Omega

Aviation in a sustainable world

A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector

Final Report

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About Omega

Omega is a one-stop-shop providing impartial world-class academic expertise on the environmental issues facing aviation to the wider aviation sector, Government, NGO's and society as a whole. Its aim is independent knowledge transfer work and innovative solutions for a greener aviation future. Omega's areas of expertise include climate change, local air quality, noise, aircraft systems, aircraft operations, alternative fuels, demand and mitigation policies.

Omega draws together world-class research from nine major UK universities. It is led by Manchester Metropolitan University with Cambridge and Cranfield. Other partners are Leeds, Loughborough, Oxford, Reading, Sheffield and Southampton.

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Executive Summary

Context and Aim

The aviation industry is both a product of and contributor to social and economic development at the global and national scales. Growth in the aviation sector strongly reflects the pace and direction of economic growth and prosperity. Simultaneously, however, environmental risks associated with aviation have increased, not only in terms of local air quality and noise impacts, but increasingly with respect to emissions such as CO_2, NO_x and the generation of contrails and cirrus clouds which have potential to cause global warming and climate change.

Although the contribution of aviation global emissions is relatively low at about 3% of anthropogenic CO_2 emissions, projections suggest that this contribution will increase to about 12% of total CO_2 emissions by 2050 (Kim *et al.*, 2007). UK Air Passenger Demand and CO_2 Forecasts (Dft, 2007) show aviation's share of UK climate change emissions increasing from between about 6% in 2005 to between 19% and 49% in 2050 using a range of policy scenarios.

Recent reviews by the IPPC (2006) and the Stern Review on the Economics of Climate Change (2007) argue that transportation, and the aviation sector in particular, must adopt measures to reduce emissions of green house gasses associated with climate change.

Thus, there is a growing call to control the environmental risks of aviation, especially in the context of predicted future growth in traffic. There is a clear need to understand the feasibility and costs of controlling the environmental risks of aviation while simultaneously securing its substantial social and economic benefits. In this context, this study aims to inform cost effective strategies that can be adopted by the aviation industry to reduce / control the environmental effects of aviation by constructing a series of marginal abatement costs (MAC) curves which show the incremental costs of achieving successive reductions in specific emissions such as CO_2 (Figure S.1) .

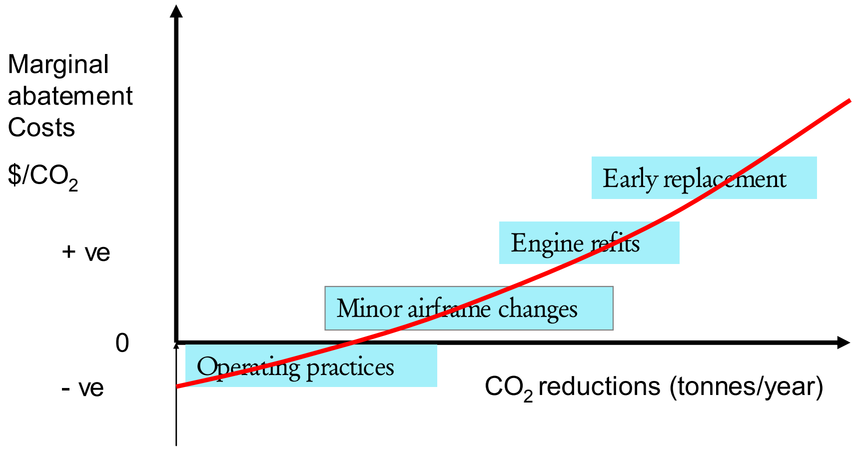


Figure S.1: Marginal Abatement Costs can Guide Selection of Best Least Cost Interventions to Reduce Emissions from Aviation.

Approach

The study methods involved a review of academic and industry research to assess the link between aviation and emissions, and the scope for abatement measures. A workshop was held with representatives from aircraft and engine manufacturers, service supply trade organisations, researchers and trade associations to explore the feasibility and sources of information on abatement options. This was followed up by email consultation and telephone interviews with about 20 key informants covering a wide range of aviation stakeholders, including airlines, airframe and engine manufactures, service providers, researchers, air traffic managers, airport authorities and regulators. This process explored existing and possible future abatement options, sources of information to support analysis, and factors influencing take up by the industry. This led to a critical review of abatement options that could be taken in short, medium and long term options, and their suitability to different aviation subsectors and to different business models.

An important aspect of the approach and a product of the work was the development and demonstration of a framework for assessing the marginal costs of abatement options. This framework was applied to two case studies which differed in detail, scale and coverage. One estimated MAC for the UK domestic sector. The other estimated MAC for European based airlines, including international routes.

Results and Conclusions

The study addressed a number of research objectives that are briefly reported in turn and constitute the results of the study.

Objective 1 set out to identify the relationship between the characteristics of aviation and environmental emissions, and the scope for improving the environmental performance of the aviation sector.

Representative aircraft. The study used representative aircraft that are indicative of generic categories of size (passenger numbers) and journey length, whether short, medium or long haul. Data sets are available to construct regional and global profiles of aviation activity, although the degree of detail varies. A range of air traffic forecasts, available from international, government and industry sources, can be used to determine aviation activity at different scales. All of these predict continued growth in aviation traffic.

Estimates of emissions from aircraft in use were conducted on the basis of a variety of industry test and modelled results. These vary in the coverage of emissions and the different stages of the LTO and cruise cycle, and in suitability for estimating MAC for specific interventions. Although various organisations predict that the aviation sector will be able in future to achieve considerable improvements in fuel efficiency, reduce CO_2 emissions and meet more stringent NO_x emissions standards, it is not clear whether such improvements are technically or commercially feasible. Much depends on the inducements provided by fuel prices and environmental regulation.

Data limitations. It was found that, although there is considerable interest in estimating MAC for aviation in order to determine the most cost effective ways of reducing emissions, there are considerable gaps in data and methods to enable this to be done with confidence. It is particularly difficult to estimate MAC for medium and long term technological changes that require considerable upfront investment in research and development and possible changes in behaviour, both by service providers and users.

Categories of abatement measures. The study identified three broad categories of abatement measures with scope to improve the efficiency of fuel consumption and reduce CO_2 and other emissions, notably NO_x. These comprise airframe and engine technology, operational improvements and fleet management.

Consultation with stakeholders identified a range of criteria to assess the feasibility and acceptability of these abatement options. These include effectiveness, costs, operational convenience, barriers to implementation and compatibility with business models and practices. It is clear that actions to reduce emissions have been driven directly by regulatory limits on emissions and indirectly by increases in fuel prices that promote fuel efficiency. While there is some agreement amongst stakeholders on the potential theoretical saving in fuel and emissions that can be achieved by these interventions, there is considerable uncertainty regarding their operational practicability and cost.

Changing emphasis. It appears that most environmental interventions in the past have focussed on meeting local air quality and noise standards that are set either internationally or at specific airports. Concern about climate change, however, has reoriented attention towards reducing CO_2 mainly by promoting increased fuel efficiency. Fuel efficiency has always been a critical commercial driver of technology change, but now concerns of global warming provide an added impetus.

Objective (ii) set out to determine, in broad terms at this stage, the cost effectiveness of alternative 'programmes of measures' to control environmental effects, and thereby the marginal costs of abatement

An analytical framework was developed that systematically determines the relative cost effectiveness of alternative measures to reduce emissions from aviation, notably CO_2, NOx and a range of other species. This is a major output from the work. The main components and steps involved are shown in the Figure S.1.

The framework combines information on aviation activity profiles and baseline 'no-intervention' emissions, now and into the future, against which the efficacy of interventions can be assessed. The framework comprises a series of linked spreadsheets that contain data and estimation routines to calculate marginal abatement costs for a range of interventions to control emissions. Estimates are applied to specific types of aircraft operating specific types of journeys, allowing for the differential effect of abatements on different stages of the LTO-cruise cycle.

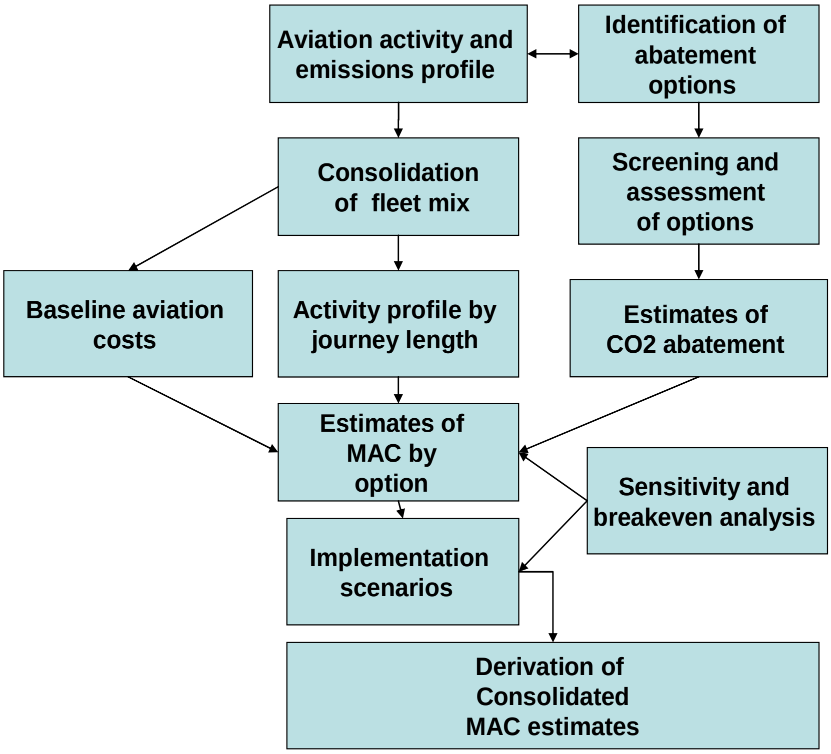


Figure S.1: This Analytical Framework was used to Assess the Marginal Abatement Costs (MAC) of Reducing Emissions from Aviation

Case Studies. The application of the framework was demonstrated using two case studies. One covers the UK domestic sector and focuses on reduced CO_2 emissions. The other covers the European-based sector including long distance international traffic and covers CO_2, NO_x and selected other species. Numeric estimates of MAC have been derived for these cases for 2007, 2012/15 and 2020/25, together with a qualitative assessment of options for 2050. A combination of methodological issues and limited data requires that the estimates must be regarded as indicative only.

Scope for abatement. The cases revealed that a range of interventions, could enable the aviation sector to abate about 12-15% of its CO_2 (and related) emissions at negative or zero cost by 2012, and more than this if fuel prices rise to 'very high' levels. As explained below, these 'win-win' interventions are mainly associated with changes in aviation operations that reduce fuel consumption per unit of output, that is, per passenger km. Analysis suggests, however, that after this point MAC rise steeply, with limited opportunity at central oil price forecasts to achieve abatement at costs below £20/t CO_2, the benchmark provided by the current price of CO_2 ETS permits (and the prevailing social cost of carbon). By 2020/5 the cases suggest that the potential for abatement at or below zero cost is about 25% of the annual sector total at central fuel prices, with improvements in ATM providing a large share of these benefits. These estimates of reductions in emissions consider interventions individually. Emissions savings will be lower once overlapping effects between abatement options are taken into account.

Cost-effective abatement options. The case studies show that the most cost effective intervention measures in the short to medium term appear to be those associated with changes in operations and management. These include increasing the use of capacity (through for example increased occupancy and consolidation of flights), reducing take-off weight, adopting in flight fuel-saving practices, matching airplanes to the short haul distances typical of UK and European sectors (through for example increasing use of turbo-prop planes), employing in-situ engine wash maintenance technologies and, by 2020, introducing European-scale ATM improvements that reduce travel distance. High fuel prices are likely to encourage early retirement and replacement of airplanes with those that incorporate improved airframe and engine design for fuel efficiency. There is too much uncertainty regarding the development costs for new technologies to construct MAC beyond 2020. This includes uncertainty about achieving ACARE compliant standards.

Objective (iii) set out to determine the main technical trade-offs and interdependencies amongst different environmental emissions, and

the implications for assessing the cost effectiveness of interventions which affect different emissions in different ways.

Searching for a unified metric. It was not possible to derive a meaningful single unified metric because the secondary effects of many aviation emissions are not well defined, especially as they occur at different altitudes. Furthermore, some emissions have primary effects on Local Air Quality (LAQ) rather than (or as well as) on global atmospheric conditions, such that a common metric is inappropriate.

Interdependencies. The study explored evidence of the trade-off and synergies amongst options to abate emissions. In most cases abatement measures designed to reduce fuel burn and CO_2 emissions result in corresponding reductions in NO_x emissions at both ground level and cruise altitude, with little or no impact on noise. Possible impacts of more efficient engines on the production of water vapour trails produced by very hot exhaust interacting with ambient humidity have not been considered because their incidence and effects are very uncertain given the current state of knowledge. There is some evidence of CO_2: noise trade-offs in engine or airframe design. Open rotor technology, which offer considerable fuel benefits for short haul operations, may be noisier than new generation turbo fans.

Objective (iv) set out to identify the main knowledge gaps and uncertainties that need to be addressed to determine best least cost strategies for environmental abatement in the aviation sector, thereby making recommendations for further research on this topic.

There are knowledge gaps and degrees of uncertainty in all aspects of the analysis reported here, namely regarding the estimation of baseline emissions, the effectiveness of abatement under given operating conditions, and costs.

Baseline emissions. There is moderate uncertainty with respect to the estimation of baseline emissions from aviation activities given the inherent variation in aircraft types, and maintenance and operating conditions.

Efficacy of abatement options. There is limited objectively verifiable data to confidently assess the efficacy of abatement options under the variety of real operating conditions. Information, where available, typically relates to very specific aircraft or operating circumstances such that generalisation is either not possible or requires great caution. Available data sources were found to be insufficiently complete in coverage of aircraft and/or of the full LTO-cruise cycle to support full appraisal of abatement options.

Costs of abatement options. There is considerable uncertainty about the costs of developing and implementing abatement options. Indeed, obtaining information on the baseline costs and incremental costs of abatements operating is challenging due to a combination of inherent variation in costs, variations in accounting methods and restrictions imposed by commercial confidentiality. Cost estimates are particularly uncertain for longer term developments such as new engine and airframe technologies, in-flight monitoring and control systems, synthetic fuels and novel air traffic management systems. It proved particularly difficult to ascertain likely research and development costs, and how these costs translate into unit costs for users implemented over a future time period at an appropriate scale.

