certain times to imitate a rebate/subsidy was included. This subsidy was added to the partial utility of purchase price and income that fed into the choice model that calculated the utility for each vehicle. All exogenous input data and endogenous feedback equations remained as developed by Walther et al., with the exception of the vehicle availabilities described in the next Section. It was not the purpose of this research to significantly develop or expand the model, but to use it as a base to establish and run scenarios of interest in exploring the proposed ethical framework, a focus not taken by the original modellers.

5.3 Model Baseline Development

In addition to the baseline having the penalties "turned off" and XS ICEV being available, a decision had to be made as to when the ZEV models would become available. A number of options were considered, based on those developed by Walther et al., and described in Section 5.1.5;

- No ZEV introduced other than a medium sized HEV in 2009 (as this model is already well established in the current market place);
- Conditional introduction of PiHEV and BEV and fixed introduction of HEV to mirror the 'conservative' scenarios, and;
- A fixed year introduction of all ZEVs to mirror the 'aggressive' scenarios.

Option 1 was discounted as it is clearly unrealistic as there are already both PiHEV and BEV models available in the market place. Option 2 is a *"Conditional Baseline",* and the Walther et al., Scenario ZEV2 (see Table 5.8) was applied. Scenario ZEV4 was used as a base for Option 3, the *"Fixed Baseline"*. The fixed introduction dates selected for this differed slightly from ZEV4, to reflect actual observations in vehicle introductions since Walther et al., built their model. For HEV, the conservative introduction was used, as no S or XS models are yet widely available. The aggressive introduction dates of PiHEV were seen to be reasonably accurate so were used. BEV introductions were not fixed by Walther et al., so fixed dates were based on actual and predicted dates from manufacturers. The resultant ZEV introductions are presented in Table 5.9.

Powertrain	Segment	Conditional Baseline	Fixed Baseline
HEV	XS	2014	2014
	S	2012	2012
	M	2009	2009
	L	2010	2010
PiHEV	XS	n/a	2016
	S	n/a	2015
	M	R_e>60 miles	2012
	L	R_e>75 miles	2013
BEV	XS	I>50%	2011
	S	I>60%	2012
	M	R>200 miles	2013
	L	R>400 miles	2015

Table 5.9: Baseline vehicle introductions
(R_e = Electric Range, I = Infrastructure coverage, R = Total Range)

The *Conditional Baseline* best represents a ‘Do Nothing’ scenario, and compares favourably with other predictions for California, shown in Table 5.10, so can be used as a baseline for market share and emission impacts. However, it cannot be used for direct comparison to the policy scenarios’ impact on vehicle costs because new vehicle models are introduced in response to *Regulation* and *Subsidies*, which makes it difficult to compare with the C*onditional Baseline*, where models are not available at the same time as in the scenarios*.* Hence, the *Fixed Baseline* is used as the baseline for assessment of cost impacts, as this overcomes the effect of vehicle availability. Interestingly, the *Fixed Baseline* PiHEV prediction is similar to one of the other predictions in Table 5.10.

SCENARIO	2020 SALES MARKET SHARE (%)		
	PiHEV	BEV	PiHEV + BEV
Californian Plug-In Electric Vehicle Collaborative (Turrentine et al, 2010)	N/A	N/A	2 – 6
US Department of Energy (Balducci, 2008)	N/A	N/A	~ 10
Boston Consulting Group (BCG, 2009)	29	2	31
Conditional Baseline	9.34	1.91	11.25
Fixed Baseline	22.1	16	38.1

Table 5.10: ZEV market share projections in 2020

It is recognised that the *Fixed Baseline* is not realistic as manufacturers are much more likely to carry out a conditional production strategy than to develop and release models at fixed times without any government intervention. Indeed, the *Fixed Baseline* allows the manufacturer to accumulate negative profits in the model. This illustrates a typical “chicken and egg” type problem that can’t be fully captured in the model baseline as government policies are required to assure manufacturers of the viability of producing new models. In effect, the *Conditional Baseline* shows what would happen if no real effort were made to introduce new models, while the *Fixed Baseline* allows the filtering out of policy impacts while accounting for the effect of introducing new models at fixed times in anticipation of government intervention or customer preferences, but not compelled by *Regulation*.

Whilst trying to determine the most appropriate inputs for the baseline, different levels of marketing were applied with the view that if the manufacturer is not motivated by policy to promote the ZEVs as strongly then the marketing effectiveness could be lower. It was found during these tests that the marketing had a much stronger effect than any of the policy variables (similar to CS1). As this was not the current focus of the work, the marketing effect used by Walther et al., was retained in all scenarios. In future work it would be prudent to explore these effects in more detail as they could be representative of *Raising Awareness* policies.

5.4 Model Testing[99]

Three policy scenarios are tested, all of which have the same fixed introduction of models as the *Fixed Baseline*. A *Fiscal Measures* policy type is tested in the *Subsidy* scenario, replicating the current Californian Rebate scheme of $1500 for PiHEV and $2500 for BEV for a 6-year period. The second is the *Regulation* policy, which the model was originally designed around, and there are complex dynamics associated with sales dependent credits and penalties as explained above. Under *Regulation*, manufacturers are assumed to meet GHG targets through increased fuel efficiency in all vehicle classes. Finally, the two policy scenarios were combined into a *Both Policies* scenario. All input parameters are shown in Table 5.11.

[99] Throughout this chapter, all scenarios are identified in the text by capitalisation and italicisation.

INPUT PARAMETER		SCENARIO				
		Conditional Baseline	**Fixed Baseline**	**Subsidy**	**Regulation**	**Both Policies**
Model Availability (year)	*ICEV (XS, S, M, L)*	2010, 2000, 2000, 2000	2010, 2000, 2000, 2000			
	HEV (XS, S, M, L)	2014, 2012, 2009, 2010	2014, 2012, 2009, 2010			
	PiHEV (XS, S, M, L)	N/A, N/A, R(60), R(75)	2016, 2015, 2012, 2013			
	BEV (XS, S, M, L)	I(0.5), I(0.6), R(200), R(400)	2011, 2012, 2013, 2015			
Penalties on		NO		NO	YES	
Subsidy ($)	*PiHEV*	NO		1500	NO	1500
	BEV	NO		2500	NO	2500
Subsidy Duration		N/A		2011-2017	N/A	2011-2017

Table 5.11: Scenario input parameters

When developing the scenarios, it was felt appropriate to understand what influence subsidy strength may exert on ZEV market penetration in this model. A number of scenarios were tested, relative to the fixed baseline, shown in Figure 5.10. These were the 6 year unlimited budget as used in the model scenarios, a capped $45m budget, a higher subsidy of $8000 for both PiHEV and BEV, and an unlimited (and unrealistic) budget for current subsidies that continues through to 2020. It was found that there is very little difference between any of these scenarios by 2020. The largest variation between scenarios was realized with the artificially high subsidy, which yielded an increase in both BEV and PiHEV market shares, mainly at the expense of HEV, but as soon as the subsidy period ended the market share returned to almost the same trajectory as the other scenarios. This is because the learning effect on price is not enough to outweigh the removal of the subsidy. Note that there is also very little difference from the fixed baseline and this is discussed in more detail later (Section 5.5.2). As there appeared to be little difference between the subsidy options, the current subsidy amounts and regime of 6 years was retained in the modelling scenarios.

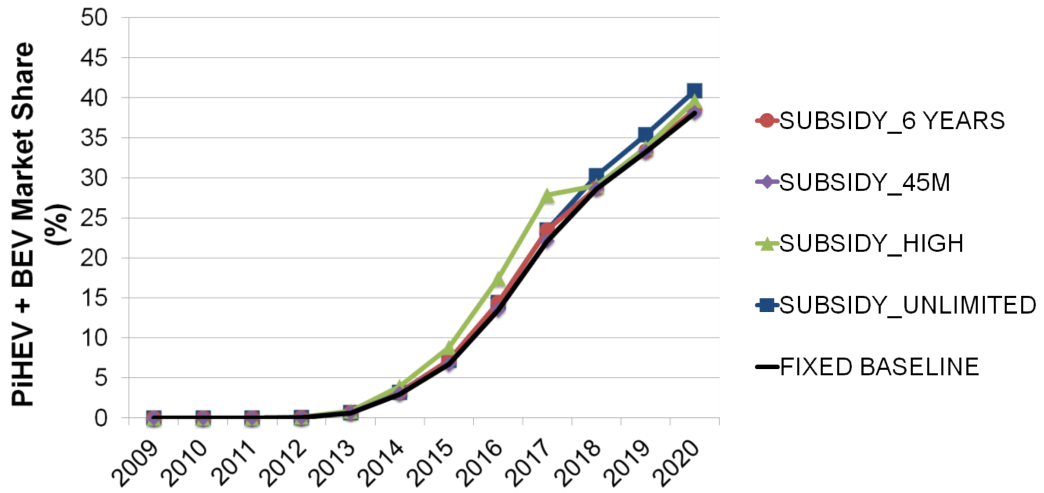

Figure 5.10: PiHEV and BEV market share of sales under different subsidy scenarios

5.5 Findings

There were three outputs of interest to this study, in relation to the ethical framework. These were the GHG emissions, the market share and the ownership costs and how these vary between segments. Further to this, the impact on overall costs may provide further indication of policy impact. In this Section, the focus of ZEVs is on PiHEV and BEV. Although the ZEV Regulations classify HEV as a ZEV, the approach is taken that as HEV aligns more with ICEV. This is because they are more established in the market, and provide less emission reduction potential and ZEV credits than PiHEV and BEV.

5.5.1 GHG Emissions

Significant reductions in GHG emissions are witnessed by 2020 under all policy scenarios compared to the *Conditional Baseline,* as seen in Figure 5.11 which shows the average fleet GHG emissions (including emissions from tailpipe and/or electricity production). Under the *Subsidy* scenario this is a reduction of around 35 $gGHGmile^{-1}$ and under the *Regulation* and *Both Policies* scenarios, the reduction is around 80 $gGHGmile^{-1}$. Assuming an average annual mileage of 15,000 miles per year[100] and a lifetime of 10 years,[101] this would equate to total savings of between 34 and 168 Mt GHG (2 and 30%) respectively from all new vehicles produced during the time period. The biggest emission reductions are made when *Regulation* is in place, and there is little extra reduction gain when subsidies are included in the

[100] From registered cars (CDMV 2009) and mileage (TSI 2009) in California.

[101] The model assumes an average vehicle life of 11 years (Walther et al. 2010). Here, 10 years is assumed so that the calculations are on the conservative side.

Both Policies scenario. This perhaps indicates that subsidies are ineffective, which is discussed more fully in the next Section. *Regulations* are successful because manufacturers are set a specific level to aim for within the model, and thus most emission reductions come from efficiencies made with ICE-based Vehicles rather than introduction of ZEVs. The *Subsidy* scenario does not meet current GHG targets by 2020, as there is no motivation for manufacturers to make efficiencies in ICEV, HEV or PiHEV, and so emission reductions only come from the introduction of PiHEV and BEV. As the price volume effect does not make any difference to the prices after the subsidy is removed in 2017 (as described in Section 5.4), there is practically no difference between the *Fixed Baseline* (which has the same models available and no ICEV efficiencies) and the *Subsidy* scenario by 2020. The *Fixed Baseline* is a useful way of separating out the effect of new model introductions and the added impact of *Regulations* on existing powertrains – so the change from *Fixed Baseline* to *Regulation* could be viewed as the *Regulation* impact over and above the impact of the introduction of new models without *Regulation*.

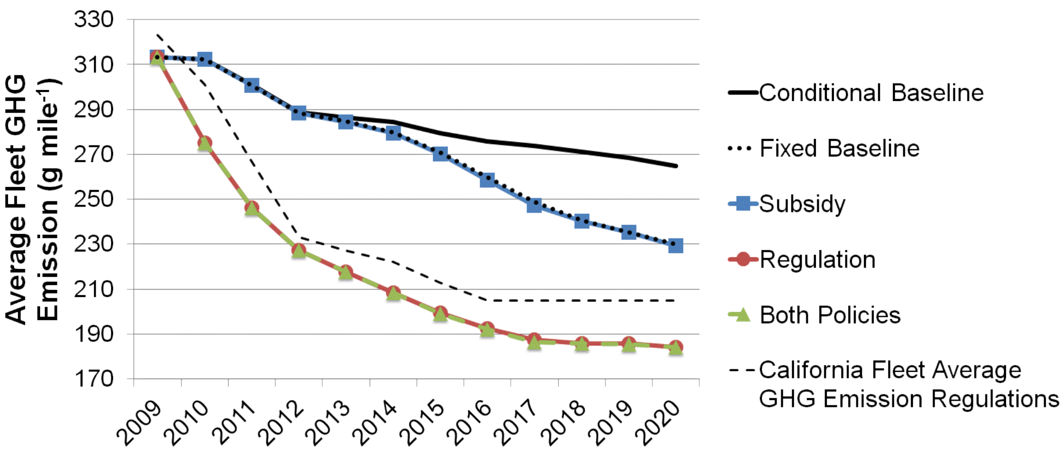

Figure 5.11: Average fleet GHG emissions for the policy scenarios

5.5.2 Market Shares

Figure 5.12 shows that compared to the *Conditional Baseline*, the policy scenarios result in more successful BEV and PiHEV new market shares. Under the *Conditional Baseline*, ICEV + HEV retains an almost 90% market share, which is reduced by nearly half with policies in place. The *Regulation* policy was more successful than the *Subsidy* policy, yielding 9.5% more PiHEVs and 17.8% more BEVs by 2020, compared to the *Conditional Baseline* (not shown in figure).