Asymmetry of information. There is fragmented and asymmetrical distribution of information amongst the different agents in the aviation sector. As the industry faces the prospect of further regulation, there is merit in greater exchange of information and knowledge amongst the various parts of the industry in order to promote industry scale responses to the management of environmental risk.

Responses to drivers. The analysis here confirmed the critical influence of fuel price and regulatory policies as these provide incentives to change. There remains considerable uncertainty how the various agents in the industry will respond to these drivers. It is clear that recent spikes in fuel prices renewed interest in fuel efficiency, indirectly helping to reduce fuel related emissions, and rekindling interest in fuel saving technologies. It is not clear how the more recent global economic downturn in late 2008, exacerbated for UK operators by falling £:US$ exchange rates, will continue to encourage fuel and emission saving practices.

An integrated approach. It is clear that analysis of the cost effectiveness assessment of abatement technologies must be placed in the wider context of the aviation industry as a whole, including aspects of business strategies and models, demand management, customer behaviour, air transport management, airport management, research management, and regional and industrial planning.

Policy Relevance

The projected baseline trends in emissions reflect current policies and expected responses to them, but do not include possible future policy interventions at the national, regional and global levels.

MAC indicate the costs that would be imposed on an industry by a mandatory regulation on emissions. MAC also indicate the likely response by industry to the introduction of pollution taxes or tradeable emission permits by defining the scope for cost-effective abatement, including negative cost, win-win opportunities. In this respect , the findings of this study may have potential to inform policy on the use of regulatory controls, or economic instruments such as fuel taxes, emissions charges or tradeable permits, as well as the promotion of improved practices, voluntary measures and targets and the funding of research and technology development.

Recommendations for Further Research and Knowledge Exchange

Six recommendations are made for consideration:

Review of data and methods. To further develop and scrutinise, under a joint government–industry initiative, the data and methods used here to assess the efficacy and costs of measures to reduce emissions with potential to cause environmental damage. This will draw on the science reviews conducted by the Omega Programme and engage the full breadth of stakeholders in the aviation sector.

Science review: To assemble the outputs of the current Omega Programme, together with the results of other ongoing research, to produce a state of science review that specifically supports the identification, appraisal and, where appropriate, promotion of abatement technologies.

Guidance: To develop and make available data and methods required to support the technical and economic appraisal of different abatement measures, drawing on available science.

Exemplars: To produce case studies, drawing on practical experience, to demonstrate feasibility, costs and benefits of abatement options suited to particular user groups and situations.

Policy aspects: To extend the type of analysis here to include a broader assessment of policy options, taking into account the possible responses of the industry to a range of policy and commercial scenarios.

Integration: Finally, it is recommended that the aforementioned initiatives with respect to environmental abatement are embedded within an integrated approach to managing the environmental performance of the aviation sector as a whole.

Closing remark

It is apparent from this scoping study that there is currently much interest in the concept of MAC both from the industry's viewpoint as it responds to environmental and commercial pressures, and from the governments viewpoint as it seeks to design environmental policies which achieve overall regulatory efficiency.

The derivation of Marginal Abatement Costs reported here represents a small part of a complex process that seeks to identify, prioritise and facilitate the development of effective options to improve the environmental performance of aviation. An understanding of the synergies and trade-offs amongst different technological, operational and policy approaches to managing the environmental effects of aviation is an important part of that process. Work elsewhere within Omega is exploring how engineering, physical and social sciences, including economics, can be integrated to help provide this improved understanding and a basis for policy and positive actions by a range stakeholders. Future work within Omega should examine how partnership work, in some cases at the feasibility level, on models and assessment processes can be developed into mutually beneficial broadly-applied decision support for the aviation sector

1.0 Introduction

This chapter explains the context, aim and objectives of the study.

1.1 Context

The aviation industry is both a product of and contributor to social and economic development at the global and national scales. Growth in the aviation sector strongly reflects the pace and direction of economic growth and prosperity. Simultaneously, however, environmental risks associated with aviation have increased, not only in terms of local air quality and noise impacts, but increasingly with respect to emissions such as CO_2, NO_x and contrails/cirrus cloud generation that have potential to cause global warming and climate change.

Although the contribution of aviation global emissions is relatively low at about 3% of anthropogenic CO_2 emissions, projections suggest that this contribution will increase to about 12% of total CO_2 emissions by 2050 (Kim *et al*., 2007). UK Air Passenger Demand and CO_2 Forecasts (Dft, 2007), for example, show aviation's share of UK climate change emissions increasing from between about 6% in 2005 to between 19% and 49% in 2050 using a range of policy scenarios.

Recent reviews by the IPPC (2006) and the Stern Review on the Economics of Climate Change (2007) argue that transportation, and the aviation sector in particular, must adopt measures to reduce emissions of green house gasses associated with climate change. Thus, there is a growing call to control the environmental risks of aviation, especially in the context of predicted future growth in traffic. In this context, there is a clear need to understand the feasibility and costs of controlling the environmental risks of aviation while simultaneously securing its substantial social and economic benefits.

1.2 Purpose, Aim and Objectives

The broad purpose of this study is to help inform cost effective strategies to control the environmental effects of aviation. The study aims to develop and apply an accounting framework to assess the feasibility and cost-effectiveness of measures to reduce the emissions to the environment of aviation. It seeks to do this by integrating the disciplines of economics, engineering and environmental science in a practical business context. This study focuses on emissions directly associated with the use of aircraft rather those associated with land-based air transport activities such as airport operations.

More specifically the objectives of the study are as follows:

(i) To identify the relationship between the characteristics of aviation, such as engine and airframe technologies, and environmental emissions, and the scope for improving the environmental performance of the aviation sector,

(ii) To determine, in broad terms at this stage, the cost effectiveness of alternative ‘programmes of measures’ to control environmental effects, and thereby the marginal costs of abatement,

(iii) An important methodological objective is to develop and apply an analytical framework which can be used for estimating the extra (marginal) costs of intervention measures to control environmental emissions

(iv) To determine the main technical trade-offs and interdependencies amongst different environmental effects, and the implications for assessing the cost effectiveness of interventions which affect different emissions in different ways,

(v) To identify the main knowledge gaps and uncertainties that need to be addressed to determine best least cost strategies for environmental abatement in the aviation sector, thereby making recommendations for further research on this topic.

1.3 Scope of Enquiry

The study is a scoping exercise which sets out to construct and populate the aforementioned analytical framework drawing on currently available data, knowledge and expert judgement.

The context and focus of the study are represented in Figure 1.1 which contains a 'conceptual model' to show the relationship between aviation characteristics, emissions, environmental impacts and measures to control emissions.

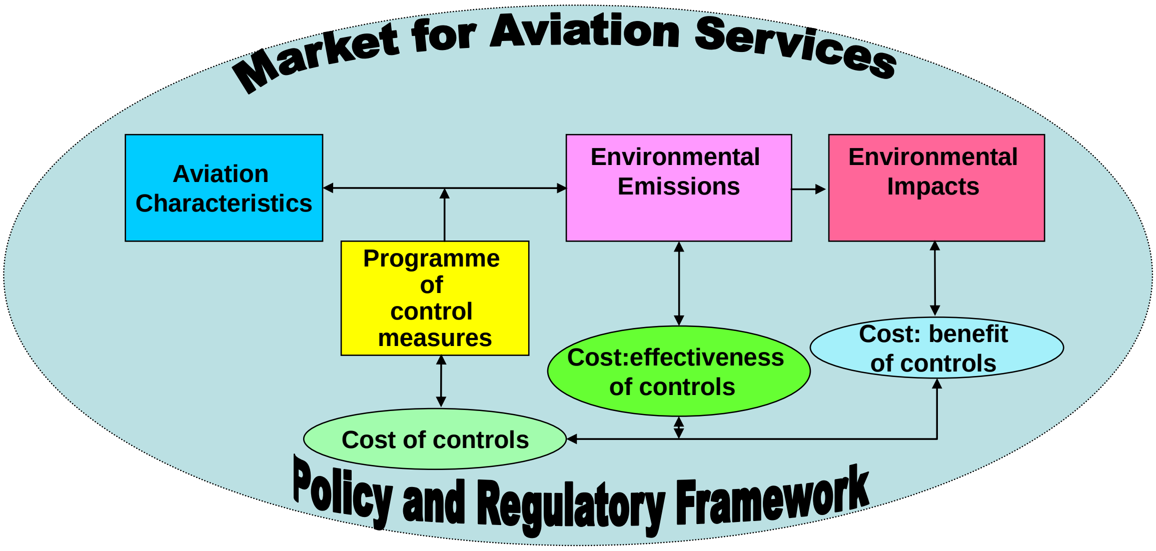


Figure 1.1 - A Conceptual Model for the Analysis of Measures to Control Emissions from Aviation

The characteristics of the aviation sector, described in terms of types of airplanes and aviation services that can generate emissions such as Carbon

Oxides (mainly CO_2), Nitrogen Oxides, water vapour trails (contrails) and noise. These emissions have potential to cause environmental and health impacts and associated social and economic consequences.

The relationship between aviation and emissions can be controlled by abatement measures. These measures are likely to result in additional costs borne by the aviation sector, although some costs may be offset by savings due to fuel and operational efficiency gains. Estimating the costs of measures can be complex. For example, reducing the interval between maintenance can improve fuel efficiency, but this may increase capital investments in aircraft due to increased down-time and lower flight-time capacity.

The ratio between extra costs and abatement of emissions provides an estimate of the cost-effectiveness of a control measure. Alternative controls can be assessed in terms of relative cost-effectiveness for specified emissions, such as CO_2 , NO_x or noise. Some measures may, however, result in reductions in one type of emission but increases in another. For example reduced CO_2 emissions may result in increased NO_x or noise. This requires consideration of trade-offs amongst emission types.

Where it is possible to ascribe a monetary value to environmental impacts associated with emissions, such as that indicated by the social cost of carbon ($/t CO_2 equivalent) for example, benefit:cost ratios for alternative control measures can be derived. The analysis here, however, focuses on the cost-effectiveness of measures to reduce emissions. This is relevant where the purpose is to determine the best, least-cost ways of meeting prescribed limits on emission limits. The benefit:cost analysis of abatement options is a logical next step for further research.

Figure 1.1 also shows that decisions to control aviation emissions are strongly influenced by market conditions for aviation services, and by national and international policy and regulatory regimes. The latter include compliance with noise and emission limits and possible entry of aviation into international carbon trading schemes.

The study seeks to understand and explain the relationships amongst the components in Figure 1.1 with a view to informing strategies for achieving cost:effective measures to reduce emissions and hence the environmental burden of aviation.

1.4 Structure of the Report

This Main Report comprises 7 chapters. Following this introduction, Chapter 2 reviews the concept of Marginal Abatement Costs applied to the aviation sector. The chapter also reviews the main characteristics of aviation and associated emissions to the environment, summarising previous work on estimation of abatement costs. Chapter 3 identifies a range of possible abatement measures to reduce aviation emissions, drawing on consultation with stakeholders. Chapter 4 summarises the methods developed to derive MAC for programmes of interventions to reduce emissions compared with a “do-nothing” scenario. Chapters 5 and 6 contain case studies demonstrating the application of the method, for the UK domestic and European-based International aviation sectors respectively. Chapter 7 draws out the main conclusions and recommendations from the study, identifying gaps in knowledge and main uncertainties. The Main Report is supported by a number of Technical Appendices that deal with particular details of the work.

2.0 Controlling Environmental Emissions from Aviation

This chapter explains the concept of Marginal Abatement Costs (MAC) applied to the appraisal of interventions to reduce emissions from aviation. It briefly reviews the main characteristics of aviation as these influence environmental emissions and the methods used to derive estimates of emissions. The chapter summarises other studies that have assessed abatement options in the aviation sector.

2.1 Marginal Abatement Costs

The main purpose of calculating marginal abatement costs is to determine the most cost effective measures that can be taken to reduce emissions (Tietenberg, 2007). Figure 2.1 illustrates the approach. The MAC curve shows the extra cost per unit of emission reduction, in this case £/tCO_2, by successive amounts within a given time period, such as one year. In ranking the individual measures according to their cost-effectiveness, the MAC curve tends to increase in steepness as successive interventions are more expensive per unit of abatement (£/tCO_2).

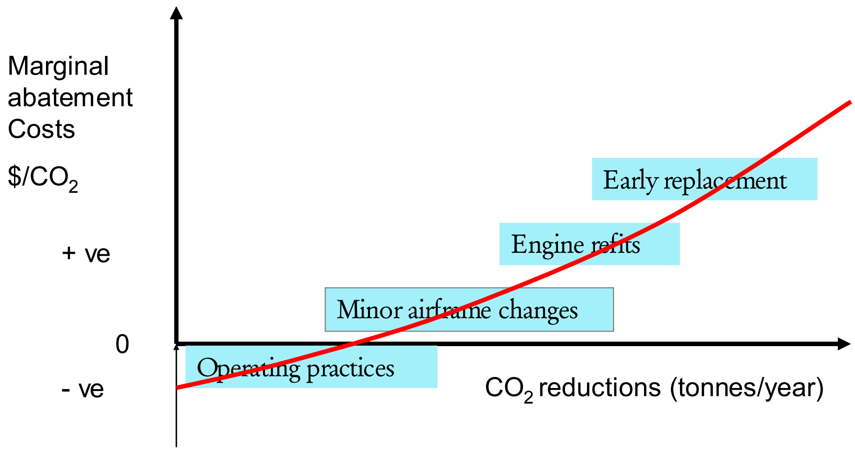


Figure 2.1 - Marginal Abatement Costs can Guide Selection of Least-Cost Interventions to Reduce Emissions from Aviation

It makes sense to adopt interventions in order of their marginal costs. In the case of CO_2, emissions are strongly and positively correlated with fuel consumption. Most abatement measures for CO_2 reduction are associated with improvements in fuel efficiency.

Figure 2.1 shows that some initial abatement options for aviation, such as change in operating practices to improve fuel efficiency, may offer "win-win" opportunities, with negative marginal abatement costs. Here, savings in fuel costs exceed the cost of adopting the intervention. Beyond the 'win-win' options, achieving further reductions will involve extra net costs per unit of emission. Marginal abatement costs might be expected to be relatively small for technical improvements to existing aircraft such as 'winglets' fitted on wing tips to provide additional lift in flight. They are likely to be higher for engine replacement and accelerated fleet replacement, and probably much higher and more uncertain for longer term developments in airframe and engine technology.

The construction of the marginal abatement cost 'curves' is a critical component of the strategic analysis of environmental policy options for aviation at a national and global level. They can show the relative ease and expense with which the aviation industry can reduce its emissions. They can indicate the financial burden on the sector of compliance with more stringent limits on emissions, such as CO_2 or NOx. Furthermore, in the event of aviation being subject to fiscal measures such as environmental taxes or tradeable permits, the MAC curve (as shown in Figure 2.2) indicates the extent to which the industry will find it advantageous to adopt measures to control emissions, or alternatively pay emission taxes or purchase emission permits. The MAC curve also shows additional net costs (whether by direct abatement or payments of taxes or permits) that would be borne by the aviation sector, and that eventually, in the absence of gains in efficiency, airlines will seek to pass these costs on to customers. Higher prices for services are likely to induce some cut back in demand for aviation services, everything else remaining constant.

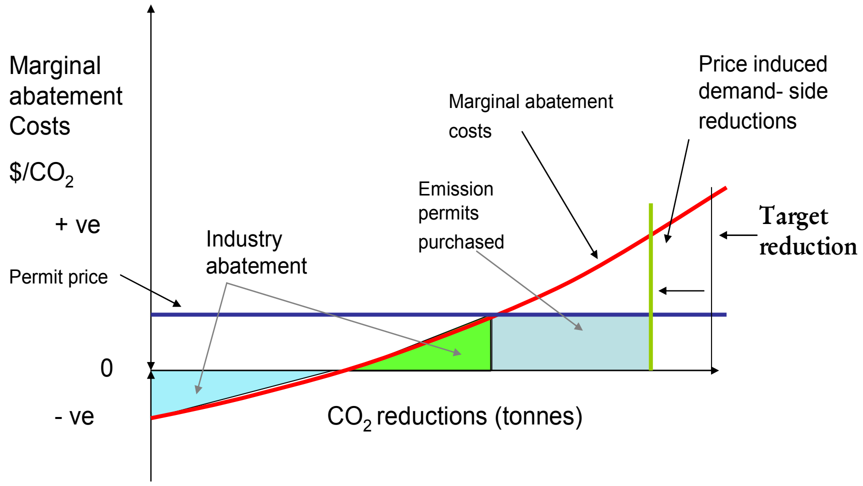


Figure 2.2 – The MAC curve shows the cost of abatement compared with the payment of an emission tax or permit.

MACs for aviation are part of a dynamic process of adjustment, as shown in Figure 2.3. Aviation emissions are strongly correlated with fuel use such that the cost effectiveness of interventions depends critically on current and future fuel prices: higher fuel prices for the most part reduce MAC for CO_2 for aviation.

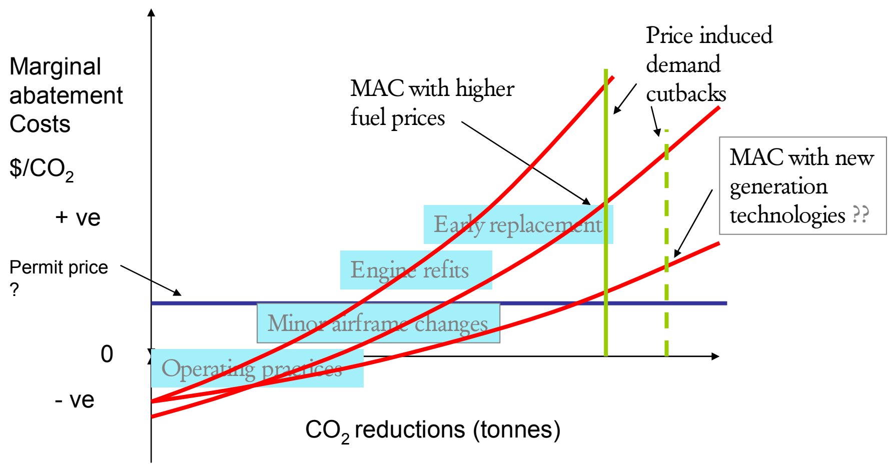


Figure 2.3 - Marginal Abatement Costs for reducing CO2 from aviation are likely to fall with increasing fuel price, and over time, due to the adoption of new 'cleaner' technology.

Furthermore, there will be inducements to drive down MAC through further changes in technologies and operating practices, through for example improved fuel efficiency. In this respect, an understanding of MAC for the control of aviation emissions is a key element of strategic management for the aviation sector, especially regarding investments in research and technology development for the future.

Characteristics of Aviation Activities

Civil aviation activities can be distinguished by the purpose and length of journeys, namely passengers and cargo, and short (<1000 km), medium (1000 - 2500 km) and long haul flights (> 2500 km). Although, there are distinct passenger and cargo carrier markets, many passenger airlines, particularly those on long haul operations, also carry some cargo on their aircraft to augment revenue, so the distinction between passenger and cargo activities is blurred. However, freight aircraft are exclusively for the carriage of cargo, mainly high value time-sensitive goods.

Currently, passenger carrying activities account for 88% of the revenue generated by the global airline industry, with freight activities generating the other 12% (IATA, 2007). For the purposes here, passenger aircraft are assumed to be exclusively for passengers and freight aircraft for cargo hauling activities.

Within these broad classifications of passenger and freight activities there are different markets, which relate to the geographical link between the departure and destination locations. These markets, such as Intra Western Europe and Western Europe- Asia, differ in terms of the average distance from point of origin to final destination and the size of the market in terms of the quantities of passengers or tonnes of freight carried. Thus, airlines and freight operators require different aircraft characteristics for different markets.

Aircraft manufacturers produce aircraft to satisfy the key operational requirements for different markets. Thus, aircraft designs tend to converge. Aircraft designed by different manufacturers to operate in the same market have similar performance in terms of range and payload characteristics (Hutcheson, 1996). This is an important point. By selecting the most representative aircraft in a given market, it is possible to determine marginal abatement costs for one aircraft that are likely to be indicative of most aircraft that carry out the same activity. This approach has been used in this study for the analysis of the UK domestic and European international sectors, as presented later. Table 2.1 lists the categories of aircraft and the number of aircraft worldwide in service within each category (excluding Russia and the Commonwealth of Independent States (CIS).

Table 2.1 - Aircraft in Service in 2006 by Manufacturer's Classification

Manufacturer classification	Size	Number of aircraft in service	% of total aircraft in service
Twin aisle	Large	580	3
	Medium	1180	7
	Small	1310	7
	Total twin aisle	3070	17

Single aisle	>175 seats	1290	7
	90-175 seats	8890	49
	Total single aisle	10180	56
Total regional jets		3000	16
Total passenger fleet		16250	89
Total Freighter fleet		1980	11
Total fleet		18230	100

Source: Boeing (2007) Current Market Outlook

Table 2.1 shows that 56% of aircraft are single aisle and are used to undertake short to medium range journeys, while 11% of aircraft are used as freighters. The two main airframe manufacturers, Airbus and Boeing, have developed families of aircraft, which can be characterised by their technical characteristics suited to particular markets.

Table 2.2 lists aircraft according to technical characteristics, excluding (50 seater) regional jets and aircraft that are currently out of production. A full listing including the latter (but excluding CIS) is given in Appendix 2.

Table 2.2 - Aircraft Model Currently in Production by Type, Model, and Numbers

Boeing classification	Aircraft model	Approx. range (nm*)	no. of engines	Engine max thrust Kn/hour	Number of seats in 3 class configuration	Numbers in service
Single aisle	A318	1500-2800	2	133.45	90-175	46
Single aisle	B737-600	1910-3195	2	86.74	90-175	69
Single aisle	A319	1900-3800	2	111.2	90-175	990
Single aisle	A320	1850-3100	2	111.2	90-175	1747
Single aisle	B737-700	2585-3260	2	86.74	90-175	866
Single aisle	B737-800	1990-3095	2	86.74	90-175	1235
Single aisle	B737-900	2060-2745	2	86.74	>175	52
Single aisle	A321	2300-3000	2	140.56	>175	407
Single aisle	B737-900ER	2700-3200	2	86.74	>175	5
Twin aisle small	B767-300ER	5700-6250	2	252.4	180-250	561
Twin aisle small	A330-200	6450-6750	2	297.44	180-250	268
Twin aisle medium	A330-300	4500-5650	2	297.44	250-370	226
Twin aisle medium	A340-600	7900	4	263.9	250-370	210
Twin aisle medium	A340-300	7400	4	138.78	250-370	77

Twin aisle medium	B777-200	3970-5210	2	369.3	250-370	84
Twin aisle medium	B777-200ER	6030-7750	2	411.48	250-370	398
Twin aisle medium	B777-300	4055-5960	2	424.1	250-370	60
Twin aisle medium	A340-500	9000	4	263.9	250-370	25
Twin aisle medium	B777-200LR	9400	2	492.8	250-370	9
Twin aisle large	B747-400ER	7300-7960	4	264	>400	32
Twin aisle large	B747-8	8000	4	293	>400	0
Twin aisle large	A380-800	5620-8000	4	340	>400	1

*Nautical miles (nm) Aircraft in operation from Air Ascend database: http://www.ascend-air.com/Air/LandingPage.aspx : excludes all aircraft held by lessors, privately owned or owned by government.

Table 2.3 shows that larger aircraft with greater engine power are typically used for longer journeys. This classification also holds true for freight aircraft, as generally operators use older aircraft models ‘passed down’ from passenger fleets. Classification of aircraft according to seat number provides a basis for distinguishing between aircraft categories and a justification for selecting ‘representative’ aircraft which are indicative of a range of similar aircraft used on similar type of work (Table 2.3). Appendix 2 contains the models and numbers of aircraft used in each market.

Table 2.3 - Representative Aircraft for Aviation market segments

Category of Aircraft	Model	Representative aircraft as a % of total number in service in a given category	Average age (years)
Regional Jet	Bombardier CRJ 100/200	29	8.4
Regional Jet	Fokker 100	9	16.4
	Total percentage	38	
Single aisle 90-175	A320	18.1	7.8
Single aisle 90-175	B737-300	10.8	16.2
	Total percentage	28.9	
Single aisle > 175	A321	25.9	6.17
Single aisle > 175	B757-200	59.9	13.8
	Total percentage	85.8	
Twin-aisle small	A300-600	15.1	14.29
Twin-aisle small	B767-300ER	30.8	10.97
	Total percentage	45.8	
Twin-aisle medium	A330-300		
Twin-aisle medium	B777-200ER		
	Total percentage		
Twin-aisle large	A380-800	0.1	0
Twin-aisle large	B747-400	51.4	13.13

Total percentage	67.2

2.3 Emissions from Representative Aircraft

Figure 2.4 shows the range of emissions generated by aircraft in use. Some emissions have an impact on land and water quality, some affect local air quality, and others have an impact on the global atmosphere.

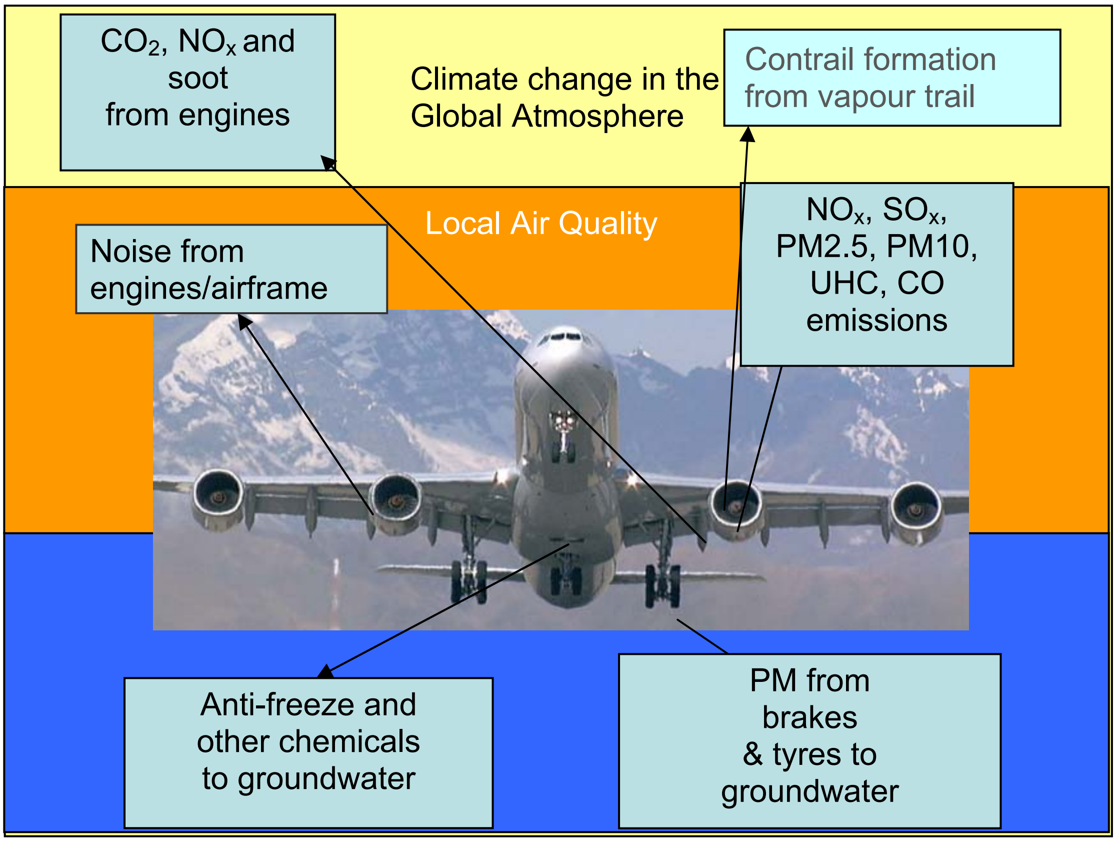


Figure 2.4 - Main Environmental Emissions from Aircraft Flight Activities

Emissions of hydrocarbons (HC), nitrogen oxides (NO_x), carbon monoxide (CO), smoke, particulate matter (PM) and noise are of concern to regulatory authorities, especially those responsible for controlling local air and environmental quality (Tesseraux, 2004). CO_2 emissions are of concern at the global scale because of their Global Warming Potential. Aviation is also associated with the terrestrial impacts of airport development, including local traffic issues, but these are not considered here.

Most emissions are attributable to the combustion of hydrocarbon fuel by aircraft. The products of combustion from a typical modern jet engine are shown in Figure 2.5.