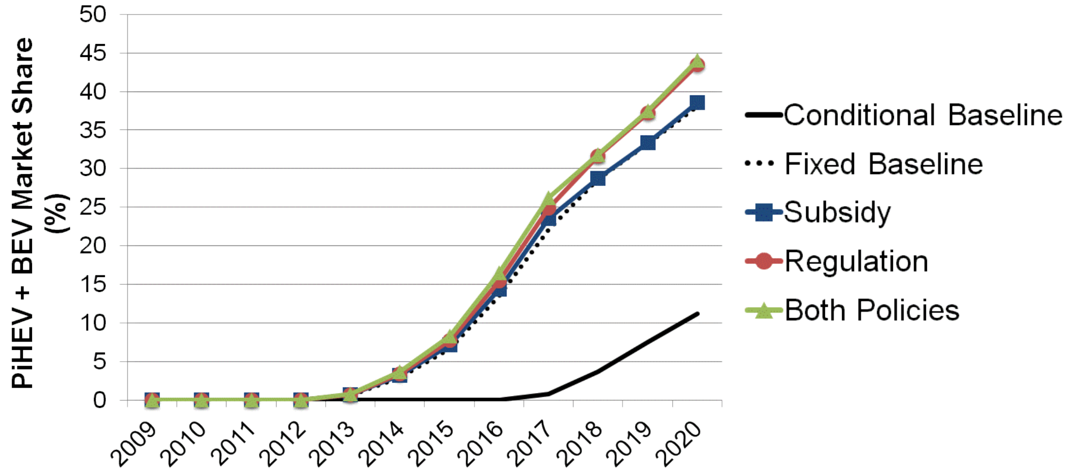

Figure 5.12: Market share of sales of BEV + PiHEV

Similar to the emission reduction findings, as shown in Table 5.12 there is only a 1% difference in market share between scenarios with and without subsidies in place. Although the *Fixed Baseline* is not wholly realistic (as explained earlier), this could suggest that the introduction of models at specific times is more important than the *Subsidy* policy being in place. More importantly, this is also related to the chicken and egg problem of government policy and manufacturer response mentioned in the baseline development (Section 5.3). However, the increase due to *Subsidy* is also relatively small when comparing between *Both Policies* and *Regulation.* Yet looking at the difference in shares in the last year of Subsidy (2017), they are almost 10% greater in those scenarios with subsidies in place. In fact, this is the peak of the impact and when subsidies are removed, then the share of sales will drop as customers have to pay the full price as under other scenarios. Although this finding may initially suggest that subsidies are not effective, what it may indicate is that subsidies need to be stronger or applied for longer than those tested here to ensure that the learning curve is sustained and prices reduced in the long term, as concluded in Section 5.4 where different subsidy regimes were tested, and a similar finding to CS1.

The finding here, therefore, is that the subsidies in the tested scenarios are not useful by 2020 when *Regulation* is in place. However, if having subsidies in place encourages manufacturers to introduce models (e.g. compared to the *Conditional Baseline)*, then they can be thought of as successful - though perhaps not directly due to the reduced purchase price. This may perhaps be comparable to the failing market case in CS1. These findings do not mean that subsidies should be disregarded, but suggest further understanding is needed around the impact on manufacturer strategies for developing new models earlier.

SCENARIO	SALES MARKET SHARE (%) 2017 PiHEV	2017 BEV	2020 PiHEV	2020 BEV
Fixed Baseline	12.6	9.4	22.1	16.1
Subsidy	13.1	10.4	22.4	16.2
Regulation	13.7	11.3	24.2	19.0
Both Policies	14.8	12.1	24.8	19.3

Table 5.12: Market share of sales of PiHEV and BEV in 2017 and 2020

Changes in segment market shares are shown in Table 5.13, and it would appear that having either of the policies in place will push the market into the XS/S segments rather than the M/L segments favoured in the baseline scenario.[102] This may be a cause for concern, and an indication that customers with legitimate claims for larger cars may be forced to downsize to a car that does not suit their needs, and are thus disadvantaged by the introduction. More of a concern however, there are now more people in the worst-off segment. The effect of fixed introduction of vehicle models is even more obvious, as there is no difference between the *Fixed Baseline* and *Subsidy* scenarios. With *Both Policies* in place, the market share becomes very slightly more biased to Medium or Large vehicles than in *Regulation* alone, perhaps suggesting that a subsidy may help people to purchase a large vehicle if they need one, or avoid becoming worst-off. This conclusion may be overly optimistic as the difference here is only 0.1%, and within the model purchase decisions are related to preferences, which do not distinguish between want and need. There appears to be little difference between preferred segments within each powertrain (not shown), which roughly follow the overall segment shares.

	SCENARIO	SALES MARKET SHARE (%) XS	S	M	L
	2009	0	24.6	41.3	34.1
2020	*Conditional Baseline*	14.1	17.6	33.6	34.8
2020	*Fixed Baseline*	16.2	19.9	31.4	32.5
2020	*Subsidy*	16.2	19.9	31.4	32.5
2020	*Regulation*	25.8	49.3	22.7	22.2
2020	*Both Policies*	25.7	49.2	22.8	22.3

Table 5.13: Segment market share of sales (%)

As the California Clean Vehicle Rebate Project has been in place for three years at the time of writing this thesis. The success of the scheme in reality can be compared to the model. It should, however, be recalled from the discussion in

[102] Purchase price, travelling costs and range are the variable attributes feeding into vehicle utility, and therefore the choice model (see Section 5.1.3 for details). As partial utilities of travelling costs and range change only marginally, this means that the greatest influence is purchase price, so it is a reasonable assumption that the increase in purchase costs have forced the change in vehicle market shares.

Chapter Three that modelling is not a perfect replication of reality, and also that this research is not focused on market predictions but in identifying and analysing the relative impacts and influences of policy interventions, therefore this comparison is purely illustrative. By early 2013, 10,036 BEV and 9,234 PiHEV rebates have been issued (CCSE, 2013). In the model, numbers are only available for year ends, but after the third year of subsidies under *Both Policies*, 8,765 BEV and 3,411 PiHEV have been sold. Although BEV sales are similar, with the model slightly under-predicting, PiHEV are a third of real sales. These discrepancies could be due to the model having different dates of vehicle availability than in reality and slightly different time scales, as in the fourth year of the subsidies in the model we see the market really take off with sales of over 20,000 PiHEVs and nearly 30,000 BEVs. This comparison could be revisited in 2014 to see if this has occurred in actuality.

5.5.3 Ownership Costs

To further understand how certain sections of society may be affected by the LCV policies, attention now turns towards the changes in purchase prices over the time scales, shown in Table 5.14, where for simplicity, only the *Fixed Baseline* and *Both Policies* scenarios are given.

VEHICLE SEGMENT	**PURCHASE PRICE ($)**			**% DIFFERENCE between *Fixed Baseline* and *Both Policies* in 2020**
	2009	**2020 Fixed Baseline**	**2020 Both Policies**	
Average	19,964	22,079	25,580	15.8
ICEV	19,964	21,014	26,958	28.3
HEV	n/a	19,880	23,481	18.1
PIHEV	n/a	21,769	23,809	9.37
BEV	n/a	28,861	29,302	1.53
XS	n/a	13,432	15,048	11.9
S	12,799	16,172	20,698	28.0
M	17,749	21,683	25,340	16.8
L	27,649	30,365	34,413	13.2

Table 5.14: Weighted average powertrain and segment purchase prices

The majority of the price changes witnessed (relative to 2009) comes from the introduction of ZEVs that are at a higher cost to begin with (due to being an immature technology with high battery costs). However, under the policy scenario, purchase costs of ICEV also rise significantly due to the cost of reducing GHG emissions, which are passed on to the customer. The average overall price is 16% higher in 2020 under *Both Policies* than *Fixed Baseline.* This is concerning as it impacts everyone, including the worst-off. The price differential between the policy and no-policy scenario for the ICE-based vehicles are much greater than those of BEV, which does not have additional costs related to GHG Regulations, is experiencing reductions in battery costs as experience builds, and has biased weightings in price adjustments (see Section 5.1.1, *Pricing and Cashflow)*.

What is also of concern from the point of view of this study is the price differential between segment sizes. Within the model, in order to meet GHG requirements, it is assumed that the manufacturer subjects each segment to the same relative reduction in emissions as the *Regulation* is based on fleet average targets. In 2020, the Small segment weighted-average purchase price has increased disproportionately compared to other segments, leading to a downsizing to XS-segment and dis-incentivising downsizing from M and L segments. Consequently, the greatest price increases compared to a no-policy scenario are in the small ICE-based vehicles, which are potentially the most affordable form of LCV for families. These figures refer to new vehicles, which are most likely to be bought by more affluent members of society, and their decisions will then pass onto the second-hand car market, reducing choice for these customers, who represent the majority of society, as (in the UK) less than 10% of car sales are new vehicles to private customers (SMMT, 2013a). However, as it is assumed that segment sizes are related to income, and XS segment increases the least, then this would suggest that the poorest in society may be the least affected by the *Regulation*. The impacts of this in relation to the ethical framework developed in Chapter Three are considered further later in this Chapter (Section 5.6.2).

BEV Payback Period

To understand the type of payback time that a typical driver may expect when purchasing a BEV over a conventional vehicle, the details for a Medium segment vehicle of each powertrain in 2013, under *Both Policies* were taken from the model, and payback time was calculated using Equation 5.15. Note this calculation uses undiscounted values of running costs so the payback period is an underestimate.

$$Years\ for\ payback = \frac{PC_{M,BEV} - PC_{M,ICEV}}{\left(RC_{M,ICEV} - RC_{M,BEV}\right) \times AM}$$

Equation 5.15

$PC_{s,}$ is Purchase Cost $_{segment,\ powertrain}$ ($) (M, ICEV = 25,2567.94; M, BEV = 29,549.29)

$RC_{s,p}$ is Running Cost $_{segment,\ powertrain}$ ($/mile) (M, ICEV = 0.0523; M, BEV = 0.0359)

AM is average annual mileage (15,000 miles)

This optimistic method gives a payback period of 16.2 years, which means that it is unrealistic for a driver to change powertrains if motivated by economic reasons alone in the US. However, although purchase costs in the model are similar to UK prices, running costs are not. For ICEV, HEV and PiHEV, running costs are based on fuel costs alone, and these are approximately two fifths of UK petrol prices, and for BEV electric costs are approximately half of current UK electricity prices.[103] Adjusting for this, the payback time in the UK could be in the region of 4.5 years, a much more attractive proposition to the car buyer.