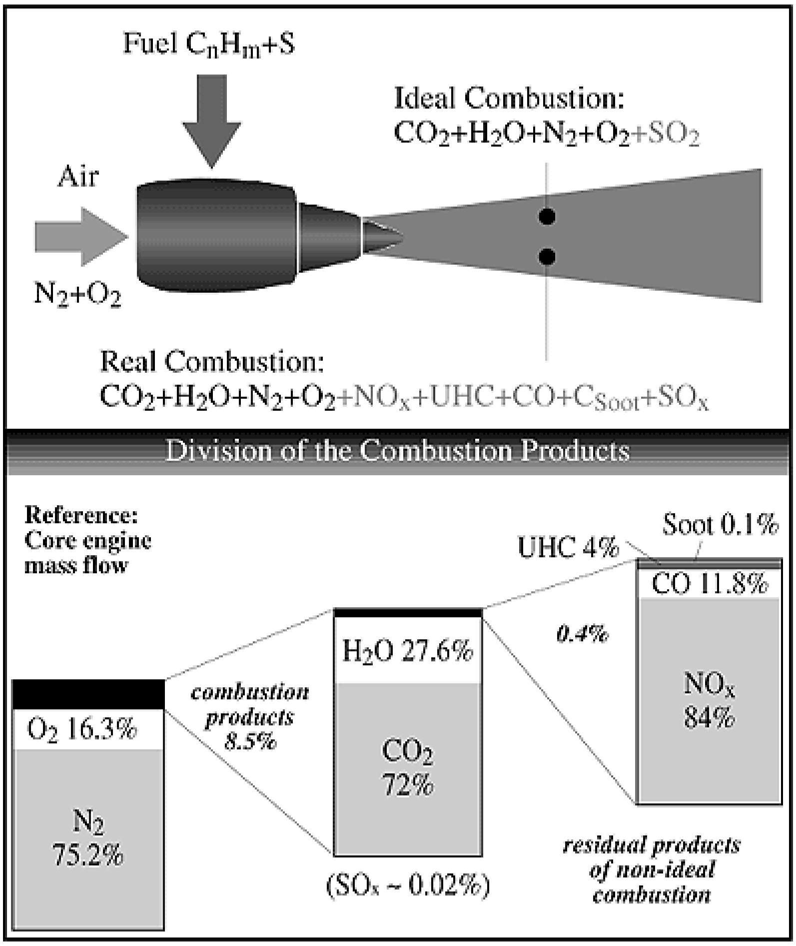


Figure 2.5 - Schematic of Ideal and Non-Ideal (All Existing) Products of Combustion in a Typical Modern Jet Engine: from IPCC, 1999

There are synergies and trade-offs amongst environmental emissions: CO_2 emission and fuel use are highly positively correlated. CO_2 can, however, be negatively correlated with NO_x, noise, and contrails. Broadly, more fuel efficient, low CO_2 emission engines, run hotter such that high temperature exhaust interacts with atmospheric gases to create a more diverse cocktail of non-CO_2 gases and water vapour.

Although emissions per aircraft have declined over time, air traffic has increased more strongly, such that overall emissions from aviation are increasing. For example, although estimates vary, the aviation industry contributes about 3% of anthropogenic CO_2 emissions (Scheelhaase and Grimme, 2006) and that in 2001 that aviation generated 3·5% of total human-induced global warming (Woodcock *et al*., 2007). Although the contribution of aviation global emissions is relatively low (aviation contributes 5% of total CO_2 emissions from transport) compared with CO_2 emissions (65%) from motor cars (Chapman, 2007), projections suggest that this contribution will increase, with aviation contributing about 12% of total CO_2 emissions by 2050 (Kim *et al*., 2007). UK Air Passenger Demand and CO_2 Forecasts (Dft, 2009) show aviation's share of UK climate change emissions increasing from 5.4% to 6.3% in 2005 to 19% to 49.2% in 2050 using a range of policy scenarios

2.4 Estimating Emissions from Aircraft

It was hoped to combine the range of emission species into a common unified metric, such as the CO_2 equivalent (CO_2e) used for measuring greenhouse gases (GHG's). However, for the purpose of this study, using a single unit to compare and combine emissions was deemed inappropriate for two main reasons. First, although the emissions of indirect greenhouse gases, such as NOx, can be estimated, it is the cocktail of gases that they generate that produces the total climate impact. The science on the transition from pre-cursor gas to GHG, at altitude, through aviation, is not sufficiently defined (IPPC 2006) to enable a CO_2 equivalent to be reliably determined. Second, several of the emission specious have primary effects which relate to Local Air Quality (LAQ) with very different potential toxicity depending on the sensitivity of local receptors. A comparative metric between different LAQ related emissions would need to capture impact on human health. There is insufficient information available at present to fully quantify the range of effects associated with aviation emissions. For these reasons, it was not possible to derive a common metric to measure emissions. One way of combining or comparing the various effects of different emission species would be to assess the costs of their various impacts. This is an important topic for further research.

Two broad approaches have been adopted to estimate emissions from aircraft. One commonly applied approach, and that used by IPPC, involves the use of standard estimates of emissions for given types of engine/airframe combinations that have been derived from ground-based testing carried out for example under the supervision of ICAO (1995) that simulate the stages of the Landing-Takeoff (LTO) and Cruise Cycle (Figure 2.6). The European Environment Agency's EMEP/CORINAIR Emission Inventory Guidebook 2007 (EEA, 2007) provides these standard estimates of fuel use and a range of emissions species for selected aircraft for LTO stages, and separately for given cruise distances. The guidance outlines methods for estimating emissions from aircraft activities for three levels of detail: very simple, simple and detailed. The latter involve combining detailed information on aircraft type, distances and frequencies with standard estimates of fuel use and emissions. (The European case reported later adopted used CORINAIR sources to estimate baseline emissions).

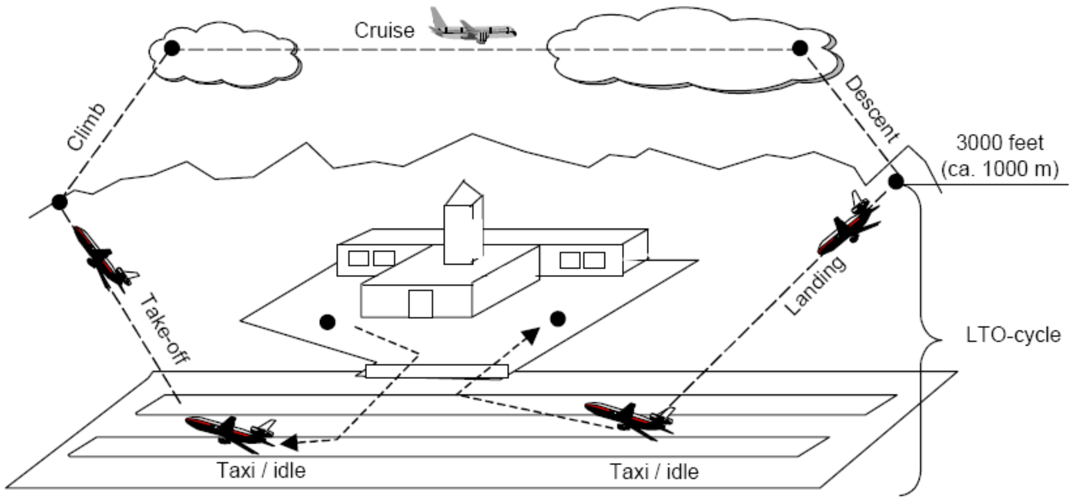


Figure 2.6 - Fuel Consumption and Emissions vary through the Landing/Take-Off and Cruise Cycle (source: EMEP/CORINAIR in EEA 2006)

Another approach involves the use of proprietary flight/aerospace models that simulate fuel consumption and emissions for given engine, airframe and operational parameters. These models work from first principles and are used essentially to assist initial aircraft design and performance appraisal. They can be used to assess the effect of abatement measures on fuel use and emissions where a clear link can be made to a particular design or performance parameter, such as take off weight. But they are not suited, for the most part, to handle abatements which involve modifications to existing aircraft. (The UK case study reported below, used PIANO (2008) and FAST (-Gauss et al, 2006) models to derive baseline estimates of fuel use and emissions)

There is no existing consolidated data base or protocol that considers the impact of abatement interventions on fuel consumption and emissions during the LTO-Cruise cycle for given aircraft operating particular routes. This study has addressed this aspect.

Table 2.4 contains estimates of emissions of GHG emissions for a typical LTO (excluding cruise) cycle by aircraft.

Table 2.4 - Default Fuel Use and Greenhouse Gas Emission Factors for Selected Aircraft over the Landing Take Off Cycle (kg/LTO)

Aircraft type	CO_2	CH_4	N_2O	NO_X	CO	NMVOCs	SO_2	Fuel
BAe 146	1800	0.16	0.1	4.2	11.2	1.2	0.6	570
A300	5470	1.0	0.2	27.21	34.4	9.3	1.7	1730
A320	2560	0.04	0.1	11.0	5.3	0.4	0.8	810
B737	2750	0.5	0.1	6.7	16.0	4.0	0.9	870
B747	10145	4.8	0.3	49.2	115	43.6	3.2	3210

Source: IPCC Guidelines on National Greenhouse Gas Inventories. Reference Manual

2.5 Predictions of Future Air Traffic

Future emissions by aircraft will depend on the type and volume of traffic, the introduction of fuel saving and/or cleaner technologies, changes in practices, and changes in the composition of the fleet. Air traffic is expected to grow. IPPC (1999) estimated that global passenger km will grow by 5% annually through to 2015, with fuel consumption growing at a lower 3% due to efficiency gains. UK Dft (2007) forecasts of UK domestic sector traffic and International traffic (using UK terminals) average about 3.5% and 5% per year respectively through to 2020. These estimates have been used in the UK and European case studies reported below.

2.6 Predictions of Future Emissions

The main driver of increased emissions and the climate change and local air quality consequences of these is the growth of aviation activity. As the demand for aviation increases in the next decades, emissions from aviation will rise. However emissions are not projected to increase in line with traffic growth for a number of reasons. With carbon dioxide, fuel prices represent a strong commercial driver in stimulating improved fuel efficiency. Recent increases in fuel prices have changed the cost effectiveness of some abatement measures and the view taken on future trends in fuel prices will be important in determining the baseline trend in CO_2 emissions. In addition policy measures such as the inclusion of aviation in the EU ETS, the implementation of the Single European Sky (SES) and voluntary measures such as the ACARE research goal for a 50% improvement in fuel efficiency between 2000 and 2020 will also be influential. For NOx on the other hand there is no strong commercial driver and the main influences on future trends will be policy measures such as the progressive tightening of ICAO standards and the ACARE target of an 80% reduction in NOx emissions over the 2000-2020 period.

Carbon dioxide emissions

The future level of CO_2 emissions will depend on underlying trends in fuel efficiency. The ACARE targets identified goals to be achieved by 2020, and work has started on longer term targets. For CO_2, these included a target 50% reduction in aircraft fuel consumption and emissions, with contributions of 20-25% from airframes, 15-20% from engines and 5-10% from optimising ATM. Evolutionary developments were seen by ACARE as capable of achieving less than half the improvements required to meet these ambitious targets, with technological breakthroughs, likely to have high costs and risks attached to them necessary to achieve the step change improvements needed to meet the targets in full.

The UK Air Passenger Demand and CO_2 forecasts published by DfT in November 2007 developed a methodology for forecasting UK carbon dioxide emissions and included forecasts for 2030, projected forward to 2050. These can be interpreted as underlying or baseline trends in fuel efficiency. Historically improvements in fuel efficiency have averaged 1-2% pa. In making forward projections, DfT took the ACARE target 50% reduction in fuel consumption per passenger km by 2020 as their starting point. With almost 10% of fuel savings expected to arise from operational improvements with the implementation of SES, new aircraft entering service would need to achieve a 40% reduction in fuel consumption relative to their current equivalents to meet this target (current new state of the art aircraft such as A350s and B787s are estimated to consume 20% less than their current equivalents). The DfT central case assumption was that the share of new aircraft that are ACARE compliant rises from 5% in 2020 to 25% in 2030. This results in a reduction of fleet fuel consumption of approximately 25% between 2007 and 2030 (1% pa) attributable to ACARE compliance. Over the longer term from 2030 to 2050 continued propagation of ACARE compliant aircraft is assumed, resulting in a trend improvement of 0.8% pa over this period. These forecasts result in an overall growth of carbon dioxide emissions of 1.8% over the period 2005-2030, slowing to 1.1% over the entire period of 2005-2050 in the central case.

A recent study by Qinetiq (2009) for the Committee on Climate Change on Aviation CO_2 Emissions Abatement Potential from Technology Innovation assessed the likely scale of fuel efficiency from abatement measures. These identified:

- 35-45% reduction in fuel consumption per passenger km across the production fleet by 2025 (20-30% by 2020) from evolutionary airframe and engine improvements
- An additional 15% reduction from radical concepts such as open rotors and blended wing bodies
- 10-15% reduction from ATM and operational improvements by 2025
- Taken together evolutionary aircraft and engine improvements together with ATM and operational changes offer a 40-50% in new production aircraft in 2025, with an additional 15% from more radical concepts.

These technology improvements identified by Qinetiq are consistent with the annual reductions in 1.5% fuel consumption assumed in the Constrained Aviation Scenarios as part of the EU CONSAVE Project (REF) . They are also in line with the ACARE research target of a 50% reduction in fuel consumption by 2020, assuming a more aggressive uptake scenario.

NOx Emissions

The main driver for improvements in NOx has been the expectation of tighter standards for NOx emissions in the LTO phase introduced by ICAO. This has resulted in significant improvements in aircraft engines with lower emissions of NOx per unit of thrust at constant pressure ratios.

There is a correlation between LTO and cruise emissions for current engine and combustor designs which has resulted in a reduction in aircraft engine NO_x emissions. In spite of more stringent standards, there has been little progress in reducing NO_x emissions per seat kilometre because aircraft have become more fuel efficient with the resulting increase in engine pressure ratios permitted under the ICAO standards. These standards allow engines with higher pressure ratios to emit more NO_x per unit of thrust. As a result, NO_x emissions per seat kilometre have remained relatively constant over time.

For the future, the inclusion of aviation in the ETS and the implementation of air traffic management improvements, such as Single European Skies, will have the effect of reducing NO_x emissions as well as CO_2 relative to baseline trends. In addition, progress in incorporating ACARE targets for NO_x in the aircraft fleet will lead to further improvements, though this will be limited prior to 2020. The key driver in the period up to 2050 will be the rate of uptake of ACARE targets. Even under conservative assumptions on uptake, NO_x emissions are likely to grow significantly more slowly than air traffic.

2.7 Evidence of MAC for Aviation

A review of academic and industry literature, reported in Appendix 1, confirms the importance of estimating marginal abatement costs in order to inform strategies for controlling emissions, but most point to limited information to enable this.

Measures to reduce aircraft emissions (mainly CO_2) that have been identified (Stratus Consulting, 2005), and in some cases evaluated, include:

- Technological changes, e.g. airframe design, engine design
- Maintenance, e.g. reduced maintenance intervals
- Operational, e.g. modifications to air traffic management

These options have implications for costs and benefits to the operators, including impacts on operational costs such as flight crew costs. Some measures to improve fuel efficiency and thereby reduce CO_2 emissions appear potentially cost-effective in their own right. Some studies suggest that relatively small fuel levies would be sufficient to encourage abatements.
The possible inclusion of aviation in carbon trading schemes has promoted interest in abatement potential, comparing costs of abatement with the option of purchasing emission permits. In the absence of formal analysis of the kind reported here, the consensus appears to have been that abatement costs are relatively high for aviation, such that the sector would opt for purchasing permits rather than abatement, at least in the short term.

The net additional costs of adoption of abatement measures would need to be recovered by higher ticket prices to passengers. Higher prices could lead to reductions in demand for air travel depending on the sensitivity of demand to prices changes, influenced, for example, by the price and availability of alternative transport solutions. Such price-induced demand management is seen by some as an important component of the sustainable management of aviation. Others are concerned that curtailing consumption could unduly compromise the social and economic benefits generated by the aviation industry (Omega Project 40).

Two recent studies explored the costs of abatement in the aviation sector in some detail, mostly in the context of possible imposition of fiscal measures to control emissions or inclusion of aviation in emissions trading schemes. Stratus Consulting, (2005) developed a spreadsheet model to construct a total abatement cost curve that considers the relative cost-effectiveness of emissions control measures. The study usefully classified interventions into technological, maintenance and operational measures. They identified a hierarchy of interventions with increasing MAC, some of which included win-win options. It was shown that relatively small fuel levies would induce reductions in emissions. The study favoured emissions trading because this would allow airlines to purchase permits from other industries more cheaply than undertaking direct abatement themselves. The Stratus study confirms the critical role of fuel prices as they affect MAC. The data and methods used in the Stratus study are not in the public domain.

ICAO (2004) considered the capital and operating costs of 'fixing' all non-compliant aircraft to meet tighter NO_x emission standards. Information was obtained from manufacturers on the extent of technology development required. The study did not develop MAC curves as such. ICF Consulting (2006) considered emissions abatement potential and costs for major aviation sub-sectors. The study noted that information is limited on the marginal costs of measures to reduce emissions, although they suggest that abatement potential exists within the sector.

Much of the debate in the UK about the environmental impacts of aviation makes reference to the important social and economic benefits for the national and local economies. UK aviation makes an estimated £9.5 bn to £11.4 bn value added contribution to the UK economy, supporting 186,000 direct jobs and £13 bn exports. An estimated £11 bn worth of spend by foreign tourists is associated with visitors travelling by air. International travel by air is now more accessible to the UK population as a whole.

The UK aviation sector contributes about £1bn to infrastructure costs through the air passenger duties, but taxation is not levied on aviation fuel. UK Government estimates environmental costs of emissions of aviation to be £1.6 bn in 2005, possibly rising to £4.1 bn in 2030 (2006 values). There is scope and justification for the industry to reduce its environmental impacts, but it is not clear how this might best be achieved: hence the debate on technology, management and policy options.

2.8 Summary of Main Points

The compilation of MAC for aviation can help to identify cost-effective interventions for the abatement of aviation emissions. In this context the following points can be made:

- It is expedient to classify aviation activities by aircraft models that represent particular types and categories of use. Essentially these are based on number of passenger seats, namely less than 70, 70-150, 150-250, and above 250 seats, and on the length of journey, whether short (less than 1000 km), medium (1000-2500 km) or long haul (over 2500km).
- Air traffic forecasts are available from international, government and industry sources, in some cases including forecast of fleet composition, although it is difficult to match these with subsector growth needed for estimating MAC for interventions.
- Estimates of the range of emissions from aircraft are available from three major sources, namely ICAO and related mainly ground based test results, estimates provided by manufacturers and modelled results using proprietary software. These vary in the coverage of emission types and the different stages of the LTO and cruise cycle, and in suitability for estimating MAC for specific interventions.
- Various regulatory and industry organisations have predicted or assumed that the aviation sector will be able in future to achieve improvements in fuel efficiency, reduce CO_2 emissions and meet more stringent NOx emissions standards, in some cases by as much as 1-2 % per year over the next 25 years. It is not clear whether such improvements are technically or commercially feasible. Much depends on the inducements provided by fuel prices and environmental regulation. The derivation of MAC can inform this process.
- There is considerable interest in estimating MAC for aviation in order to help inform policies on the possible use of mandatory regulation, environmental taxes and tradeable emissions permits. There are, however, limitations of data and methods required to estimate with confidence the net costs, effectiveness and likely take up of measures to reduce emissions. It is particularly difficult to estimate MAC for medium to long term technological changes that require considerable upfront investment in research and development and possible changes in behaviour, both by service providers and users.

- Fuel prices are a key driver of emission abatement.

3.0 Options and Stakeholder Views

This chapter identifies and categorizes the abatement measures to reduce emissions from aircraft, with particular reference to C02. The feasibility of these options is explored, including their likely take-up, barriers to implementation, timeframe and interdependencies with other emissions.

3.1 Approach

This assessment is based on knowledge gained from academic and industry published research and the expert judgement of key aviation stakeholders obtained through consultation. The latter involved (i) a workshop attended by 10 representatives of the manufacturing, aviation services and research communities and (ii) an electronic survey, followed up by telephone discussions, of 20 respondents from airframe and engine manufacturing, carriers, air traffic management, aviation services and research organisations.

During consultation, stakeholders identified the following criteria for judging the suitability of interventions to reduce environmental emissions from aircraft:

- effectiveness in reducing emissions
- Capital and operating cost of abatement measure
- Impact on safety and aircraft reliability
- Impact on airworthiness certification
- Operational practicability
- Industry familiarity with the measures
- Customer acceptance

These criteria were used to inform the feasibility of possible intervention options.

3.2 Categories of Intervention Options

A review of literature and preliminary discussions with key informants identified three main categories of intervention measures to reduce environmental emissions. While in the past most attention was paid to reducing emissions that have impacts on local air quality, notably noise and particulates, attention has more recently turned to controlling emissions of CO_2 as a global Green House Gas (GHG). More attention has also been given recently to controlling NOx emissions as they affect both local and global (via impact on ozone) air quality For this reason, attention is focused here on measures to reduce fuel consumption and hence CO_2 emissions, while noting the scope for reducing other species of emission species, as well as noise.

Table 3.1 shows the range of possible intervention measures, covering timescale of likely implementation, likely effects upon aircraft performance and costs. The table also identifies linkages between interventions, using interventions ID code, and the effect that an intervention might have on other non- CO_2 emissions.

Table 3.1 - Summary of abatement intervention characteristics and effects

abatement interventions				timescales			change drivers			areas of effect					linkages	
group	sub-set	intervention		now	pre 2020	post 2020	weight	drag	lift	fuel use	capital costs	maintenance costs	crew costs	journey time	interventions	emissions
technologies	airframe	winglets	T1	√	√		+	-	0	-2.00%	+	+	0	0	F1	- NOx
		riblets	T2		√		+	-8.00%	0	-	+	++	0	0	T6	- NOx
		tailcone replacement	T3	X			-	-	0	-0.50%	+	0	0	0		- NOx
		lightweighting - new aircraft materials	T4		√		-15%	0	0	-	+++	?	0	0	F1	- NOx
		lightweighting - existing aircraft systems	T5	√			-0.50%	0	0	-	+	0	0	0		- NOx
		blended wing	T6			X	-14%	+	+	-30%	+++	+	+	0	T4, F1	- Noise, - NOx
		aircraft surface polish	T7	√			-0.15%	0	0	-0.1 to 0.75%	0	+	0	0	F3	- NOx
	engine	engine replacement	T8	√			0	0	0	-0.5% / year of engine	++	-	0	0	T10	?
		engine upgrades	T9	√			0	0	0	ave 1%	++	-	0	0		+ NOx
		open rotors	T10		√		+			-30%	++	+	0	+	F1	+ Noise - NOx
		APU removal operation / design	T11		√	√	-	0	0	-110 kg / hr APU use	0 / ++	0	0	0	F1	- NOx
	fuels	biofuels	T12		√		0?	0	0	~	+++	+	0	0		- NOx
		alternative fuels	T13			√	+?	0	0	~	++++	+	0	0?	T12, T8	?
	general	optmised aircraft design	T14		√		-	0	0	-30%	++	-	0	0/+?	F1, F6, F9	+ Noise - NOx
operational improvements		ATM improvements	O1				0	0	0	-10.5%	++++	+	0	-	O2, O3	- Noise, - NOx
		continous decent approach	O2	√	√		0	0	0	-	++	0	0	0	O1	- Noise, - NOx
		optimise flight - speed & altitude	O3		√		0	0	0	-0.2%	0	0	0	+	O1	+ NOx
		optimise flight - LTO practice	O4	√			0	0	0	-	0	-	+	0		- NOx
		reduced fuel tankering	O5	√			-	0	0	-0.4%	0/+	0	0	0		- NOx
fleet management		retirement of aircraft	F1				0?	0?	0?	-1% / year of aircraft	++	0?	0	0	T1,4,6,10, 11,12,13,F6	- Noise, - NOx
		maintenance - engine intervals	F2	√			0	0	0	-1.2%	0	+++	0	0	F4	- NOx
		maintenance - aerodynamics	F3	√			0	-	0	-0.46%	0	+	0	0	Meng	- NOx
		maintenance - engine wash	F4	√			0	0	0	- 0.5 to - 1.2%	0	++	0	0		- NOx
		fuel reserves	F5	?			-	0	0	-	0	0	0	0	O1	- NOx
		increase turboprop use	F6		√		-	0?	0?	-	-	+	-	+	F1	+ Noise - NOx
		better use of capacity	F7	√			-/+	0	0	-	+	- / 0	0	0	LW	?

Three broad grouping of interventions are identified and these are discussed in turn. Further information is provided in Appendix 3, where technical information from academic and industry published research is collated and referenced.

Airframe and engine technology

These include:

Improvements to existing airframes. such as the retro fitting of wingtip extensions (winglets) to reduce cruise drag, and riblets (small raised grooves airframes) to reduce turbulence, friction drag and hence fuel consumption. Winglets re already in widespread use.

Light weighting existing aircraft through refits with lighter cabin materials and equipment, reduced passenger information material and ‘duty frees’, and light weighting new aircraft with new materials such as composites and layouts.

Airframe Surface polishing, rather than painted surfaces which deteriorate with age, polished surfaces can reduce drag and fuel use, although painted surfaces are commonly used for branding purposes. Improved maintenance of painted surfaces could probably achieve similar fuel savings.

Engine replacement, replacing original with new generation engines on existing airframes. The advantages of this options are perceived to be limited by many stakeholders, mainly due to relatively high costs and because airframes and engines are matched at the design stage.

Engine upgrades to incorporate new features for fuel efficiency or noise reduction, particularly ‘hushkits’. Even small component upgrades can be expensive to introduce. As with engine replacement, much depends on the cost of the modification relative to the remaining life and value of the airframe.

New airframe technology. such as advanced materials, changes in airframe configuration such as open rotor engines and blended wing bodies, advanced flow techniques and increased use of electrical systems. These could provide large reductions in fuel burn over the medium to longer term (post 2020), but much depends on commercial and regulatory drivers.

New engine technologies, such as geared turbo fans or open rotors, are seen to offer considerable improvement in fuel efficiency in the medium to long term. Increased use of turbo props for short haul flights offers much scope, subject to effective noise abatement**.**

Removal of Auxiliary Power Unit (APU), to reduce weight, providing power supplies to stationary aircraft by airport generators. The feasibility depends on alternative supplies at airports. Reduced use of APUs could affect passenger comfort.

Biofuels, whereby aviation fuels contain a biofuel fraction, are unlikely to significantly displace aviation kerosene in the near future according to most stakeholders due to a range of technical and operational factors, but could offer more potential over the longer term.

Other alternative fuels made from gas and coal are feasible but will not abate carbon emissions. Hydrogen is a possible long term alternative to kerosene but would require major design, infrastructural and operational changes. Synthetic biofuels offer other possibilities.

Operational improvements

These interventions include:

ATM improvements. such as the Single European Skies project, to achieve more direct routing of aircraft travel, is seen as a short-term win-win option capable of delivering significant one-off fuel burn improvements over the next 10 years, but its success is dependent on overcoming a number of institutional, financial and political barriers..

Continuous descent approach rather than a stepped approach and/or being put on hold**.** This is already practiced for some airports, closely linked to ATM improvements.

Reduced fuel tankering. whereby aircraft would reduce the carriage of fuel in excess of that required to complete a particular journey. Fuel tankering has been encouraged by the need for rapid turn round times on domestic operations, limited fuel availability at some airports and fuel price differentials.

Changes to flight speed and altitude. Changes can yield benefits where, for a variety of reasons (often associated with ATM factors), operating practices prevent travel at the speed and altitude for which aircraft are designed.

Fleet Management

These interventions include:

Early replacement of aircraft. in order to maintain a young fleet with the latest best available environmental performance. Fuel prices, regulatory compliance, technology change, second hand prices, and ability to fund replacements by operators are likely to determine attractiveness of early replacement.

Reduced maintenance intervals to maintain operational efficiency. It is noted, however, that engines are now designed for longer maintenance intervals to reduce downtime. In service care such as engine washing could help maintain fuel efficiency between overhauls.

Reducing fuel reserves required to provide safety margins. This is unlikely to be amended, but improved fleet management and ATM could reduce the amount of fuel reserves required.

Use of turboprops, referred to earlier, is viewed as increasingly attractive for short-haul operations with higher fuel prices, although the perception remains that turboprops represent old technology and offer reduced cabin comfort.

Better use of capacity. Increased seating densities and load factors, coupled with reduced weight carried and incentives to passengers to carry less baggage, can reduce emissions per passenger kilometre. Consolidation of other wise competing flights is not popular amongst operators.