5.5.4 Carbon Abatement Costs

Finally, abatement costs were calculated for each policy measure, using cumulated discounted costs for customers, government and industry, and compared against the *Fixed Baseline.* Recall that this baseline was used as it allows for the filtering out of policy impacts, but is a hypothetical scenario showing an extreme situation where the manufacturer produces the new ZEV models without government intervention. As such these results may be pessimistic, but the main interest is in the comparison between policy scenarios. Whilst the *Fixed Baseline* would imply costs for manufacturers related to the introduction of new models, the costs which are of interest here are those additional costs related to *Regulation* or *Subsidies*. Though this does not account for the costs of new models per se, it does give the effect of policy scenarios. Abatement was calculated using Equation 5.16 to Equation 5.20, a similar method to that used in CS1, the EC "GHG TransPoRD" project (Schade et al., 2011) and the well established McKinsey MAC curves (McKinsey, 2007).

$$Carbon\ Abatement\ Cost\ \frac{C_{FB} - C_P}{\mathrm{T}E_{FB} - \mathrm{T}E_P}$$

Equation 5.16

C_{FB} is the NPV of Costs under Fixed Baseline

C_P is NPV of Costs under Policy Scenario

TE_{FB} is total GHG Emissions from new vehicles under Fixed Baseline

TE_P is total GHG Emissions from new vehicles under Policy Scenario

[103] This is based on publically available prices (AA 2013; EIA 2013a,b).

$$Emissions = \sum_i (\mathrm{EF_i(t)} \times \mathrm{NV_i(t)} \times \mathrm{AM} \times \mathrm{l})$$

Equation 5.17
EF_i (t) is emission factor (gGHG/mile) of new vehicles i in year t

NV_i (t) is the number of new vehicles i sold in year t

AM is the annual mileage (15,000 miles) (see previous footnote)

l is the vehicle lifetime (assumed to be 10 years).

$$NPV\ User\ Costs\ of\ new\ vehicles\ in\ year\ t$$
$$= \frac{\sum_{\mathrm{i}}(\mathrm{PC_{S,i}}\ (t) \times NV_i(t))}{(1+r)^t} + \sum_{\mathrm{x=0}}^{9} \frac{\sum_{\mathrm{i}}(RC_{\mathrm{i}}\ (t) \times NV_{\mathrm{i}}(t) \times AM)}{(1+r)^{t+x}}$$

Equation 5.18[104]
$PC_{S,i}$(t) is the purchase cost of new vehicle i after subsidy in year t ($)

RC_i(t) is the running costs of new vehicle i

r is the discount factor (0.02)[105]

t is the number of years since 2009

x is the year of vehicle life up to 10 years

$$NPV\ Government\ Costs = \sum_t \frac{\mathrm{S}(t)}{(1+r)^t}$$

Equation 5.19
S(t) is the overall spend on subsidies at time t

$$NPV\ Industry\ Costs = \sum_{\mathrm{t}} \frac{IS(t) - IR(t)}{(1+r)^t}$$

Equation 5.20[106]
IS(t) is the overall industry spend at time t

IR(t) is the overall industry revenue at time t

Table 5.15 shows the discounted costs and emissions of all vehicles bought up to 2020, for the policy scenarios compared to *Fixed Baseline* and corresponding abatement costs are shown in Table 5.16. For reference, the abatement costs for customers and industry from *Conditional* to *Fixed Baseline* are in the region of 500$/tGHG. Both parties experience costs because although average purchase prices increase, not all production costs are passed on to customers. All the scenario abatement costs are in line with the general range of abatement costs presented in Table 5.17 from the EU GHG TransPoRD project referred to in CS1.

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[104] This includes purchase cost and ten years of running costs.
[105] This is consistent with the US discount factor at the time the model was developed.
[106] Industry costs are the negative of profits.

SCENARIO	COSTS ($b)					Emission Reduction (MtGHG)
	Users		Government	Industry	Overall	
	Purchase	Running				
Subsidy	-0.95	-0.16	1.18	0.13	0.20	0.97
Regulation	50.66	-25.78	0.00	-1.05	23.83	134.95
Both Policies	49.38	-25.87	1.35	-0.93	23.92	135.57

Table 5.15: Discounted costs and emission reduction (by 2020 cf Fixed Baseline)

SCENARIO	CARBON ABATEMENT COSTS ($/tGHG)			
	Users	Government	Industry	Overall
Subsidy	-1142.40	1216.12	137.37	211.09
Regulation	184.35	0.00	-7.78	176.56
Both Policies	173.40	9.95	-6.88	176.46

Table 5.16: Carbon abatement costs of policies (by 2020 cf Fixed Baseline)

Abatement Measure	Abatement Cost ($/tCO$_2$)[107]					
	User		Authority		Social[108]	
	Max	Min	Max	Min	Max	Min
Universal Policy Measures (e.g. feebate, vehicle maintenance)	47.9	-795.6	263.9	-217.2	149.8	-794.5
Urban Policy Measures (e.g. public transport, infrastructure)	1629.7	-1536.8	4157	-2010.2	3361.4	-795.6
Car technologies (e.g. electrification, downsizing)	140.2	-685.3	Not reported		Not reported	

Table 5.17: Carbon abatement costs (Schade et al., 2011)

With Subsidies, users effectively benefit by $1142 per ton of GHG removed, but at the expense of 1216 $/tGHG from Government and 138 $/tGHG from Industry. This is because the emission savings from the policy of *Subsidy* alone are relatively small compared to the *Fixed Baseline* and many users are being subsidised to purchase vehicles that may have been purchased anyway. User abatement costs for feebates[109] were much less beneficial in the GHG TransPoRD report (Schade et al., 2011), which were -86 €/tonCO_2 or -144 $/t$CO_2$, possibly due to the reference scenario used or the differences between feebate and subsidy levels in the studies. The government abatement cost is approximately 60% greater than that of the most costly scenario in CS1 (459 £/tCO_2 = 734 $/t$CO_2$), and nearly five times that of the GHG TransPoRD authority abatement cost for feebates (170 £/tCO_2 = 267 $/t$CO_2$), which were also mentioned in CS1.[110]

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[107] Converted from €/tCO_2.

[108] Authority + User.

[109] Feebates are slightly different than subsidies as they are related to purchase tax rather than direct purchase price reductions (i.e. increased costs for high emitters and rebates of that for low emitters), but this is the closest comparison found in literature.

[110] Although CS1 and GHG TransPORD consider CO_2 and CO_2 equivalent (resp.) rather than GHG, it is assumed that any difference will be minimal.

The Policy options of *Regulation* or *Both Policies* yield user abatement costs that are very close to the User abatement costs for road technology improvements in Table 5.17, and even more so to another EU study that reported user abatement costs due to the Fleet Emission Regulations of 175 \$/t CO_2 (Schroten et al., 2012). Under the *Regulation* only scenario, users bear 184 \$/tGHG whereas government have no direct costs and Industry benefit by 8 \$/tGHG. Whilst these values appear reasonable per ton of GHG removed, the users incur an additional spend in the region of \$50b on purchasing vehicles and only save around \$26b from fuel savings under the *Regulation* policies.

With *Regulation* in place, the manufacturers have passed on the cost of technology improvements to the consumer and see an increase in their profits of around \$1b (or 8%) from selling the higher priced vehicles. Industry has a \$130m (1%) decrease in profit under *Subsidy* only. This may explain why manufacturers are not bringing in these models without policies in place. While the overall change in costs for consumers is small when subsidies are applied, they are benefiting only a small share of the consumers, most seeing a significant increase in purchase prices. Thus combining policies distributes cost burdens only at the margin but does lower overall abatement costs.

5.6 Discussion and Conclusions

This Chapter has described the development and testing of a complex model that has built on the findings of the first case study. The model, which is based in California over the short time period 2009-2020, considers conventional ICEV and three pro-electric models, HEV, PiHEV and BEV. The first step in this study was to develop the base model in order to create two baselines that reflect a no policy situation. One of these illustrates an introduction of LCVs based on minimum range and infrastructural requirements that results in similar market share to other studies by 2020, and the other reflected the fixed introduction of LCVs at certain times in order to make direct comparisons to the impacts of policy scenarios.

Three policy scenarios were tested, which were *Subsidy* (as an example of Fiscal Measures), *Regulation* and a combination of the two (*Both Policies)*. These policies were chosen to be tested as they are currently the most high profile and were found in Chapter 3B to have the most potential for bringing about distributive injustice within society. Once baselines and scenarios were established, a comparative study of policy approaches to LCV uptake was carried out. The outputs of interest were the relative impact on GHG emissions and the opportunity for car ownership (through market shares and costs of ownership), which would be needed to assess them within the ethical framework developed in Chapter Three.

It was found that although all scenarios results in emission reductions compared to the *Conditional Baseline*, the greatest emission reductions were achieved when *Regulations* were in place, and that the *Subsidy* scenario did not offer any additional savings to the fixed introduction of vehicles. This is because the most substantial emission reductions come from efficiency in ICE-based vehicles. Changes in sales market shares of powertrains showed that subsidies had not been in place for long enough for price learning effects to occur, but may be thought of as a successful policy if they encourage manufacturers to produce vehicles which they otherwise wouldn't. It did seem to be the case though, that there was very slight increase in EV share when *Both Policies* were in place compared to *Regulation* only, which coincides with the recommendation of the IEA mentioned in the literature review that manufacturer standards would be more effective if they were alongside policies to stimulate demand (Onoda, 2008).

It was assumed that vehicle size segments, which have distinct average prices, were an appropriate proxy for segmenting society into four income brackets, and that the change in market shares and ownership costs in these segments could be used to understand impacts on inequality. Taking this as the case, having the policies in place have resulted in much greater shares in the XS and S segments, an indication that they have made people worse off (as more people are now in these 'poorer' segments). In terms of ownership costs, the overall average vehicle purchase price is almost 16% more expensive when *Both Policies* are in place than under the *Fixed Baseline.* This has important implications for affordability of vehicles, particularly for the worst-off. ICE-based vehicles increase more in price than BEV because of the *Regulations,* which is concerning due to the infrastructural and cultural lock-in and the fact that these are the more affordable vehicle types. However, HEV and PiHEV are most affordable now, which may be advantageous in the development of an affordable pro-electric fleet. In addition to this, average Small segment vehicles are nearly 30% more expensive, almost double the overall average difference between the two scenarios. This is particularly concerning because as more people are in the Small segment they may be at risk of becoming amongst the worst-off. A payback period of purchasing a medium sized BEV over an ICEV was calculated and found to be over 16 years, which would not motivate such a purchase. However, adjusting for UK running costs, a much more reasonable time of 4.5 years was estimated.

Finally, carbon abatement costs were calculated to understand the effect of the policy scenarios. It was revealed that although *Subsidy* abatement costs are much greater than those reported elsewhere, due to the effect of the fixed introduction of vehicles, when *Regulation* is in place the costs are more in line with other studies. More importantly, when *Both Policies* are implemented together, costs burdens are distributed marginally more evenly between customers, government and industry, and lower overall abatement costs.

5.6.1 Reflection against Case Study One

Although this case study is not directly comparable to the first case study, as it was not possible to calibrate the model to the UK, there are some general observations that can be made, as the UK and California are similar, as described in Section 5.2. CS1 served a different purpose, in terms of building skills with a focus on sensitivity testing and long term impacts, which allowed for deeper understanding in the development of this case study. In future work, it may be appropriate to carry out some of the sensitivity tests from CS1, on vehicle lifetime, energy mix and word of mouth, within this model over a longer period. As the first case study was simpler (in terms of modelling), the impacts of the sensitivity tests were readily identifiable, which would not be the case here. Decreasing the ICEV lifetime was found in the first case study to have a potentially beneficial impact on EV uptake. In this case study, the vehicle lifetime was already the same as the decreased lifetime in CS1, but all vehicles were assumed to have the same lifetime. Modelling a scrappage scheme policy scenario may assist the manufacturer in meeting the *Regulation* as there is greater turnover of vehicles, and therefore more vehicles can be sold to qualify for ZEV credits (though this neglects the embedded emissions). Unlike CS1, this model did not consider any loss in government revenue from fuel duty, a consideration for future model developments.

Regarding the findings related to subsidies, it was found in this model that subsidies appeared to make little long term impact on the uptake of LCVs if the vehicles were already available, though had the potential for making a greater impact if they were kept in place for longer. This is a very similar finding to the previous case study and Brand et al., (2013), who found feebates beneficial in LCV uptake when they were in place for a long period, but also decreased overall fleet due to increased purchase costs overall. Their most ambitious feebate scenario quadrupled take up by 2020 compared to the reference scenario. If this reference scenario is more comparable to the *Conditional* rather than *Fixed Baseline,* this would suggest a similar finding, as subsidies increase 2020 market share by four times the *Conditional Baseline.*

No conditional marketing was carried out in this case study because this would have further complicated the model. If a failing market were created in this model, it would be expected that the beneficial effect of subsidies tipping a failing market into success would be repeated. Although the abatement costs of subsidies proved to be much greater in this study (in the region of £800/tCO_2 as opposed to £460/tCO_2), it should be recalled that the first case study is set over a period of 40 years so these may not be realistically comparable. Comparison to the *Regulation* tests is not appropriate as in CS1 they were simply an exercise in observing the impact of changing emission factors and were not able to capture manufacturer response or include costs of technology as they did in this case study.

5.6.2 Assessment against the Ethical Framework

Recall the ethical framework developed in Chapter Three was based on two claims:

> **CLAIM 1***: In order to limit the harms of climate change, there is a strong case in favour of coercive policies that promote the introduction of low carbon cars – even if these policies may limit people's opportunity for car ownership.*
>
> **CLAIM 2:** *In the short-term, many people are somewhat locked-in to car ownership for access and mobility. As such, policies should not allow additional unfair burdens on those who are already amongst the worst-off in society, or result in a different group of people being similarly disadvantaged.*

In practise, this means that a policy that allows coercion for the uptake of low carbon cars is permissible, as long as unfair burdens on the worst-off are prevented, limited or rectified.[111] In the model, the success of policy interventions in reducing GHG emissions is used to assess if Claim One has been met. The impact on car ownership through changes in market share and purchase cost is identified in order to assess if further intervention is required to satisfy Claim Two.