3.3 Interdependencies Amongst Abatements and Emissions

Abatement measures to reduce CO_2 may result in trade-offs or interdependencies with other emissions or noise. In most cases abatement measures designed to reduce fuel burn and CO_2 emissions will result in corresponding reductions in NOx emissions at both ground level and cruise altitude, with little or no impact on noise, but there are a few potential exceptions.

Interdependencies may arise with major changes to engine technology designed to improve fuel efficiency. There is some evidence of a CO_2: NOx trade-off in engine design, though the scale of this relationship is unclear and could be small.

The CO_2:NOx relationship becomes more complex at the level of the whole aircraft as both aerodynamic and structural efficiencies come into play. Modern engines have higher overall pressure ratios (OPRs) than the older ones they are replacing, resulting in lower fuel consumption. At the same time, however, they have higher NOx emissions per amount of thrust. Lower specific fuel consumption of newer engine design coupled with structural and aerodynamic improvements embodied in newer airframe designs have tended to offset these higher NOx emissions. As a result, the trend in NOx emissions per seat km has remained broadly constant over time. However, over the next 10 years, if the CAEP mid-term NOx goal is met by modified engine design, the reduced LTO NOx emissions should more than match the OPR effect, resulting in a reduction of NOx per seat km compared with first generation turbo-fan engines.

CO_2: NOx trade-offs are likely to be of limited relevance for the engine technology abatement options identified in this study. They do not arise with engine retrofits or upgrades and have not been identified with major changes in aircraft technology such as geared turbofans or blended wing bodies. However there is evidence that open rotors may have lower LTO NOx, but higher NOx and noise at cruise. Most of the operational and fleet management measures will result in corresponding reductions in NOx. For major engine architecture changes LTO NOx should be reduced, but cruise NOx could be somewhat worse than current types. One abatement measure that may result in a CO_2: NOx trade-off is flying at higher altitudes where any CO_2 reductions will be offset by higher NOx emissions at cruise, with the net climate change impact subject to scientific uncertainty.

There is some evidence of CO_2: noise trade-offs in engine or airframe design, particularly where an increase in drag and weight arises from measures to tackle noise. This has arisen with the design of the A380 where such measures to reduce noise have resulted in higher fuel burn, due to drag increasing as a result of greater nacelle surface area and some weight gain.

3.4 Summary of Main Points

- Three categories of environmental abatement measures with scope to improve the efficiency of fuel consumption and reduce CO_2 emissions are identified, namely: airframe and engine technology, operational improvements and fleet management.
- Stakeholders apply a range of criteria to assess the feasibility and acceptability of these options, including effectiveness, costs, operational convenience and compatibility with business models and practices.
- Most interventions in the past have focussed on meeting local air quality and noise measures introduced at the international or airport levels. Concern about global warming, has reoriented attention towards reducing CO_2, mainly by means of increased fuel efficiency.
- There are interdependencies, both synergies and trade-offs, in the emissions arising from different abatement measures. Some measures to improve fuel efficiency through hotter, leaner burn engines have potential to increase NOx emissions and create water vapour trails especially at high altitude.

4.0 A Framework for Estimating Marginal Abatement Costs of Aviation

This chapter provides an overview of the methods that have been developed to estimate the marginal costs of interventions to reduce emissions from aviation, that is, marginal abatement costs (MAC). The overall purpose is to determine the relative extra (marginal) costs of interventions, measures that can be taken by the aviation industry to achieve reductions in environmental emissions, and thereby determine the most cost-effective portfolio of measures. This chapter draws on the theory and principles of MAC referred to in Chapter 2, and on information derived from academic and industrial research, published information and stakeholder consultation. The development and application of such a framework is a main objective of this study.

4.1 Methodological Framework

Figure 4.1 shows an analytical framework for estimating MACs for aviation. This method is compatible with detailed assessment contained in guidance issued by CORINAIR (EEA, 2007). Operationally, it comprises a set of linked spreadsheets which contain data and calculation routines which can be modified to suit particular applications.

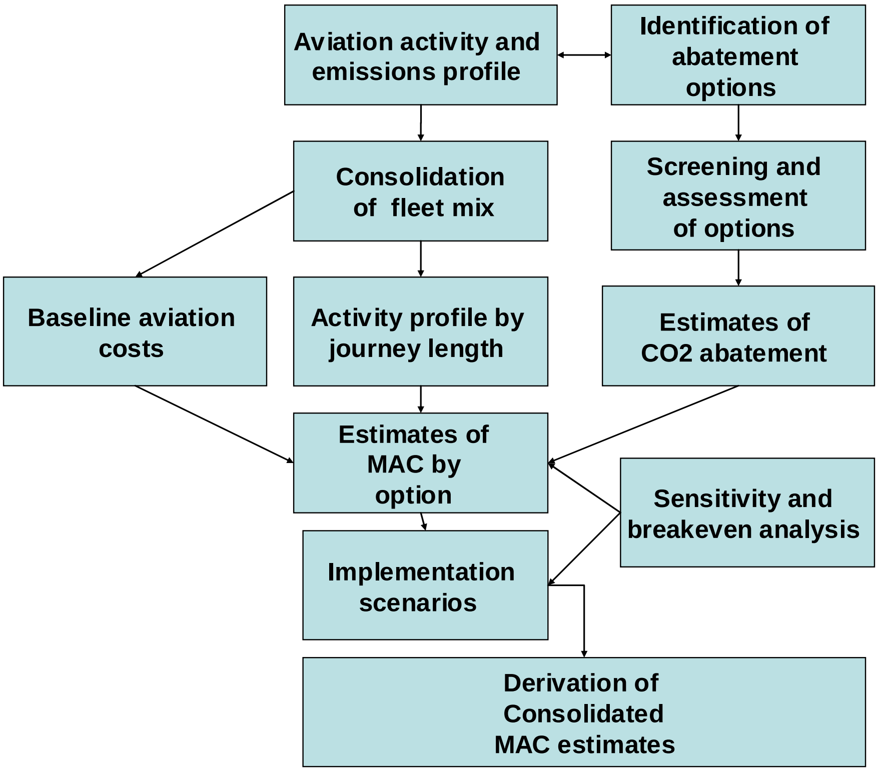


Figure 4.1 - Framework for Assessing MAC for Reducing Emissions from Aviation

The main components of the framework are discussed in turn**.**

Activity and emissions profile – provides estimates of total distance travelled in a given aviation sector, seat kilometres offered (SKO) and fuel use, classified by journey length and airplane type. This draws on traffic data from national and international official published sources to provide a baseline. Future projections allow for growth factors and changes in fleet composition. The effects of abatement are assessed against a counterfactual no-intervention

Consolidation of fleet mix – selects 'representative' airplanes for given aviation sectors that account for the largest proportion of distance travelled, fuel consumed, CO_2 and other species emitted, drawing on published sources by international and national aviation organisations

Activity profile by journey length – different aviation sectors demonstrate different haulage distances, short, medium and long, with implications for fuel use per Seat Kilometres Offered (SKO). Estimates of fuel use and SKO are assembled for representative airplanes for selected journey lengths, drawing on official sources.

Baseline aviation costs – estimates of average capital and operating costs per hour of use for selected airplanes (referred to as 'block' hours – to denote time between removal and replacement of wheel blocks at airports at the beginning and end of journeys). These are derived from various sources, namely: Form 41 USA data reporting costs by aircraft types, UK CAA data reporting costs by aviation operator (some of which operate virtually single aircraft type fleets), the Association of European Airlines (AEA) for European operators, published financial results of operators, and data from manufacturers' websites.

Screening of abatement options – 'candidate' abatement interventions are identified and screened against criteria such as technical suitability, benefits, costs, acceptability to stakeholders and timescale of adoption. Interventions include technological, operational and fleet management options.

Effectiveness of emission abatement options – with respect to reduction in fuel use, expressed as a % saving, CO_2 emissions and other emissions. These are estimated for each journey stage, namely taxiing, take-off, climb-out, cruise, descent and landing for each aircraft type. This draws on data from ICAO test sources and CORINAIR data sets as well as modelled data using PIANO and FAST programme outputs. This approach recognises different interventions have different affects on different LTO/cruise stages.

Estimates of CO_2 and other abatements – the potential reductions in fuel use and CO_2 and other emissions attributable to each abatement option are estimated for representative aircraft, allowing for the particular activity profile, i.e., distance travelled by airplanes on different journey lengths.

Estimates of Marginal Abatement Costs (MAC) for individual interventions – the extra annual costs of achieving the aforementioned abatements are estimated by aircraft type. Costs include additional investment costs, spread over the relevant investment life to give an annual equivalent cost, plus changes in annual operating costs such as fuel, maintenance, crew time, and other costs such as training where relevant. Additional investments in items such as air traffic management and research and development for new engine/airframe technology are charged as extra investment costs per plane, where these can be estimated and attributed. An estimate of £/tCO_2 (and other emissions) abated within a given year is derived for a specified intervention for a specific plane employed on a specified mix of journeys. 2008 constant prices are used throughout, although allowance is made for changes in relative fuel prices.

Implementation Scenarios - assumptions are made to derive estimates of the likely implementation and effectiveness of abatement interventions to reduce CO_2. This involves consideration of three aspects:

Potential feasibility – reflecting the feasibility of implementation of an intervention in terms of technical and practical suitability, which could be reasonably achieved in the time frame allowing for current circumstances and practices. For example, it is assumed that winglets could be fitted on 90% of the B737 fleet, if there was a wish to do so.

Actual adoption – this allows for take-up below technically feasible levels due, for example, to barriers and inertia, such as embedded practices, and the effect of incentives to adopt interventions, for example fuel prices.

Additivity – interventions may not be independent of one another; some interventions may overlap with or substitute for others, such that the effects of successive interventions are not cumulative. The effects of early replacement of aircraft, for example, may substitute for the effects of engine/airframe modifications to older aircraft. The efficacy of individual abatement options may depend on the order in which interventions are actually implemented.

Derivation of consolidated MAC estimates – outputs from the preceding analyses are aggregated for a specified year to give, with respect to CO_2 abatement for example, (i) total CO_2 abated by intervention and aircraft type (ii) total annual costs by intervention and airplane and (iii) average £/tCO_2 abated per intervention. Where appropriate this can be done for selected future years allowing for changes in the availability and uptake of abatement options, in the mix of the fleet, and in fuel prices. The analysis can be repeated for other emission species.

These estimates are assembled into MAC curves (as shown above in Figure 2.2) to graphically represent the relative costs of achieving successive increases in abatement in a given year (over and above some counterfactual no-adoption baseline) by successively adopting interventions in order of rising marginal costs. As mentioned earlier, some interventions may offer win-win opportunities whereas others may prove very expensive to introduce.

Sensitivity and breakeven analysis – estimates of MAC depend on 'supply side' factors such as fuel prices, discount rates, investment life and fleet mix. Higher fuel prices make options to reduce fuel use and CO_2 emissions more attractive. Table 4.1 shows alternative fuel price estimates used for sensitivity analysis.

Table 4.1 - Predicted Future Oil Prices used to estimate MAC for Aviation.

	BERR estimates								IATA
year	low		central		high		very high		forecast
2007	73	(0.33)	73	(0.33)	73	(0.33)	73	(0.33)	104
2012	45	(0.21)	65	(0.29)	85	(0.38)	107	(0.48)	85
2020	45	(0.21)	70	(0.31)	95	(0.43)	150	(0.68)	95
2030	45	(0.21)	73	(0.33)	100	(0.45)	150	(0.68)	100
2050	45	(0.21)	75	(0.34)	105	(0.47)	150	(0.68)	105

all prices in US $/barrell, then (£/litre).
converted at 159 litres/barrel; US$;£ at 1.86

MACs are also affected by possible changes in 'demand side' factors associated with changes in traffic demand and revenue from ticket sales. Some abatement measures, such as reduced use of Auxiliary Power Units or increased capacity utilisation, might be associated with lower average ticket prices. This could impose a demand side penalty which should, as far as the industry is concerned, be included as part of the cost of abatement. This goes beyond the scope of the current assessment and has not been investigated.

The change in fuel price necessary to achieve a breakeven zero cost for a particular abatement is identified. Similarly, the implication of alternative carbon permit prices is also considered.

4.2 Uncertainties and Robustness of the Estimates

The compilation of the framework and its application to two case study aviation sectors (UK Domestic and EU-based international) revealed that the MAC are subject to many uncertainties and unknowns. While there is broad agreement amongst stakeholders about the potential of abatement options for fuel savings and related emissions reduction, there is currently little robust information on the costs of the options considered given uncertainties regarding their stage of development, likely timing of introduction, applicability to the wider fleet and amount of investment in Research & Development in new technology. Caution is required in the presentation and interpretation of results. The MAC curves derived, given the current state of shared knowledge, are therefore necessarily illustrative and intended to indicate broad orders of magnitude and significance.

4.3 Summary of Main Points

An analytical framework has been developed to systematically determine the relative cost-effectiveness of alternative measures to reduce emissions from aviation, notably CO_2.

The framework combines information on aviation activity profiles and baseline ‘no-intervention’ emissions, now and into the future, against which the efficacy of interventions can be assessed. The interventions comprise changes in aviation technology, operations and fleet management. While there is some agreement amongst stakeholders on the potential theoretical savings in fuel and reductions in emissions that can be achieved by these interventions, there is considerable uncertainty regarding their operational practicability and cost.

The analytical framework confirms the need for enhanced knowledge and data to enable reliable estimates of MACs that can guide the development and promotion of intervention measures to abate aviation emissions.

5.0 Case Study: MAC for the UK Domestic Aviation Sector

This chapter considers the application of the framework for estimating MACs for UK domestic aviation, with particular reference to reducing CO_2 emissions. It draws on a project undertaken in 2008 for the Department of Transport (Dft) by the Omega Project 14 team in collaboration with Manchester Metropolitan (Morris, Rowbotham, Morrell, Poll, Bethan, Raper, Mann and Ralph, 2008). This case was developed as an integral part of the Omega project, demonstrating the application and validity of the approach to MAC estimation.

The case study reported here focuses on potential interventions available to the UK domestic aviation to reduce CO_2 emissions as part of its obligations under the Kyoto protocol. Domestic is defined as internal flights within the UK of passenger aircraft only. Whilst informed by measures available at the European and global scale, the potential and cost effectiveness of some options may be different for the UK domestic aviation sector than for the industry as a whole.

Appendix 4 contains details on the application of the methods used to derive MAC, following those described in Chapter 4 above. This chapter focuses on the results obtained. The estimates are indicative and require cautious interpretation.