[111] Recall from Chapter Three, that concern for the worst-off also considers those in danger of becoming the worst-off and only car owners are considered, though anything that benefits the worst car owners will also benefit the non-car owning worst-off.

Ideally, it would have been possible to replicate scenarios more strongly representative of coercive policies. An example of a stronger coercive policy would be one that greatly increases the price differential between ICEV and ZEV by placing premiums on ICEV as well as subsidies on ZEV, or targeting running costs as well as purchase costs. As the model has a short time scale, in early days it may be that weaker coercive polices are more appropriate as market share builds up. However, the model has shown that *Regulation* (which is coercive on the supply side, not the demand side), has lead to the increase in purchase price of all vehicle types (relative to the no-policy baseline), arguably making it a form of coercion towards drivers (albeit brought about by intervention with manufacturers rather than directly to the public). The *Regulation* policy did however, bring about reductions in emissions (against both baselines), thus satisfying Claim One, even though the purchase cost increases may limit opportunity for ownership.

The *Subsidy* policy may be a soft form of coercion as it does not force people away from ICEV but rather, it attracts them towards ZEV. Even if it is not coercive, however, it still may only be permissible if it results in an emission reduction. Although there is no reduction in emissions relative to the *Fixed Baseline*, as stipulated, this was only introduced to show the extra impact policy interventions would have in addition to the fixed introduction of vehicles. Thus, in terms of emission reductions, if we compare against the *Conditional Baseline*, then emission reductions are achieved, therefore it is permissible.

In order to assess adherence to Claim 2, it is necessary to establish what impact the policies may have on the worst-off. This is identified in the model by the impact on the market share and purchase price of the four vehicle segments, representing the opportunity for car ownership, and the interest is specifically in the XS and S segments. Although only the *Fixed Baseline* and *Both Policies* are shown in Table 5.14, under the *Subsidy* policy, there is a negligible difference in purchase price to the *Fixed Baseline* and under *Regulation* there is a negligible difference to the *Both Policies* scenario (similar to the impact on market share) at the end of the modelling period, though there was a reduction in purchase price when subsidies were in place. This suggests that subsidies may have little impact on share or prices, and therefore do not directly affect the opportunity for ownership, though this finding is specific to the subsidy duration.

The findings when *Regulation* is in place indicate an increase in purchase price across all segments alongside an increase in market share of the smaller vehicles. This is particularly concerning as S segment has increased disproportionately more than then other segment, suggesting that L segment (remembering that they are proxy for most well off) may be favoured by the policies. Although the category containing the worst-off (XS) are least affected, the fact that any increase has occurred suggests that they have been made even worse off, and so for Claim 2 to be satisfied, compensatory measures will be required. Furthermore, the fact that the S segment are disproportionately affected means that there are more people in danger of becoming amongst the worst-off, and as the market share in XS segment is greater under *Regulation* than in the *Fixed Baseline*, it would seem to be the case that there are more people in the worst-off segment. Of course, it could be that other factors, such as preferences, have caused this downsizing but the interpretation of these findings is constrained by the model design and assumptions regarding segmentation.

Regarding Claim 2, the finding is that *Regulation* and *Both Policies* have caused additional burdens on the worst-off in society, or made others equally worse off. As such, compensatory measures would be required in order for the policies to satisfy the ethical framework. As suggested in Chapter Three, this could come from some form of exemption, or through intervention with further regulation to ensure that not all costs are passed on to customers (or at least not the poorest).

In summary, although these policies successfully result in emission reductions which benefit the whole of society, *Subsidies* may only benefit the more well off who are likely to have access to private charging and can afford a more expensive EV in the first place, but in the long term may benefit the less well off as an affordable used EV market develops. *Regulation,* on the other hand, increases the cost of vehicle ownership, and as the least well off are most sensitive to price changes (and therefore car-poverty), they risk being impacted the most, especially as Small segment vehicles increase disproportionately. Both of these concerns are somewhat dependent on residual values in the used car market, which wasn't included in this research.

There are some further caveats to these findings. Firstly, as people are not able to drop out of the market in this model, individual movement between segments is not identifiable, and so it is possible that those who are unfairly burdened by the policies, have not been accounted for. Despite this, the assumption that just viewing the changes is an appropriate measure still stands. Secondly, for simplicity, only aggregate segment or powertrain market shares were considered regarding purchase prices. It may be that, by looking more specifically at the powertrain/segment combination, further insight may be gained, especially as not every powertrain is available in every segment at all times, so this may distort apparent purchase prices. This is why the *Fixed Baseline* was used to compare the impact of policies as the vehicles are available at comparative times. Finally, only the end of the time period was considered in detail. Picking a point in time when subsidies were in place may lead to a different conclusion, depending on what impact the subsidies have on size segment prices and market shares.

5.6.3 Model Limitations and Development Potential

There are numerous model criticisms that it may be beneficial to address in future work. Firstly, the time scale may be too short to make any definite policy recommendations, however, nearly all vehicles at the start of the period will be replaced, as an average life of 11 years is assumed. In further defence of this, it needs to be reiterated that this model is not being applied in a strictly predictive capacity, but to understand the impact of certain policy interventions. Although it is accepted that the timescale may be too short to fully assess the impact within the ethical framework (as the concerns regarding protection of the most vulnerable may be more pertinent when LCVs are more widespread and a second-hand car market has been established), the policy impacts can still be seen to give a feel or indication of the longer term effects. What is more, a shorter timescale may allow the consideration of a level of detail which is unobserved on a longer time scale such as that applied in CS1. As this model was carried out starting in 2009, and at the time of writing, the mid-decade is being approached, it may allow for some comparison to real world experiences. This can help to improve future models, or adapt this one for purpose.

Two significant omissions were acknowledged in the introduction of the thesis, being fleet and used vehicles. Recall that fleet sales account for approximately half of all new car sales and the used car market is more than twice the volume of the new car market (SMMT, 2013a). In the model it is assumed that cars are bought new, privately and retained for the entire lifetime, which is clearly not the case in real life for the vast majority of car owners. Although the findings from this research remain applicable despite this, as any learning from the impacts arising from LCV policies can be transferred to both the fleet and used markets, there are limits to this and implications have to be considered. Fleet buyers are *“more likely to consider the total cost of ownership and practical issues”* (Element Energy, 2013). As such, they may be more amenable to EV than private buyers, due to the low running costs. On the other hand, company vehicles are driven twice as far as private vehicles and purchasing decisions are complex but poorly understood (Nesbitt and Sterling, 2002). Therefore, policy tailoured specifically to encourage fleet buyers to consider the benefits of LCVs is required. As fleet accounts for half of new vehicles this would mean that the technology transition could look quite different to this model. Therefore inclusion of a fleet choice model and disaggregation of the market would be useful in future, but of the little research in this area, a great deal of inconsistency between fleet managers has been identified (Hutchins and Delmonte, 2012). Used car buyers may also make different purchase decisions, but as little evidence of research in this area was identified in the literature review, it is an area that requires further study. It is particularly concerning for this research as the used car market is more likely to include those most vulnerable to car-poverty.

It was also a concern that in the model the automobile industry was represented by one aggregate manufacturer. Newer models have been identified which capture competing manufacturers within the automobile market (Boksberger et al., 2012) that could improve the model to some degree. However, it is uncertain if this would in actuality just make the model more complicated and cloud out some of the more important details and findings. Further to this, within the model, it was found that under certain scenarios that the manufacturer could experience (in some case quite large) negative profits, yet does not adapt to this within the feedback processes. This is an unfortunate limitation to modelling, in that unrealistic behaviours are allowed to occur. In the real world, the company would go bankrupt and drop out of the market, yet this is not possible in this model as it represented the whole industry. This may be another advantage of Boksberger et al.’s, model, which did allow bankruptcy, and had multiple manufacturers.

Within the ethical framework an important output is the reduction of GHG emissions from policy interventions, and it is not certain if the unit emissions in the model are wholly accurate. Tailpipe emissions are related to fuel efficiencies of ICE-based vehicles that are based on standard test cycles. Although this is how emissions are currently accounted for in policy and reporting, there is growing interest and move towards more realistic emission reporting, based on ‘real-world’ emission tests. For BEV the emission is a standard and set amount for all segments (as set out in the ZEV Regulations), and although similar to the findings in the literature review, it is unlikely that all segments would be the same (as heavier cars require more power to overcome inertia), and the emission rating itself is sensitive to electricity generation mix. Due to the small time scale, this may not make much difference to the results, but should be considered if this model is developed in the future. Further, as suggested in the literature review, the most beneficial way of measuring the emissions would be to use life cycle emissions. Although the problems related to developing a standard method for doing this are many, as highlighted in the literature review, moving towards this way of reporting would more adequately capture any realistic emission savings, especially if one recalls the high embedded emissions in EVs. Additionally, this may allow a better representation of the emissions related to non-conventional ICE fuels (which will be used in ICEV, HEV and PiHEV), such as biofuels and CNG. Finally, as PiHEV are a relatively new technology, there is no standard in reporting their emissions, as the pure electric drive contribution is under-researched. In the model a percentage of the ICEV emissions were assumed but there was no accounting for the emissions from electricity when recharged, though this may be implicit in the ICE contribution.

Although the model was set up to understand manufacturer strategies to the GHG and ZEV Regulations, there was no intrinsic motivation captured within the model for a manufacturer to reduce GHG emission or encourage uptake of ZEV. Their responses are merely a reaction to meeting targets, as the model is set up to respond in this way in order to minimise penalties. Because of this, it does allow for some increases in ICEV emissions in later years following the reductions, as targets are still met when ZEV shares increase under certain scenarios. This may partly be due to GHG targets being constant for the final few years, and should they be tightened in reality, this could prevent GHG emission rises. Although this is quite likely an accurate reflection of manufacturers response, it also goes to show that such regulations, although successful in meeting targets, are not successful in bringing about real institutional change in ways of thinking or core business virtues (though any change in this is not captured in the model). Although there may be arguments as to if it is political acceptable to do so, the growing public interest in companies that are socially responsible (in a true sense rather than being seen to be so), may motivate such change.

On the demand side, the model does not capture any ‘rebound effects’ that may occur if reduced running costs lead to increased mileage (Atkins, 2009). This could erode up to a third of fuel savings from *Regulation* type measures, but empirical estimates have been found to be very sensitive to assumptions about other vehicle attributes, household car ownership and gasoline prices (Linn, 2013). This has implications not only for congestion and safety concerns (which are outside the remit of this research), but also because the benefits of reduced energy and carbon may not be realised. Rebound effect could be captured in future model development through fuel price elasticities, and could be important as recent research suggests that lowest mileage households exhibit largest elasticities and rebound effects (Froundel et al., 2012). Possible policy options to overcome such impacts could be similar to those discussed elsewhere, such as road pricing or taxation based on miles travelled.

The vehicle attributes within the model were developed by the original authors in conjunction with an automobile manufacturer, however, it is not clear if these are entirely realistic. For instance, a Large BEV is available with a range nearly 350 miles by 2015, and this is not currently predicted by any manufacturer. As such results could be biased. Another attribute criticism is that both fuel and electric prices are constant. Although the same was assumed in CS1, as recognised in that discussion, this may not be the case in real life. Fuel prices are predicted to rise, particularly in the US. Likewise, electricity prices are set to rise as fossil fuel supplies dwindle and expensive alternatives are used or demand increases. Again, the short time scale of this particular model may not make much difference, but as longer scale research is carried out this needs to be incorporated. Further to this, any introduction of fiscal measures on running costs would need to be reflected in fuel prices.

Although the model included a module on infrastructure, this was not as extensive or integral as other modelling studies (e.g. Kohler et al., (2012)), so future modellers should perhaps take more account of these. One further concern with the charging infrastructure was that charging was assumed to be fast charging taking only half an hour, and charging location was not explicitly considered. As many lower income drivers may not have access to home charging (as discussed in Chapter Three), they may be under represented in the model. Remembering that these people may again be amongst the worst-off, this could be concerning so should be addressed in future model development. Such extensions could be beneficial when building a *Facilitating Adoption* policy scenario.

This model has assumed a constant vehicle fleet and drivers do not choose to leave the vehicle market. This may be unrealistic, especially under the *Regulation* scenario where prices rise significantly. Actual trends would suggest it is possible that the market may grow further, though car ownership is starting to plateau or even reduce in younger portions of society. Due to this, it was not possible to capture if someone was priced out of car ownership, a pivotal element in the ethical framework. Additionally, it means that people leaving the car market out of choice (to change mode or join a car club for example) are not captured. This is important in the context of wider low carbon transport policies that require a significant modal shift. As the time scale is short this may not be relevant, and modal shift is not the focus of this thesis, but the point is worthy of recognition.

An obvious limit of the model was the inability to identify specific societal segments, in relation to income, access or mobility. As previously noted, vehicle segments were taken as a proxy for income, but this may not be wholly realistic. Although recognised as a constraining assumption, in future model development a consumer choice model that included such segmentation would be required in order to improve assessment within the ethical framework.

The model was not initially designed with a no-policy baseline. Although the baseline implemented in the model served the purposes that were required to identify impacts of policy interventions, it is not certain that the baselines were appropriate. Firstly, the *Conditional Baseline* is likely to be pessimistic. Due to the minimal infrastructural and range requirements set out by the original authors, many ZEV models did not become available in the timeframe, or only near the end. However this may reflect the time that the model was developed and availability would appear to be more optimistic now. Another reason may be that the minimal requirements themselves were unrealistic, as previously remarked. It does not look likely that a BEV battery with 200m range would become available in the near future (although this may be overcome by rapid charging or battery swaps, which is not considered in the model). On the other hand, the *Fixed Baseline* is certainly over-optimistic. The availability of the models had a much greater impact than the policy interventions (due to the structure of the model, if a ZEV model was available and unconstrained by production capacity, people would purchase them), hence the reason that it could only be used as to differentiate policy intervention. The significant impact of vehicle availability does however concur with Yeh (2007) as reported in the literature review. Further, artificially making the model available does not accurately reflect technological process. In conclusion, in future model development it will be necessary to develop a suitable and realistic baseline alongside any model improvement.

Similar to the previous case study, marketing was found to have a strong effect and similar to model availability, a much stronger effect than policy intervention. Although this could be used in the future to replicate different policy scenarios, such as one for *Raising Awareness*, further understanding of the parameters and their suitability for use would be needed. Again they are similar to the previous study in that they were developed from consumer technologies which may not be similar enough to automobiles (in terms of cost, commitment, durability or emotional reasoning), to be appropriate. Further to this, marketing was applied individually to each segment and was constant as long as the model type was available, making it potentially artificially high. This helps explain why when any model was available it sold, though the nature of choice models means that there will always be some sales unless utility is infinite.

5.6.4 Summary of Findings

The conclusion of this Chapter is therefore that *Regulations* on the manufacturer are more successful in reducing GHG emissions and increasing LCV uptake than *Fiscal Measures* (in the form of subsidies) for the consumer. However, both of these may cause issues of injustice, as both options may favour the richest in society. *Regulation* forces an increase in purchase price of cars across the fleet, and disproportionately so for the Small segment. *Subsidies* may be beneficial only to those who were able to purchase an LCV anyway, at a cost to the public in terms of a carbon abatement cost. Despite these issues, if the opportunity for car ownership for the worst-off can be protected (in support of Claim 2), then these policies are permissible within the ethical framework developed in Chapter Three. This would suggest that interactions between policies should be considered, and designed to complement each other. For example, as it was found that implementing both policies together can ease distributional issues, designing policies together in this way would be advantageous.

CHAPTER SIX: CONCLUSION

In this final Chapter, the conclusions from the previous Chapters are brought together. First of all, the fulfilment of research objectives is established. Following this, policy recommendations are presented and then a modelling and appraisal framework for policies is proposed, based on the method used in this thesis. Next, there is a review of suggestions for future research. The Chapter then concludes with a final summary, which describes the high-level conclusions and the novel contribution of the research.

6.1 Main Conclusions

The main objective of this thesis was to investigate an approach to modelling Low Carbon Vehicle (LCV) uptake policies, which incorporates an ethical framework that identifies distributional impacts. This involved interdisciplinary study combining technological review, policy appraisal, modelling techniques and applied ethics. The challenges in doing this were in considering claims related to issues of justice that may arise from the introduction of LCVs, the permissibility of the role of models within policy appraisal, and the practical implementation of ethics within the modelling process. In achieving this, an ethical framework for LCV policies was developed and implemented alongside a system dynamic model of LCV uptake, allowing scenario analysis and policy appraisal.

A review of literature provided the focus of the research. It was concluded that Electric Vehicles (EVs) had the greatest potential of all LCVs in reducing passenger car emissions, but have significant barriers to adoption that need to be overcome within the next decade. The range of policies being implemented to do so were categorised into five generic areas and the policies of *Regulation* (aimed at the manufacturer) and *Fiscal Measures* (aimed at the customer) were identified as currently being given the most attention. Although there have been numerous modelling studies of LCV uptake to understand preferences and diffusion, few combine both approaches using system dynamics. Of those that do, none are UK-based, none explicitly consider ethical issues and few directly compare supply and demand side policies. Finally, despite the growing debate regarding climate and transport ethics, there is little philosophical literature that specifically considers the transition to LCVs or addresses the permissibility of modelling in policy appraisal.

An ethical framework for LCV policy appraisal was proposed in Chapter Three (Part A). It was argued that it is permissible for governments to use coercive policies for the introduction of LCVs, due to the potential harms of climate change, even if that limits the opportunity for car ownership, but also that provision should be made to ensure that such policies do not amplify existing, or create new inequalities that burden the worst-off or result in a different group of people being similarly disadvantaged.[112] Special consideration for vulnerable groups, such as the poor and the disabled, is required in the short term due to a cultural and infrastructural lock-in of car ownership to ensure equitable levels of accessibility and as a form of mobility. It was suggested that if an amendment was required, it could be achieved by tighter market regulations, tax exemptions or fiscal support, analogous to existing public policy in other areas. These arguments were broadly supported in the evaluation of the framework presented in Part B of that Chapter, which also suggested that the high profile policies *Regulation* and *Fiscal Measures* may cause the greatest negative impact on the opportunity for car ownership.

Also in Chapter Three, in a comparison to existing philosophical criticisms of Cost Benefit Analysis (CBA), it was argued that there are limitations to modelling that must be recognised. This is no reason for rejecting its application, however, as modelling is an important tool in policy appraisal when used correctly and in awareness of its limitations. The implication of this means that both modeller and policy-maker need to clearly identify objectives, needs and burdens, and communicate model boundaries and parameters.

Modelling skills and understanding of policy sensitivities were developed in a relatively simple UK case study model (CS1) in Chapter Four. There was only a small EV market share in all but the most optimistic cases, meaning that reducing ICEV emissions makes a larger impact on overall emissions than EV introduction. Despite this, any shift to an LCV fleet will have a significant impact on government revenue, regardless of the emission reduction achieved. Social exposure to EVs was found to be important for uptake, which would indicate the importance of *Raising Awareness* polices not investigated in this research. The key finding, however, was that subsidies, as a form of *Fiscal Measures* are only effective in an otherwise failing market.

[112] Recall in this work that the concern is for anyone who may be most disadvantaged compared to other people at any point of the timeframe.

The findings of Chapter Four were built upon in a second case study (CS2) in Chapter Five. This model allowed study of both *Regulation* and *Fiscal Measures* (in the form of subsidies), and captured the complex business processes of an automobile manufacturer, as well as social diffusion feedbacks and the identification of approximate income-based societal segments. *Regulation* was shown to be more successful in reducing emissions than subsidies, but through ICE-based emission reductions rather than BEV introduction. It was revealed that interrelationships between policies are important feedback mechanisms to understand in policy appraisal. A policy aimed at the supply side has important impacts on demand side as costs can be passed on. In this study, the costs were unevenly spread out across the fleet, with the poor experiencing the worst impacts, as the cost of smaller ICE-based vehicles increase the most. This identification of impacts on societal segments is pivotal in appraising the permissibility of a policy, as argued in Chapter Three. Therefore, although aggregated policy models are useful, to really understand the distributive impacts of a policy, a disaggregated model with recognised specific groups is essential. Such models may be more useful for comparing policy options, than being used purely as a predictive tool, but importantly should be used in conjunction with other appraisal approaches and alongside ex-ante ethical evaluation of policies.

The research outlined above sought to understand policies that satisfy an ethical framework that seeks to strike a balance between climate change concerns and protecting special claims for car ownership from the worst-off. In response to this, policy recommendations are made in the next Section of this Chapter, and then an alternative policy modelling and appraisal framework is proposed, based on the experience of this research.

6.2 Policy Recommendations

As suggested by the ethical framework, real world policies for LCV uptake would greatly benefit by accounting for distributional impacts as well as focusing on carbon reductions, with provisions made to protect vulnerable groups where necessary. Three policy options were studied in this research. These were: *Fiscal Measures* on the demand side, *Regulation* on the supply side, and a combination of *Both Policies*. Chapter Five concluded that these were permissible within the ethical framework as long as there is provision to protect the worst-off from impacts on the opportunity for car ownership.

6.2.1 Fiscal Measures

In both case studies, it was found that under Business as Usual (BAU) conditions, *Subsidies* as a form of *Fiscal Measures* made little difference to LCV uptake (and related emission reductions), as the price reduction did not overcome strong preferences towards conventional vehicle technological attributes. *Subsidies* were only successful in increasing uptake significantly under a failing market, in which case they are pivotal. This has morally relevant implications as under a BAU scenario there is a significant cost to government that effectively subsidises the rich who would probably have made the purchase anyway, and the worst-off do not directly benefit at all. As it is not possible to be certain about the BAU uptake in reality however, and it can be assumed that manufacturers would not retain high levels of marketing for sustained periods, then to ensure LCV penetration *Subsidies* should be supported. Furthermore, it has been argued, that such policies need to be in place, to ensure manufacturers of government commitment to a low carbon fleet in order to encourage them to produce the vehicles (though this is an assumption made for the purposes of the model). As *Subsidies* lead to emission reductions against a failing baseline, and there was no evidence to suggest that the policy as tested in this research could burden the worst-off, then it is permissible within the ethical framework.

It should be recalled that significant portions of the worst-off will not find an EV appropriate due to lack of access to private infrastructure or being able to afford one even under *Subsidies*. Although the model findings suggest that the worst-off are not unfairly burdened by *Subsidies,* and so are permissible, supporting a policy that only benefits the better off for a potentially small reduction in emissions does not seem wholly appropriate. In addition, indirect burdens have not been addressed. Consideration of these concerns in more detail would also require a more thorough empirical consideration within the ethical framework of permissible levels of pain. Within this work, the view was taken that the only unacceptable outcome in this respect was a reduction in the current level of the worst off. Other approaches or extensions of this work could adopt different distributive principles as defined by Khisty (1996), or a more severe view on allowing luxury emissions (Odenbaugh, 2010), our responsibilities and obligations towards climate change (Hourdequin, 2010; Garvey, 2008), or the moral significance of our individual actions (Hillar, 2011).

As such, a feebate scheme (based on vehicle emissions and personal income) or means-tested subsidy would be more appropriate to promote fairness, but these were not examined in this research. As it was found, however, that the success of *Subsidies* is also dependent on the period of implementation, further study is required to understand if a longer period than considered here could indirectly benefit the less well off by bringing forward the development of economies of scale and a second-hand EV market, as well as accelerating public charging infrastructure. This latter point regarding the co-dependence between uptake and infrastructure, which was remarked upon in the literature review though not fully represented in either model, would make *Subsidies* even more important under failing market circumstances. This is especially so if, as also mentioned in the literature review (JTRC, 2010), *Subsidies* have been offered too early before vehicles are sufficiently developed.

6.2.2 Regulation

It was found in Chapter Five that in the short term, *Regulations* for overall fleet average emission target and mandated introduction of LCVs have greater potential for reducing GHG emissions than *Subsidies*. They also, however, increase the purchase price of all vehicles and disproportionately increase that of small vehicles. As vehicle size segments were assumed to be related to income, this therefore has the greatest negative impact on the poorer segments of society, though it is accepted that using vehicle size as a proxy of income is a simplification. Indeed, the model findings suggest that the XS segment, which contains the worst-off, was larger under the policy. Although the purchase price of XS segment vehicles increased the least, the fact that purchase price has increased for them at all would make the policy impermissible without amendment. Further to this, ICE-based vehicles experienced a greater increase in purchase price than BEV under the *Regulations.* Though significant emission reductions were achieved, as ICE-based vehicles are the most affordable form of vehicle, in the short term the poorest in society are at risk of car-poverty also requiring amendments or further regulation. Due to this, within the *Regulations* manufacturers should be prevented from passing on significant costs to the most affordable vehicles, transferring any legitimate costs towards larger or luxury vehicles in the fleet.