5.1 UK Sector Profile and Baseline and Predicted Traffic and Emissions

Estimates of total distance travelled in the UK domestic sector, SKO and fuel use, classified by journey length and airplane type, were compiled using flight route and frequency data provided by the UK CAA for 2007. Aircraft used on

UK domestic flights, mainly 150 seater turbofan jets, are typical of those used on short-haul European routes for busy domestic trunk services, with a mixture of regional jets and turboprops on less busy routes. Six airlines account for over 90% of domestic seat kilometres with three (easyJet, BA and flyBe) accounting for almost two thirds.

The engine design model, 'PIANO', was used to determine fuel flow during the various flight phases (Lissys, 2008). It was shown that 11 aircraft types currently account for 96% of distance travelled, fuel consumed and CO_2 emitted (Table 5.1). Subsequent analysis focussed on this sub-set, as well as their ACARE compliant substitutes.

Table 5.1 - Contribution of selected aircraft type to total fuel usage, distance and SKO for UK domestic sector

Aircraft	% fuel	% distance	% SKO
A319	24	18	26
A320	9	7	10
B7373	12	8	10
B7375	6	4	4
B7377	9	6	9
B7378	5	3	6
B7572	5	2	4
E145	4	8	4
Bae146/RJ85	7	7	6
Medium turboprops	4	14	5
Large turboprops	10	17	12
Share of total for fleet	96	96	96

Source: Morris et al., 2008.

Predictions of traffic, fuel use and CO_2 emissions for future years were based on DfT forecasts (Dft, 2007) allowing for growth factors, changes in fleet composition and assumed improvements in fuel efficiency, due for example to improved ATM, already built into the Business as Usual Case (Table 5.2). The latter effects were subsequently taken out of the baseline estimates in order to assess the impacts of the interventions considered here.

Table 5.2 - Time Series of Business as Usual (BAU) Carbon Dioxide Emissions to 2050 showing comparison with Dft Domestic Carbon Dioxide Emissions (Central Case)

CO_2 (million tonnes or Tg)	Source	2007	2010	2020	2030	2040	2050
BAU (this study)	This study	2.1	2.3	2.4	2.9	3.3	3.5
BAU with APU and freight	This study	2.4	2. 6	2.8	3.3	3.7	3.9
DfT with APU and freight	DfT, 2008[1]	2.4	2.6	2.9	3.3	3.7	3.9

(Source: Morris et al., 2008)

5.2 UK Domestic Aviation MAC for 2007

Table 5.3 shows the assumed potential take-up of individual interventions categorised by type of aircraft for 2007. A nominal adjustment for actual adoption is applied to the estimates in Table 5.1, such that 90% of what is a technically and operationally feasible volume of abatement is assumed in most cases.

[1] As 18 above.

Table 5.3 - Assumed Technical Potential Take-up of Abatement Options, as % of Aircraft Adopting Options in 2007

abatemment	A319	A320	B7373	B7375	B7377	B7378	B7572	E145	PROP6	PROP7	RJ85
technology											
winglets	0%	0%	90%	50%	25%	90%	25%	0%	0%	0%	0%
riblets	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
lightweighting- new	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
lightweighting - existing	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
blended wing	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
aircraft surface - polish	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
engine replacement	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
engine upgrades	25%	25%	50%	50%	25%	10%	50%	25%	10%	10%	25%
open rotors	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
APU - removal	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	100%
APU - tech replacement	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bio-fuels blend (20%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Alternative fuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Optimised aircraft design	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Operational											
ATM improvements	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
CDA	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Optimise - speed/altitude	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Optimise - LTO practice	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Reduce fuel tankering	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Fleet Management											
Aircraft retirement1&2	0%	0%	100%	100%	0%	0%	100%	0%	0%	0%	0%
maintenance - engine	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
maintenance - aero	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
maintenance - engine wash	80%	80%	80%	80%	80%	80%	80%	80%	0%	0%	100%
fuel reserves	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
increase turboprop use	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	100%
better use of capacity	60%	60%	60%	60%	60%	60%	60%	75%	75%	75%	75%
reduce APU use	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%

Table 5.4 shows the MAC for CO_2 for UK Domestic Aviation 2007, assuming the prevailing fuel price of £0.33/ltr (US$73/brl). All prices are mid 2008 values and exchange rates at £1:US$ 1.86. Table 5.4 shows, for the assumptions made, the incremental abatement of CO_2 for each successive abatement option introduced in order of increasing abatement cost (£/tCO_2). It is noted that each intervention is considered independently. Table 5.4 shows the potential annual abatement attributable to each intervention expressed as a percentage of total annual UK domestic aviation CO_2 emissions considering each intervention. Eight abatement options have potential to achieve emission abatements at negative net cost, that is offering overall financial benefit. Most of them are operational interventions, which seek to reduce fuel expenditure. Indeed, there is evidence, collected during stakeholder consultation, that many of them are being adopted in 2008 in response to high fuel prices (these recent introductions have not been included in the base line estimates). It is noted however that some, such as better use of capacity and reduced APU use, can have a demand-side affect through modifying the ‘product service’, with possible implications for revenue

and hence MAC. The increased use of turboprops appears to offer advantage given the amount of short haul traffic. Table 5.4 suggests that abatement options when considered independently are associated with a reduction of up to 12% of the sector's 2007 CO_2 emissions, however, when additivity effects between abatement options are taken into account these savings will necessarily decrease.

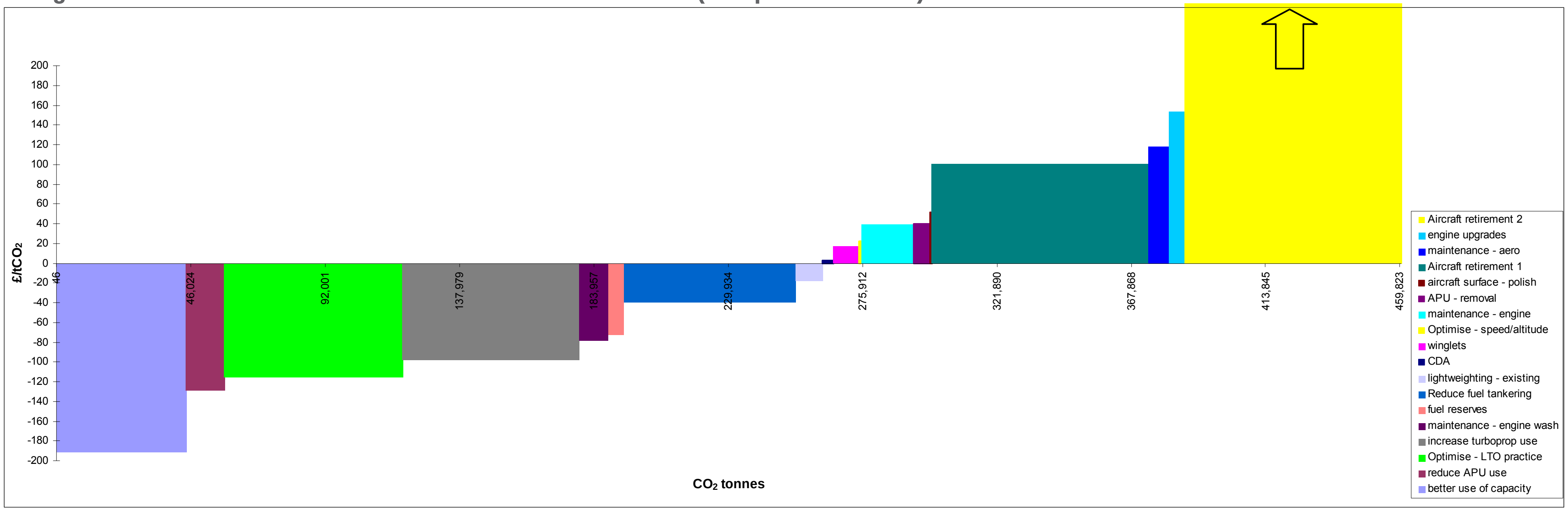
Table 5.4 - UK Domestic Aviation Illustrative MAC for 2007 (fuel price £(2008) 0.33/ltr)

health	id	intervention	total abated (CO_2 tonnes)	total cost (£)	unit cost (£/tCO_2)	% of total annual sector emissions
	F8	better use of capacity	44399	-8521803	-192	2.18%
	F9	reduce APU use	12902	-1668614	-129	0.63%
	O4	Optimise - LTO practice	61102	-7057190	-115	3.00%
	F7	increase turboprop use	60393	-5932666	-98	2.96%
	F5	maintenance - engine wash	9927	-782888	-79	0.49%
	F6	fuel reserves	5363	-389202	-73	0.26%
	O5	Reduce fuel tankering	58814	-2352602	-40	2.88%
	T4	lightweighting - existing	9137	-166266	-18	0.45%
	O2	CDA	3836	10202	3	0.19%
	T1	winglets	8773	154116	18	0.43%
	O3	Optimise - speed/altitude	624	13707	22	0.03%
	F3	maintenance - engine	18064	712471	39	0.89%
	T10	APU - removal	5622	225747	40	0.28%
	T6	aircraft surface - polish	677	34914	52	0.03%
	F1	Aircraft retirement 1	74143	7464747	101	3.64%
	F4	maintenance - aero	6924	820440	118	0.34%
	T8	engine upgrades	5393	829286	154	0.26%
	F2	Aircraft retirement 2	74143	30014421	405	3.64%

NB: Assumed annual emissions without interventions = 2 039 000 tCO_2

Figure 5.1 contains (based on Table 5.4) a MAC curve showing the incremental costs of increasing abatement by successive interventions. The win-win opportunities under prevailing (mid 2008) fuel prices are apparent. Marginal costs of abatement rise steeply beyond the point where the MAC curve crosses the breakeven point (at 0 £/tCO_2) indicating that achieving further reductions in CO_2 becomes relatively expensive

Figure 5.1 - UK Domestic Aviation Illustrative MAC for 2007 (fuel price £0.33/ltr)



5.3 UK Domestic Aviation MAC for 2012

Table 5.5 shows the MAC for CO_2 for UK Domestic Aviation in 2012, assuming an increased rate of uptake of intervention options (detailed in Appendix 4) and the central fuel price of £0.31/ltr. A similar pattern to 2007 is apparent – the same eight abatement options have potential to achieve emission abatements at negative cost, that is offering win-win opportunity. It is noted that no new major technological developments are expected by 2012, with only small improvements in ATM through CDA by that time. Table 5.5 suggests that, considering interventions independently, up to 14% of the sector's 2007 CO_2 emissions could be abated with potential financial benefit in 2012. However, when additivity effects between abatement options are taken into account these savings will necessarily decrease.

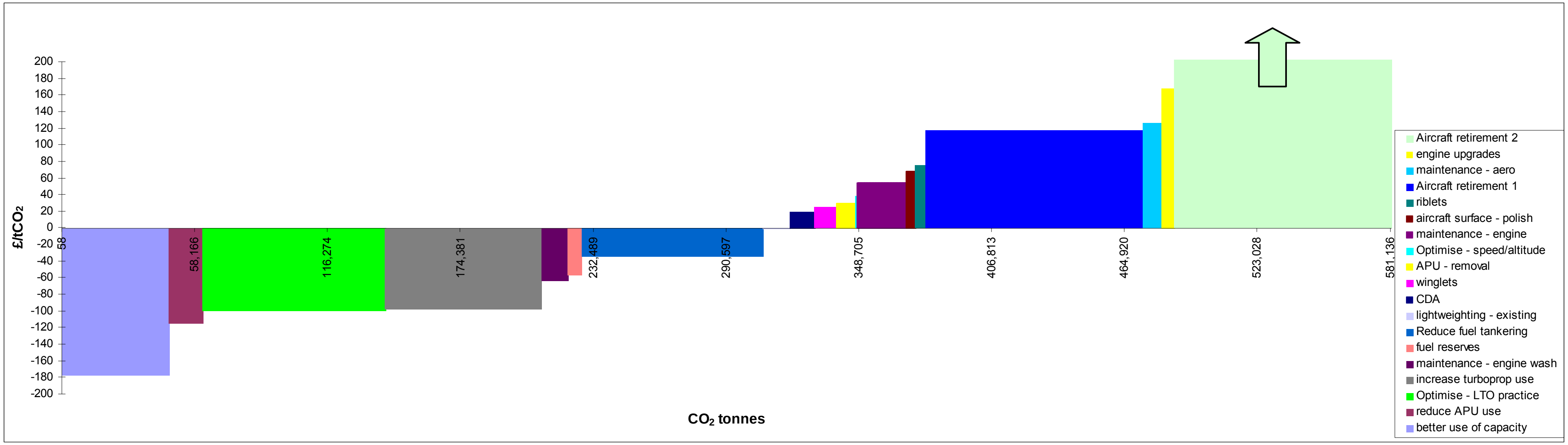
Table 5.5 - UK Domestic Aviation Illustrative MAC for 2012 (central fuel price £0.29/ltr)

health	id	intervention	total abated (CO_2 tonnes)	total cost (£)	unit cost (£/tCO_2)	% of total annual sector emissions
	F8	better use of capacity	46740	-8277680	-177	2.03%
	F9	reduce APU use	14881	-1714597	-115	0.65%
	O4	Optimise - LTO practice	79776	-8037779	-101	3.47%
	F7	increase turboprop use	68428	-6694757	-98	2.98%
	F5	maintenance - engine wash	11554	-741404	-64	0.50%
	F6	fuel reserves	6000	-341090	-57	0.26%
	O5	Reduce fuel tankering	79351	-2737677	-35	3.45%
	T4	lightweighting - existing	11817	-22730	-2	0.51%
	O2	CDA	10683	205450	19	0.46%
	T1	winglets	9876	243835	25	0.43%
	T10	APU - removal	8235	240259	29	0.36%
	O3	Optimise - speed/altitude	708	27157	38	0.03%
	F3	maintenance - engine	21475	1151997	54	0.93%
	T6	aircraft surface - polish	3790	256382	68	0.16%
	T2	riblets	4477	340483	76	0.19%
	F1	Aircraft retirement 1	95111	11214219	118	4.14%
	F4	maintenance - aero	8232	1039829	126	0.36%
	T8	engine upgrades	5413	908946	168	0.24%
	F2	Aircraft retirement 2	95111	41295773	434	4.14%

NB: Assumed annual emissions without interventions = 2 299 000 tCO_2

Figure 5.2 contains (based on Table 5.5) a MAC curve showing the incremental cost of increasing abatement by successive interventions. The

Figure 5.2 - UK Domestic Aviation Indicative MAC for 2012 (Central Oil Fuel price £(2008)0.29/ltr)



win-win opportunities under prevailing fuel prices are apparent, and the interpretation is similar to that of the 2007 MAC curve. Abatement costs rise steeply beyond the breakeven point where MAC equals zero. Early retirement of aircraft (shown separately for replacing 5 (F1) and 10 year (F2) old aircraft respectively) offer considerable abatement potential, but at relatively high cost (replacing younger aircraft benefits from higher aircraft resale value).