It was also found in Chapter Five that under *Regulation* once emission reduction targets are achieved, if they are overshot, the manufacturer can allow them to increase again. Although this may be a modelling issue, it does highlight the weakness of an average fleet emission target, as it does not encourage continual improvement. This is in addition to allowing high emitting vehicles within a fleet. To avoid this occurring, *Regulation* should be altered so that rather than an average fleet emission target, targets should be based on capping the upper bound or range of emissions and that rewards for over-attaining targets are implemented in addition to penalising deficits. Should this be related to fiscal incentives, there is a concern of what is the true motivator for change (and if that matters). If having polices in place simply encourages the manufacturer to produce vehicles they would not otherwise produce, this is a legitimate reason for the policy (assuming costs are acceptable).

6.2.3 Combining and Comparing Policies

Although the full dynamics of the *Regulations* were not captured in the CS1 model, the tests related to *Regulations* suggested that reduction of ICEV emissions are more successful in reducing overall emissions than subsidising EVs, though this is due to the low EV share in these scenarios. However, this finding is consistent with CS2, where subsidies alone did not meet fleet average emission targets, and with the findings of the IEA mentioned in the literature review that regulatory emission standards were important in emission reductions (Onoda, 2008). This finding is particularly pertinent when considered in terms of the carbon abatement costs calculated in CS2. These suggested that not only did *Subsidies* have a greater overall abatement cost than *Regulation*, but also that customers would benefit at the expense of all tax payers, whereas under *Regulation* customers bear the greatest costs whilst industry benefits.

When *Both Policies* were combined the burden on the tax payer is reduced. There was greater success in both LCV uptake and emission reduction alongside reduced abatement costs, both overall and for government, compared to *Subsidy* alone. Customers no longer benefit and industry does, with reduced impacts compared to *Regulation* alone, meaning costs are more equally distributed between customers, governments and industry. Customer abatement costs were calculated over all customers in this work, rather than focusing on specific segments, leaving the argument that *Subsidies* offered under *Both Policies* are still only assisting the better off to purchase an EV. Furthermore, there was only a marginal increase in emission reductions and marginal decrease in overall abatement cost when *Subsidies* are offered in addition to *Regulation*. Despite this, the important point to note is that *Subsidies* are more cost effective when combined with *Regulation* than when offered alone. Although undesirable for industry, having *Subsidies* in place with *Regulation* reduces the industry profit compared to *Regulation* alone, because although both costs and revenue are greater with *Subsidies* in place than *Regulation* alone, production costs have been increased more by the introduction of *Subsidies* than revenue has. Even though the impact on purchase decisions from *Subsidies* have only marginally increased EV uptake, customers have benefited compared to *Regulation* as a smaller portion of costs have been passed on. Overall, these findings suggest that although combining policies does not result in significant high level impacts, it does mutually reinforce positive aspects of single policies, and has potential to reduce some negative impacts if applied wisely.

6.2.4 Principals of Policy Design

It is the recommendation of this research that, based on the findings summarised above, the policies which have been modelled in this study are appropriate short-term mechanisms, but would only be permissible if they are implemented together and monitored subject to the following conditions:

Ensure Affordability

If, as expected, the trend of increasing vehicle purchase prices continues into the second-hand car market, then there will be more people counted amongst the worst-off. They may have to keep an older, less efficient vehicle for longer than otherwise, which could counteract GHG concerns (subject to vehicle use and embodied emissions) and have running cost implications for the owner. Further to this, they may no longer have the opportunity for car ownership due to higher average costs. The most affluent in society are the most likely to be purchasing new cars and are also most likely to be able to bear these higher purchase costs. If prices do rise, however, then some will move to the second-hand car market, reducing the new car market. This could have many knock on effects such as increased residual values. Therefore, as part of the concern for the worst-off, to ensure a sustainable and affordable car market in the short term, purchase prices of the cheapest vehicles must not be allowed to rise too rapidly. *Fiscal Measures* must be carefully designed that encourage responsible choices (biased towards

LCVs), and manufacturers must be prevented from passing excessive costs on to customers. Different ownership models, such as car clubs (which are already becoming popular in some areas), should also be given greater support, but these were not directly considered in this study.

Protect the Vulnerable

Segments of society with special claims for car ownership need protection from increases in purchase price or decreases in utility. In order to achieve the emission targets and introduce LCVs, it was discovered in the model that market shares of ICEV will be reduced greatly from what they are today. Though this is desirable, as the aim is to reduce emissions, even if it is assumed that such a significant change in purchase habits in just over a decade is realistic, it is unlikely that LCV attributes will have improved sufficiently to equal ICEV, particularly in terms of costs. Under this assumption, those segments who have most reliance on car ownership or are most sensitive to changes in costs will be most impacted. This is because they may be priced out from owning a vehicle suiting their needs or have to bear high costs because of their needs by the introduction of these policies. Thus, they would qualify for protection from the negative impacts on mobility which are indicated within the model, through amendments in regulations. These amendments should be analogous to existing policies, such as those suggested in Chapter Three, including welfare benefits similar to fuel poverty schemes or tax exemptions similar, and access regulations similar to equality laws. For instance, provision could be made that forces manufacturers to bias production costs, so that those purchasing smaller (cheaper) vehicles would not be unfairly burdened when they contribute less in terms of emissions. However, this would also have specific implications for those who legitimately require a larger vehicle (e.g. people with wheelchairs), and so would need further assistance, similar to the current ‘Motability’ scheme.

Distribute Burdens

This research found that customers bore the highest costs of the market transformation when *Regulation* is in place compared to BAU. Although customers should expect to bear some costs, as it is not argued that car ownership outweighs climate change obligations, costs should be more equally shared, particularly by industry who pass on a significant amount of their incurred penalties to the customer (though this was an assumption in the model). The *Subsidies* tested here, which reduced customer costs, were not strong enough to make a noticeable impact to market share, meaning that those wealthier people who would have bought an EV anyway have benefited from public money. In addition, the EV owner also benefits from low running costs. This situation is analogous to the feed-in tariffs offered with solar panels that, due to their high purchase price and the need to own your own home, are only accessible to the wealthier members of society. In both these cases, the tax payer is subsidising the well off at the expense of the less well off (or those without access) to bring down production costs of a technology which will, it is argued, benefit the whole of society in the longer term. When considering the impact on revenue that was highlighted in CS1, subsidising EVs could further impact the least well off as government income is reduced. The revenue preserving tax proposed in Chapter Four could not only prevent this, but also prevent the well off from benefiting disproportionately. The ethics of this as a policy approach is questionable though, as it reduces payback times that could have been a purchase decision factor. Other options to reclaim the income (if justifiably needed) could be related to electricity use or vehicle mileage, but any overhaul of vehicle taxes must be carefully designed, and remain emission-related.

6.3 Modelling and Appraisal Framework Proposal

The final objective of this research to be met is to propose an alternative modelling and policy appraisal framework for LCVs that other researchers or policy makers could adopt. As such, a four step approach is recommended, following the method which was carried out in this research. This framework is transferable to other forms of transport policies, or similar situations where there are conflicting policy concerns between societal and individual impacts. The four steps are:

1. Identify existing and potential ethical issues

This includes the reason for the drivers of the policy (which was climate change in this study), and what direct and indirect impacts the policy could have on distributive justice (e.g. in this study they were explored in Chapter Three and include direct limits on opportunity for car ownership and indirect impacts on accessibility and mobility). Further to this, it must be recognised that this needs to be carried out in a real world situation, where there are existing injustices. Of course, there will likely be quite different types of ethical issues to consider in other cases than this study.

2. Defend an approach to justice

In this study, the focus was on identifying policies that could prevent (or minimise the occurrence of) the worst-off from becoming even *more* worse off or another group becoming amongst the worst-off. This was defended in Chapter Three, where the obligation to minimise the harms of climate change (through the harm principle and tragedy of the commons) and the protection of those vulnerable to changes in the opportunity for car ownership (through special claims and analogous policies) was argued for. Other approaches are also legitimate, such as the six principles of distributive justice described by Khisty (1996) mentioned in the literature review. The validity of these arguments would be strengthened if also evaluated by peers.

3. Develop a model which captures identified ethical issues

Importantly, this means that a disaggregated model, which is able to represent different, and relevant, segments of society, is required. Further to this, users need to be aware of the assumptions, boundaries and limitations of the model, as argued in Chapter Three. The modeller and policy-maker must both be confident that identified issues are demonstrable.

4. Recognise that the model should not be used in isolation

As pointed out in Step 3, one of the arguments developed in Chapter Three was that modellers and policy makers should be aware of the limits and application of models in order for them to be permissible for policy appraisal. In particular, there are limits to the extent that the complexity of real-world systems can be captured within a model and that ethical issues can be included in any model (due to the non-empirical nature of ethics and the empirical focus of models). In recognising these limitations the alternatives would appear to be to either attempt to include ethics within the model or accept that models are prevented from capturing ethics and continue with current practises, of ex-ante or parallel ethical appraisal of the model and policies. In this research, both approaches have been adopted, as neither adequately captures the full importance or integration of ethical appraisal within the process. It should also be the case that other policy appraisal approaches, such as CBA, should not be neglected but also carried out alongside modelling and ethical evaluation to ensure a holistic and robust policy decision.

This framework is an improvement on existing practices that do not appreciate the importance of incorporating explicit ethical evaluation as a central focus of policy appraisal. This can lead to policy decisions that increase existing inequalities and burden those already worst-off in society. Furthermore, by also emphasising the importance of recognising the limitations of models and their application within the appraisal process, this approach overcomes issues of over-reliance or mis-interpretation that can lead to inappropriate policy decisions that do not achieve expected outcomes. By employing this framework, a policy-maker or researcher can develop a greater appreciation of ethics, risks, benefits and uncertainties related to specific scenarios, prompting more informed, confident and successful policy decision-making.

6.4 Future Research

The appraisal framework proposed in Section 6.3, may be adopted by other researchers with different interests in the field of LCVs by altering the stipulations, boundaries and assumptions of this research. An obvious example of this is to go deeper into the concerns relating to biofuels, which has already attracted much attention (NCB, 2011). Perhaps one interesting limit to remove would be the timeframe. This is because other morally relevant factors will emerge in the mid and long term, as other powertrains (such as HFCV) become available, and modal shift, car ownership models or wider transport attitudes evolve. In addressing this, one could begin from the arguments presented here. Likewise, the arguments regarding climate change could be explored more fully should one wish to enter the established debate in this area with a particular focus on transport. Further to this, consideration of car ownership (particularly the rapid development and increase thereof) in developing countries would be interesting to consider in relation to the arguments presented here as the “status quo” in these regions will differ. Finally, the framework is not necessarily limited to LCVs, or even transport, but can be expanded to consider the wider energy system, due to the competing nature of lifestyles locked-in to carbon-intense technology and obligations to mitigate climate change, or even any type of public policy that has conflicting issues of distribution.

Improvements to the model were discussed in detail in Chapter Five. Exploring these model limitations and suggested amendments would lead to a model that more accurately reflects the dynamic nature of technological development and demand response, and so be able to be used to identify more appropriate policy recommendations. The most important of these will now be highlighted.

Automobile industry and car markets

A more realistic automobile market would greatly improve the model. Firstly, within the ethical framework, recall that the attention is on those who are amongst the worst-off in society. CS1 considers the impact on the poorest in society, with the focus on purchase costs. Yet it is normally only the most affluent in society who can purchase new rather than second-hand cars. Further to this, many new cars are actually purchased as fleet cars, something that is not considered at all within this study. Also, many people do not buy cars (new or second-hand) with one up front purchase cost, but buy them on credit, choosing to pay back monthly, or (particularly in the US) on some sort of lease or hire-purchase scheme. These different forms of paying are not captured in the model or fully recognised in the ethical framework. Such payment schemes are though likely to cost more than outright payment (due to interest on loans), which is morally relevant (although well accepted in current practice). The interaction between new and second-hand cars, and the responses of both manufacturer and customer would be very relevant to include but unfortunately no system dynamic model that explicitly considered the second-hand car market was identified in this research. As there is no significant LCV second-hand market yet, this may not be a problem, but should be accounted for if the ethical framework is amended to consider a longer term. Additionally, the influence of competing manufacturer strategies was neglected in the models, which were set up to mimic an aggregate manufacturer rather than be representative of the automobile industry with individual players. This has been attempted in another recent work (Boksberger et al. 2012).

Emissions and scenarios

Within any model expansion, it would be more accurate to include GHG emissions as "Well to Wheel" or life cycle emissions, rather than tailpipe only. This is a move currently being given much consideration by the EU for fleet emission regulations (EC 2012b). In this study only two policies were considered, and future work should involve more complex scenarios. Larger models should be able to cope with mimicking different or multiple policy options, such as the UK Transport Carbon Model developed through UKERC (Brand et al., 2012) or the JRC EU TIMES energy system model, which has recently been expanded to include transport.[113] Furthermore, future models would need to consider potential rebound effects that occur from lower running costs.

Segments and indicators

The model would be greatly improved by the development of a choice model with more appropriate segments that can be readily identified in regards to the impact of the policy on the opportunity for car ownership. As far as it is known there is no such model publically available (though commercially sensitive models may do so),

[113] The author will be working with this model in a post-doctoral position from late 2013.

though it is likely that an amalgamation of existing models would approximate segments more effectively than those used in this model. Psychology based methodological approaches have begun to be applied for market segmentation and it may be that this could be utilised to refine the segments within a choice model (Anable, 2005; DfT, 2010; Element Energy, 2013; Morton, 2013). Once segments are identified, it may be beneficial to consider how *willingness to consider* parameters within the model may vary between such segments and also how these may vary over time.

As opportunity for car ownership comprises of both vulnerability to car-poverty and car-utility, it is recommended that segment vulnerability to car-utility (the accessibility and mobility a car provides an individual), which was not represented in CS2, should be captured in order to fully reflect the framework concerns. Although it is not certain how this could be achieved, it would need to be based on reliance on car ownership due to limitations in personal mobility (through e.g. disability, location or commitments), in comparison to segment vulnerability to car-poverty, which was represented in CS2 by income.

The actual assessment of policies would be made more efficient if specific ethical indicators could be developed within the model that highlighted the permissibility of the policies[114]. Should segments be developed that capture the vulnerabilities to car-poverty and car-utility, and it is possible to combine these with outputs in the model of the impact on cost and utility of car ownership, then policy assessment could be much more in line with the ethical framework developed. Developing a robust approach for achieving this will raise both ethical and empirical issues. For instance, ethical dialogue will be required to justify the definition of equity within the indictor (for example, minimising the equity gap versus preventing reduced opportunity for the worst off), and once this is determined, there will be issues around measuring and quantifying such factors, as data may be limited or subject to interpretation based on judgement rather than repeatable methods.

6.5 Final Summary

The concern of this work was that governments are obliged to reduce GHG emissions due to climate change, but policies to achieve this via new passenger

[114] An attempt to do so was made by the author in some separate work to this thesis that was awarded a Youth Prestige Grant at the 2013 World Conference in Transport Research.

cars could increase inequality in society. Arguments were developed that supported these concerns and identified groups with specific claims for car ownership in the short-term, making an important timely contribution to growing philosophical debates regarding climate change and transport, as well as filling a research gap with an ethical framework for LCV uptake policies that recognised the limitations of modelling in policy appraisal.

A unique approach was then taken that combined that ethical framework with a system dynamic model of such policies, comparing and combining supply and demand side policies. It was found that putting regulatory penalties in place would achieve the greatest GHG emission reductions but this also imposes large costs on customers, which are disproportionate across market segments. Subsidies tested here reduced user costs at the expense of public money, were not as successful in reducing emissions and unless they are introduced within a failing market, they only benefit the more affluent in society. However, when combined, the positive aspects of single policies are mutually reinforced and some negative impacts are reduced. This appears to defend a claim that governments are indeed obliged to introduce such policies on both the supply and demand sides, but also that stronger policies and co-ordination are needed for the substantial reductions required. As the opportunity for car ownership was found to be affected by LCV policies, some policy amendments will be required, which can be analogous to existing public policies such as tax exemptions. These must be targeted towards the worst-off to ensure that they are not unfairly burdened.

From this, three key policy recommendations have been made. Firstly, there must be provision in the policy to ensure affordability of car ownership (due to the societal and infrastructural lock-in of car-dependence) for the worst-off in society. Following this, policies must seek to protect those with special claims towards car ownership and are therefore most vulnerable to changes in the opportunity for car ownership. Finally, policy makers should be aware of where the costs related to policy interventions are falling, between customers, government (through the general tax payer) and industry, and try to ensure that burdens are fairly distributed.

Drawing from the research that has been carried out, a modelling and appraisal framework has been proposed, which will allow future researchers and policy makers to explore other issues related to LCVs, and is also transferable to other areas of public policy. The four steps in this process are 1. Identify existing and potential ethical issues; 2. Defend an approach to justice; 3. Develop a model which can capture the identified ethical issues, and; 4. Recognise that the model should not be used in isolation. This framework improves upon existing practices that do not fully appreciate the importance of integrating ethical evaluation into the policy appraisal process and offers a new perspective on the limitations of modelling.

The novel contribution of this research is the argument for the implementation of ethics within a model for policy appraisal, with a specific focus on LCVs. This was achieved within the limits of the study. An improved modelling and appraisal framework was proposed, where it was recognised that there are limitations to being able to combine ethics and modelling. This is due to the complexity of real-world systems and the incompatibility between non-empirical ethical evaluation and empirical modelling. Despite the limitations, the proposed framework will allow future researchers, automobile manufacturers and policy makers explore ethical issues not only related to LCV policies, but also other areas of public policy, particularly related to transport and energy. Through following the framework, policy decision-making will be more informed and holistic, reducing the occurrence of poorly designed policies that fail to achieve their purpose or burden the worst-off.

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APPENDIX A

Survey

NEW FUELS, NEW RULES?

UNIVERSITY OF LEEDS

Doctoral Training Centre in Low Carbon Technologies

Page 1 of 6

INTRODUCTION

NEW FUELS, NEW RULES?
An interdisciplinary exploration into the impact of low carbon passenger vehicles on society

This project aims to bring together the understanding of experts involved in the development and implementation of a low carbon vehicle fleet, by opening a dialogue between the fields of vehicle technology, transport policy and applied ethics, all of which must work together in order to secure a sustainable low carbon vehicle market. It consists of two parts - this questionnaire and a workshop which will take place in September.

Although it is recognized that low carbon vehicle technologies are necessary in decarbonising our transport system and to meet climate change targets (alongside other concerns), government policies are required to support their uptake. The driving concern in this work is that these policies themselves may create disproportionate impacts across society due to vulnerabilities within certain sections (most likely those already worst off, including the poor and the disabled), and these should be identified and minimised where possible.

Note that once you have clicked on the CONTINUE button you cannot return to the previous page.

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BACKGROUND

This questionnaire should be answered by those who are experienced in the field of low carbon vehicles with a broad knowledge of technologies and/or policies.

There are three parts:

In **Part A**, you will be asked to give opinion on conflicting attributes and vulnerabilities of car ownership, the results of which will be used to form the framework of a facilitated discussion at the workshop in September. The workshop is designed to enable cross disciplinary discussion on the impacts of new low carbon vehicle technologies and their supportive policies.
This should take you around five minutes to complete

In **Part B**, you will be asked to give your judgment on the impact that low carbon vehicle policies may have on the average cost and utility of car ownership. The results will be used to help assign inequality impact indicators of low carbon vehicle policies.
This should take you around fifteen minutes to complete.

Part C consists of some background questions about you.
This should take you less than five minutes to complete.

This survey should take you less than 30 minutes to complete.

Thank you for agreeing to take part in this research. Please see this link for more information regarding data protection.

Continue >

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PART A: CONFLICTING ATTRIBUTES AND VULNERABILITIES OF CAR OWNERSHIP

In this section you will be asked to give your own opinion on attributes and vulnerabilities regarding car ownership. Please read the definitions carefully in order to give your best judgment with these in mind, and considering it within a current UK context. There will be an opportunity to comment on judgements and assumptions, which will be taken into consideration.

DEFINITIONS

CAR-POVERTY = Being unable or with limited ability to own and run a car that meets ones need due to the costs associated with ownership (both purchase and running).

CAR-UTILITY = Reliance on owning and running a car that meets ones needs for gaining access to goods and services that are important to the individual. This can relate to physical disabilities, work, family or social commitments or distance between home and amenities. It is also related to the technical attributes of a vehicle and it's ease of use.

LOW CARBON VEHICLE = A car using an alternative fuel (eg biofuel) and/or powertrain that has lower carbon emissions than a conventional vehicle. This can include plug-in hybrid and full battery electric vehicles, as well as Hydrogen fuel cell vehicles.

1. Please indicate your opinion on the following statements:

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
a. The introduction of low carbon vehicles will change the way we view and use cars in the UK.	○	○	○	○	○
b. There is a general and defensible claim that one should be able to own and run a car that meets ones needs.	○	○	○	○	○
c. Certain segments of society may have a stronger claim for owning a vehicle than others.	○	○	○	○	○
d. It is important to limit increases in Car-Poverty.	○	○	○	○	○
e. It is important to limit decreases in Car-Utility.	○	○	○	○	○
f. Limiting increases in Car-Poverty is more important than limiting decreases in Car-Utility.	○	○	○	○	○
g. Some increases in Car-Poverty are permissible in the context of climate change.	○	○	○	○	○
h. Some decreases in Car-Utility are permissible in the context of climate change.	○	○	○	○	○

2. Do you have any comments on the questions or answers above?

3. Do you have any questions or comments on collaboration between industry, academia and policymakers in the fields of technology, policy and ethics regarding the impact of low carbon cars on society that should be raised at the workshop?

Part B: IMPACT OF POLICIES

In this section you will be asked to estimate the overall impact of five different policy measures on average cost and utility of car ownership for the consumer by 2020 compared to today, should the policy be implemented within the next year.

Definitions of terms, policy descriptions and background assumptions are given below the questions. You will need to read through these carefully in order to give your best judgement when answering the questions.

Please answer this section based on your knowledge in the field of low carbon vehicles and thinking about newly purchased cars in the UK in 2020.

4. Please indicate the overall impact of each policy measure on the average cost of car ownership to the consumer.

More Info

In order to do this, you will need to consider the impact on purchase and running costs associated with each powertrain, as well as their market shares by 2020. See *More Info* for an example.

	OVERALL IMPACT ON AVERAGE COST						
	Significant increase	Notable increase	Minimal increase	No impact	Minimal decrease	Notable decrease	Significant decrease
a. REGULATION	○	○	○	○	○	○	○
b. COMPETITION & COLLABORATION	○	○	○	○	○	○	○
c. FACILITATING ADOPTION	○	○	○	○	○	○	○
d. FISCAL MEASURES	○	○	○	○	○	○	○
e. RAISING AWARENESS	○	○	○	○	○	○	○

MORE INFORMATION

Question 4

Example

You may think that a policy measure will incur the following impacts by 2020:

cICEV will have a significant increase in purchase costs, a notable increase in running costs and a 50% market share

PiHEV will have a notable decrease in purchase costs, no or little change in running costs and a 30% market share

BEV will have a notable decrease in purchase costs, notable decrease in running costs and a 20% market share

So you would then consider these together to judge what the overall impact on the average cost of car ownership to the consumer may be, and may conclude that in your opinion it is a notable increase.

OK

5. Please indicate the overall impact of each policy measure on the average utility of car ownership to the consumer.

More Info

In order to do this, you will need to consider the impact on technical attributes and ease of use associated with each powertrain, as well as their market shares by 2020. See *More Info* for an example.

	OVERALL IMPACT ON AVERAGE UTILITY						
	Significant increase	Notable increase	Minimal increase	No impact	Minimal decrease	Notable decrease	Significant decrease
a. REGULATION	○	○	○	○	○	○	○
b. COMPETITION & COLLABORATION	○	○	○	○	○	○	○
c. FACILITATING ADOPTION	○	○	○	○	○	○	○
d. FISCAL MEASURES	○	○	○	○	○	○	○
e. RAISING AWARENESS	○	○	○	○	○	○	○

MORE INFORMATION

Question 5

Example

You may think that this policy measure will incur the following impacts by 2020:

cICEV will have no impact on technical attributes, notable decrease on ease of use and a 50% market share

PiHEV will have a minimal increase in technical attributes, notable increase in ease of use and a 30% market share

BEV will have a notable increase in technical attributes, significant increase in ease of use and a 20% market share

So you would then consider these together to judge what the overall impact on the average utility of car ownership to the consumer may be, and may conclude in your opinion it has no impact.

OK

DEFINITIONS

AVERAGE COST OF OWNERSHIP = an average lifetime ownership monetary cost to a consumer of owning a car, considering all powertrains and their shares of the market. This includes all purchase and running costs.

PURCHASE COST = outright purchase cost to the customer when new.

RUNNING COSTS = these are the annual and daily running costs of car ownership and include:
Fuel, Vehicle tax (VED), Maintenance and parts, Insurance, Charges (tolls/parking etc).

AVERAGE UTILITY OF OWNERSHIP = an average utility or usefulness in daily life to a consumer of owning a car, considering all powertrains and their shares of the market. In this context this can be represented by the technical attributes and ease of use of a vehicle.

TECHNICAL ATTRIBUTES = attributes of the vehicle which define how the consumer is able to use the car, which include range, fuelling availability, size and power/performance.

EASE OF USE = the convenience which a vehicle gives the consumer in their daily lives, eg being able to use it at any time and for any journey.

MARKET SHARE = the percentage of the new car market for a particular powertrain in 2020.

POWERTRAINS = As the timeframe for this exercise is up to 2020, only three powertrains are considered:

cICEV = Conventional Internal Combustion Engine Vehicle: a conventionally fuelled (ie petrol or diesel) internal combustion engine vehicle, such as that which the majority drive on our roads today.

PiHEV = Plug-in Hybrid Electric Vehicle: a vehicle powered by an electric motor which can be charged by electricity but also has an on board generator powered by conventional fuel (eg the Vauxhall Ampera).

BEV = Battery Electric Vehicle: a fully electric battery operated vehicle powered by an electric motor which is charged by electricity (eg the Nissan Leaf).

IMPACTS

SIGNIFICANT = over 10% change.

NOTABLE = 5-10% change.

MINIMAL = up to 5% change.

POLICY DESCRIPTIONS

REGULATION

Regulatory measures force manufacturers to accelerate the development of low carbon technologies in order to meet emission or technological quota targets. Failing to adhere can lead to legally administrated fiscal and civil penalties, whereas overreaching targets can be rewarded with incentives.

For the questions use this example and assume even higher targets will be set for post-2020:
The current EU average fleet target for 2020 is 95g/km. Under EU strategy, a premium of €5 for the first g/km of exceedance is set to rise to €95 from 2019,and the percentage each manufacturer's newly registered cars that must comply will rise from 65% to 100% from 2015 onwards. When calculating the average emissions of each manufacturer's fleet, each low-emitting (<50g/km) car will be counted as 3.5 vehicles until 2013, reducing to 2.5 in 2014, 1.5 vehicles in 2015 and one vehicle from 2016.

COMPETITION AND COLLABORATION

Competition between companies accelerates R&D, whereas collaboration assists in overcoming barriers of high R&D costs and skill shortages. Government commitment to future transport technologies is indicated by the encouragement of collaboration between industry and academia, tackling commercial barriers to knowledge sharing and harmonising investment in research programmes.

For the questions use this example and assume further investment is secured to engage all car manufacturers and research institutions:
Industry and academia are being encouraged to work more closely and competitively through the introduction of government grants, such as the low carbon vehicle innovation platform integrated delivery programme. This is a £250 million programme up to 2017 of government and industry investment for initial academia research up to industry led C, R and D.

FACILITATING ADOPTION

To encourage low carbon vehicle uptake, early adopters can be compensated for the lower utility of low carbon vehicles's relative to cICEV, by implementing programmes that introduce favoured traffic management and accelerate the building of complementary infrastructure.

For the questions use this example and assume that further investment is secured to extend the scheme to all areas of the UK:
The Plugged in Places programme seeks to invest in an electric charging infrastructure. It has £30m available to match fund pilot projects with up to 8500 charging points in 8 key locations across the UK, allowing the testing of charging technologies, grid connections, business models and interoperability. In some areas this can include free charging and parking.

FISCAL MEASURES

The UK government are implementing fiscal measures to overcome the current high cost differential between ownership costs of cICEV and LCV. They will often take the form of taxes and subisides, and are levied on the consumer at the point of sale, on annual costs or on day-to-day operating costs. They reduce the purchase cost differential and increase the running cost differential between LCV and cICEV.

For the questions use this example and assume that these policies are continued and increased up to 2020:
Since January 2010, the Plug-in Car Grant has given a subsidy of 25%, up to £5000 off the cost of a plug in vehicle, and furthermore VED banding has been moved in line with CO2 emissions, with zero tailpipe emissions being exempt from VED and highest emitters charged up to £475 a year. Although the price of conventional fuel may rise as resources deplete, fuel tax can be used as another fiscal measure.

RAISING AWARENESS

Behaviour and attitude change is required to overcome the lack of desire for, and awareness of, attributes and potential of new technologies, as well as to encourage the adoption of more responsible and considered behaviors in transport choices. This can be achieved by increasing marketing and visibility of LCVs, decreasing marketing of cICEVs and making appeals to conscience regarding responsible behavioral change.

For the questions use this example and assume that the programme is rolled out further to involve the use of low carbon vehicles by all local councils and large businesses, alongside an advertising campaign:
The Technology Strategy Board low carbon vehicle demonstration programme has £25m for business led demonstration projects, including real world testing, studying customer perceptions and concerns and expose different drivers. It has so far involved 340 vehicles and covered both personal and fleet drivers.

BACKGROUND ASSUMPTIONS

For illustrative purposes, these are the current attributes for new C-Segment (small family car) cICEV, PiHEV and BEV. Further information on these figures is available on request.

	Attribute	cICEV	PiHEV	BEV
COST	Purchase Price (£'000)	20	37	31
	Operating Cost (ppm)	26.3	13.1	6.8
UTILITY	Maximum speed (mph)	125	100	90
	Maximum Power (kW)	102	54	80
	Maximum Full Tank Range (miles)	630	360	100
	Fuel Availability (%)	100	90	40
	Maximum refuel/charge time (hrs)	0.25	6	12
	Refuel/charge location	Service stations	Service stations, home, public charge points	Home, public charge points

6. Do you have any comments on the questions or your answers on this page?

T C: Personal Information

is section you are asked questions about yourself in order to frame the answers you have given.

the research has been completed the results of your questionnaire will be anonymised and the original research material destroyed. Until destroyed, the research material will remain dential and no personal data will be kept on file once the research is complete. You will not be able to be identified in any reports or publications resulting from this work.

7. Please indicate which discipline best describes your main area of expertise.

- ○ Philosophy and Applied Ethics
- ○ Policy and Behaviours
- ○ Technology and Engineering
- ○ Other/Mixed

If you answered Other/Mixed, please give detail

8. Please indicate which of the following car-owning segments you belong to.

More Info

For more information on segments click on the box to the right. If no segment fits please choose closest possible and leave a comment in the box provided.

- ○ Older less mobile car owner
- ○ Less affluent urban young families
- ○ Less affluent older sceptics
- ○ Affluent empty nesters
- ○ Educated Suburban Families
- ○ Town and rural heavy car use
- ○ Elderly without cars
- ○ Young urbanites without cars
- ○ Urban low income without cars

Please give details if you feel your segment is not wholly approporiate

9. Please indicate your gender.

- ○ Female
- ○ Male

10. Which indicate which category includes your age.

- ○ under 20
- ○ 20-29
- ○ 30-39
- ○ 40-49
- ○ 50-59
- ○ 60-69
- ○ 70 and over

11. If you wish to attend the workshop on **Monday 10th September at the University of Leeds** or would like to hear more about this project please provide your name and contact details. Alternatively, you may register for the workshop at a later date by visiting http://tiny.cc/NFNRworkshop or emailing G.Harrison09@leeds.ac.uk.

Please also use this box if you have any final comments on this survey.

APPENDIX B

Parameters of CS1 base model

PARAMETER	EQUATION OR BASE VALUE
Average life car	14
Average life EV	14
BERR case	1
Budget factor	IF THEN ELSE(budget limited=1:AND:budget<=0,0,1)
Discards ICEV	IF THEN ELSE(Time<=3,total vehicles/average life car,Installed base ICEV/average life car)
Discards EV[EV]	IF THEN ELSE(Time>3,Installed base EV[EV]/average life EV,0)
Drivers considering EV	Willingness to consider EV
Effect of contact c121	0.15
Effect of contact c122	0.25
Epsilon	1/(2*reference rate soc exposure)
Fractional WtC decay rate	exp(-4*epsilon*(Total social exposure ICEV to EV-reference rate soc exposure))/(1+exp(-4*epsilon*(Total social exposure ICEV to EV-reference rate soc exposure)))
Generalised cost BEV	beta Price*Price BEV+beta operating cost*operating cost BEV+beta max speed*max speed BEV+beta fuel availability*fuel availability BEV+beta emission rating*emission rating BEV+beta range*range BEV+beta fuel location*fuel location home BEV+asc penalty BEV+preserver annual charge BEV/1000
Generalised cost ICEV	beta Price*price ICEV+beta operating cost*operating cost ICEV+beta max speed*max speed ICEV+beta fuel availability*fuel availability ICEV+beta emission rating*emission rating ICEV+beta range*range ICEV+preserver annual charge ICEVPIHV/1000
Generalised cost PIHV	beta Price*Price PIHV+beta operating cost*Operating cost PIHV+beta max speed*max speed PIHV+beta fuel availability*fuel availability PIHV+beta emission rating*emission rating PIHV+beta range*range PIHV+beta fuel location*fuel location home PIHV+asc penalty PIHV+preserver annual charge ICEVPIHV/1000
Initial fleet size	3.2e+007
Initial number ICEV	initial fleet size-sum(initial number EV[EV!])
Initial number EV[PIHV]	1000
Initial number EV[BEV]	3000
Installed base ICEV	INTEG (sales ICEV-discards ICEV, initial number ICEV)
Installed base EV[EV]	INTEG (sales EV[EV]-discards EV[EV], initial number EV[EV])
Market blip	IF THEN ELSE (Time>15:AND:Time<16,negative market impulse,0)
Market share EV[EV]	Installed base EV[EV]/total vehicles
Marketing duration	IF THEN ELSE(BERR case=1:OR:share of purchases EV[PIHV]+share of purchases EV [BEV]>0.075,100,10)
Marketing effect	0.025
Marketing for EV	IF THEN ELSE(Time<marketing duration:AND:Time>=0, marketing effect,0)
Negative market impulse	0

PARAMETER	EQUATION OR BASE VALUE
New vehicle requirement	sum(discards EV[EV!])+discards ICEV
Perceived affinity with EV[PIHV]	drivers considering EV*perceived utility PIHV
Perceived affinity with EV[BEV]	drivers considering EV*perceived utility BEV
Perceived utility BEV	exp(theta*(Gen cost BEV-subsidy factor BEV))
Perceived utility ICEV	exp(theta*Gen cost ICEV)
Perceived utility PIHV	exp(theta*(Gen cost PIHV-subsidy factor PIHV))
Reference rate soc exposure	0.025
Sales ICEV	discards ICEV*(1-sum(share of purchases EV[EV!]))+share of purchases EV to ICEV*sum(discards EV[EV!])
`Sales EV[PIHV]	share of purchases EV[PIHV]*discards ICEV+share EV to PIHV*sum(discards EV[EV!])
Sales EV[BEV]	share of purchases EV[BEV]*discards ICEV+share EV to BEV*sum(discards EV[EV!])
Share EV to BEV	IF THEN ELSE(stick with EV=0,perceived utility BEV/(perceived utility BEV+perceived utility ICEV+perceived utility PIHV), perceived utility BEV/(perceived utility BEV+perceived utility PIHV))
Share EV to PIHV	IF THEN ELSE(stick with EV=0,perceived utility PIHV/(perceived utility BEV+perceived utility ICEV+perceived utility PIHV),perceived utility PIHV/(perceived utility BEV+perceived utility PIHV))
Share of purchases EV[EV]	perceived affinity with EV[EV]/(perceived utility ICEV+sum(perceived affinity with EV[EV!]))
Share of purchases EV to ICEV	IF THEN ELSE(stick with EV=0,perceived utility ICEV/(perceived utility PIHV+ perceived utility BEV+perceived utility ICEV),0)
Social exposure and word of mouth drivers EV	effect of contact c122*sum(Installed base EV[EV!])/total vehicles
Subsidy BE	0
Subsidy duration	10
Subsidy factor BEV	IF THEN ELSE(Time<=subsidy duration,subsidy BEV/1000*budget factor , 0)
Subsidy factor PIHV	IF THEN ELSE(Time<=subsidy duration,subsidy PIHV/1000*budget factor , 0)
Subsidy PIHV	0
Theta	GET XLS CONSTANTS('car choice inputs.XLS', 'Sheet1' , 'i3')
Total social exposure ICEV to EV	Marketing for EV+social exposure and word of mouth drivers EV+word of mouth non EV drivers+market blip
Total vehicles	sum(Installed base EV[EV!])+Installed base ICEV
Willingness to consider EV	INTEG (WtC Gain-WtC Loss,0)
Word of mouth non EV drivers	effect of contact c121*Willingness to consider EV*Installed base ICEV/total vehicles
WtC Gain	Total social exposure ICEV to EV*(1-Willingness to consider EV)
WtC Loss	Fractional WtC decay rate*Willingness to consider EV