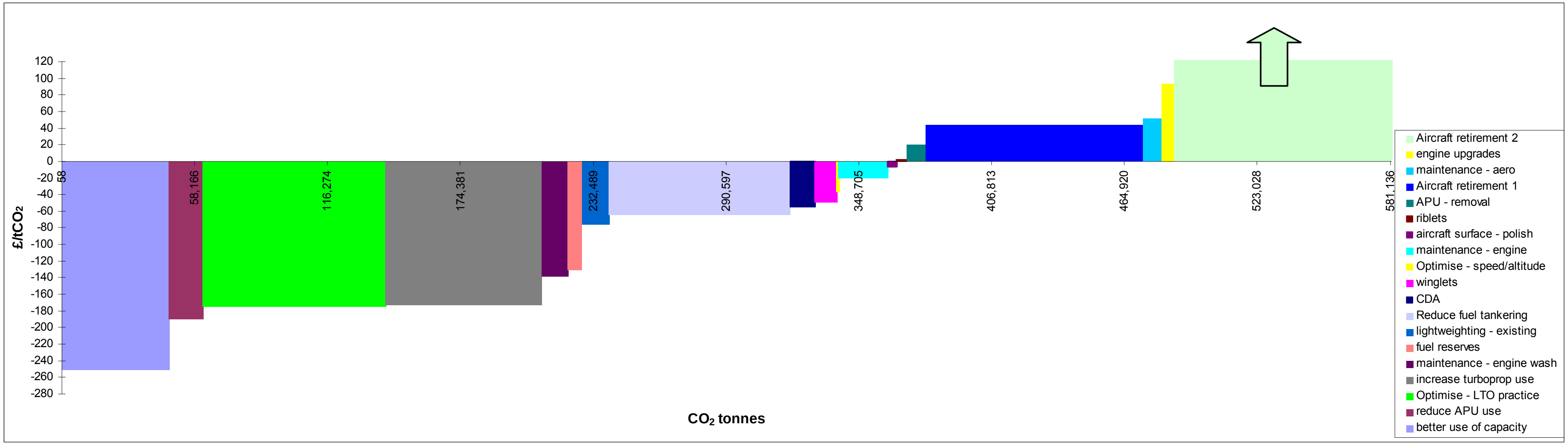
Table 5.6 shows estimates of MAC for 2012 for the range of fuel prices in Table 4.1 above. Interventions above the continuous horizontal lines in the columns can be adopted at negative or zero cost (for the assumptions made). Higher fuel prices make all interventions more attractive. There are some changes in the relative costs and ranking of interventions in response to fuel prices, but the overall pattern remains much the same. The highest fuel price assumed in Table 5.6 appears to be sufficient to induce abatements associated with up to about 17% of total annual sector CO_2 emissions, when interventions are considered independently. However, when additivity effects between abatement options are taken into account these savings will necessarily decrease. Early retirement/replacement of aircraft (where F1 in Table 5.6 indicates replacement at 5 years old) offers considerable scope for abatement and appears more attractive under high oil price scenarios.

Table 5.6 - Estimates of UK Domestic Aviation MAC for 2012 by Alternative Oil Price Scenarios

Oil price scenario		low		central		high		very high
US$/Brl Oil		45		65		85		107
£/l aviation fuel		0.21		0.29		0.38		0.48
Interventions								
F8	better use of capacity	**-142**	F8	**-177**	F8	**-213**	F8	**-252**
F9	reduce APU use	**-80**	F9	**-115**	F9	**-151**	F9	**-190**
O4	Optimise - LTO practice	**-65**	O4	**-101**	O4	**-136**	O4	**-175**
F7	increase turboprop use	**-63**	F7	**-98**	F7	**-133**	F7	**-172**
F5	maintenance - engine wash	**-29**	F5	**-64**	F5	**-100**	F5	**-139**
F6	fuel reserves	**-22**	F6	**-57**	F6	**-93**	F6	**-131**
O5	Reduce fuel tankering	**-20**	O5	**-35**	O5	**-49**	T4	**-76**
T4	lightweighting - existing	**33**	T4	**-2**	T4	**-38**	O5	**-65**
T10	APU - removal	**34**	O2	**19**	O2	**-16**	O2	**-55**
O2	CDA	**55**	T1	**25**	T1	**-11**	T1	**-50**
T1	winglets	**60**	T10	**29**	O3	**3**	O3	**-36**
O3	Optimise - speed/altitude	**74**	O3	**38**	F3	**18**	F3	**-21**
F3	maintenance - engine	**89**	F3	**54**	T10	**25**	T6	**-7**
T6	aircraft surface - polish	**103**	T6	**68**	T6	**32**	T2	**2**
T2	riblets	**111**	T2	**76**	T2	**40**	T10	**20**
F1	Aircraft retirement 1	**153**	F1	**118**	F1	**82**	F1	**43**
F4	maintenance - aero	**162**	F4	**126**	F4	**91**	F4	**52**
T8	engine upgrades	**203**	T8	**168**	T8	**132**	T8	**93**
F2	Aircraft retirement 2	**469**	F2	**434**	F2	**399**	F2	**360**

For illustration, the MAC curve for the very high price scenario for 2012 (£0.48ltr) is contained in Figure 5.3.

Figure 5.3 - UK Domestic Aviation Illustrative MAC for 2012 (high fuel price at £0.48/ltr)



5.4 UK Domestic Aviation MAC for 2020

By 2020, it is assumed that there is further increase in the range and intensity of the adoption of interventions. For example, ATM improvements are assumed to be fully implemented, with 90% of each aircraft type taking advantage of the associated benefits. Some new interventions emerge, such as the availability of bio-fuels, with an assumed 10% of all aircraft types using bio-fuels as a blend with aviation fuel.

Table 5.7 shows the MAC for CO_2 for UK Domestic Aviation in 2020, assuming the central fuel price of £0.31/ltr At the central fuel price of £0.31/ltr, eight interventions are shown to offer opportunity for abatement at negative or zero cost. These abatement options are associated with about 24% of the sector's 2020 CO_2 emissions when considered independently of one another.

Table 5.7 - UK Domestic Aviation Illustrative MAC for 2020 (central fuel price £0.3/1tr)

health	id	intervention	total abated (CO_2 tonnes)	total cost (£)	unit cost (£/tCO_2)	% of total annual sector emissions
	F8	better use of capacity	51999	-9704109	-187	2.00%
	F7	increase turboprop use	126623	-16648737	-131	4.88%
	F9	reduce APU use	17052	-2118428	-124	0.66%
	O4	Optimise - LTO practice	88025	-9604244	-109	3.39%
	F6	fuel reserves	8202	-489513	-60	0.32%
	O5	Reduce fuel tankering	90710	-3624691	-40	3.50%
	F5	maintenance - engine wash	17016	-516800	-30	0.66%
	O1	ATM improvements	221426	-4385865	-20	8.53%
	T1	winglets	11502	179144	16	0.44%
	O2	CDA	28449	458230	16	1.10%
	T10	APU - removal	9139	216237	24	0.35%
	T2	riblets	9789	344085	35	0.38%
	O3	Optimise - speed/altitude	1583	56663	36	0.06%
	T4	lightweighting - existing	41685	1612494	39	1.61%
	F3	maintenance - engine	27225	1163387	43	1.05%
	T6	aircraft surface - polish	6724	425789	63	0.26%
	F10	ACARE	1900	185015	97	0.07%
	F4	maintenance - aero	10436	1108017	106	0.40%
	T8	engine upgrades	8433	961501	114	0.33%
	F1	Aircraft retirement 1	291836	36047672	124	11.25%
	T3	lightweighting- new	16232	2633668	162	0.63%
	T12	Bio-fuels (20% blend)	28777	4781513	166	1.11%
	T7	engine replacement	8826	1819194	206	0.34%
	F2	Aircraft retirement 2	291836	144970902	497	11.25%

NB: Assumed annual emissions without interventions = 2 595 000 tCO_2

It is noted that ATM improvements account for around a third of aggregate abatements. The adoption of ATM improvements, which reduce journey time, would reduce the potential gain from other interventions that reduce fuel consumption per km travelled for a given payload. This illustrates that when additivity effects between abatement options are taken into account the identified savings will necessarily decrease.

Table 5.8 shows estimates of MAC for 2020 for a range of predicted fuel prices. As before, interventions above the continuous horizontal lines in the table columns can be adopted at negative or zero net cost (for the assumptions made). Higher fuel prices extend the range of win-win abatement options, and the proportion of the sector's emissions that could be adopted at zero or relatively low net cost.

Table 5.8- UK Domestic Aviation Illustrative MACs for 2020, compared by Oil Price Scenario

	Oil price scenario	low		central		high		very high
	US$/Brl Oil	45		70		95		150
	£/l aviation fuel	0.21		0.31		0.43		0.68
Interventions								
F8	better use of capacity	**-142**	F8	**-187**	F8	**-231**	F8	**-328**
F7	increase turboprop use	**-87**	F7	**-131**	F7	**-176**	F7	**-273**
F9	reduce APU use	**-80**	F9	**-124**	F9	**-169**	F9	**-266**
O4	Optimise - LTO practice	**-65**	O4	**-109**	O4	**-153**	O4	**-251**
O5	Reduce fuel tankering	**-21**	F6	**-60**	F6	**-104**	F6	**-202**
F6	fuel reserves	**-15**	O5	**-40**	F5	**-75**	F5	**-172**
F5	maintenance - engine wash	**14**	F5	**-30**	O1	**-64**	O1	**-162**
O1	ATM improvements	**24**	O1	**-20**	O5	**-59**	T1	**-126**
T10	APU - removal	**28**	T1	**16**	T1	**-29**	O2	**-126**
T1	winglets	**60**	O2	**16**	O2	**-28**	T2	**-107**
O2	CDA	**60**	T10	**24**	T2	**-9**	O3	**-106**
T2	riblets	**79**	T2	**35**	O3	**-8**	T4	**-103**
O3	Optimise - speed/altitude	**80**	O3	**36**	T4	**-6**	O5	**-99**
T4	lightweighting - existing	**83**	T4	**39**	F3	**-2**	F3	**-99**
F3	maintenance - engine	**87**	F3	**43**	T6	**19**	T6	**-79**
T12	Bio-fuels (20% blend)	**107**	T6	**63**	T10	**19**	F10	**-44**
T6	aircraft surface - polish	**108**	F10	**97**	F10	**53**	F4	**-36**
F10	ACARE	**142**	F4	**106**	F4	**62**	T8	**-28**
F4	maintenance - aero	**150**	T8	**114**	T8	**70**	F1	**-18**
T8	engine upgrades	**158**	F1	**124**	F1	**79**	T10	**9**
F1	Aircraft retirement 1	**168**	T3	**162**	T3	**118**	T3	**20**
T3	lightweighting- new	**207**	T12	**166**	T7	**162**	T7	**64**
T7	engine replacement	**250**	T7	**206**	T12	**225**	F2	**355**
F2	Aircraft retirement 2	**541**	F2	**497**	F2	**452**	T12	**356**

The effect of fuel prices on the cost of and therefore the incentive to adopt abatement measures is apparent in Figure 5.4 that shows the 2020 MAC curves for central (US$70/bbl, £0.31/ltr) and very high (US$150/bbl, £0.69/ltr) aviation fuel prices respectively. Higher fuel prices make nearly all interventions more attractive. There are some changes in the relative costs and ranking of interventions in response to fuel prices, but the overall pattern remains much the same. Blended aviation bio-fuels are a notable exception. These fuels are assumed to be heavier per unit of calorific value compared with conventional aviation fuel. Their use results in extra take-off weight such that much of the potential benefit of the bio-fuel component emissions reduction is lost.. The win-win abatements at very high prices are associated with about 40% of the sector's 2020 CO_2 emissions when considered independently of one another. Again, when overlapping effects between abatement options are taken into account, these savings will necessarily decrease.

Figure 5.4 - UK Domestic Aviation Illustrative MACs for 2020 (central and very high fuel prices).

(a) Central: US$70/bbl, £0.31/ltr aviation fuel

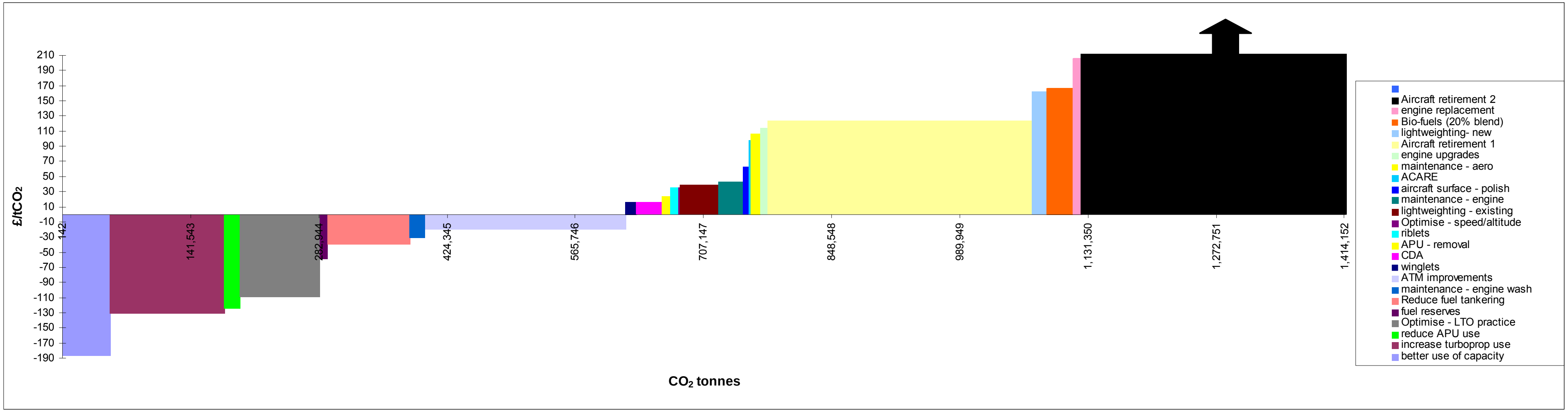
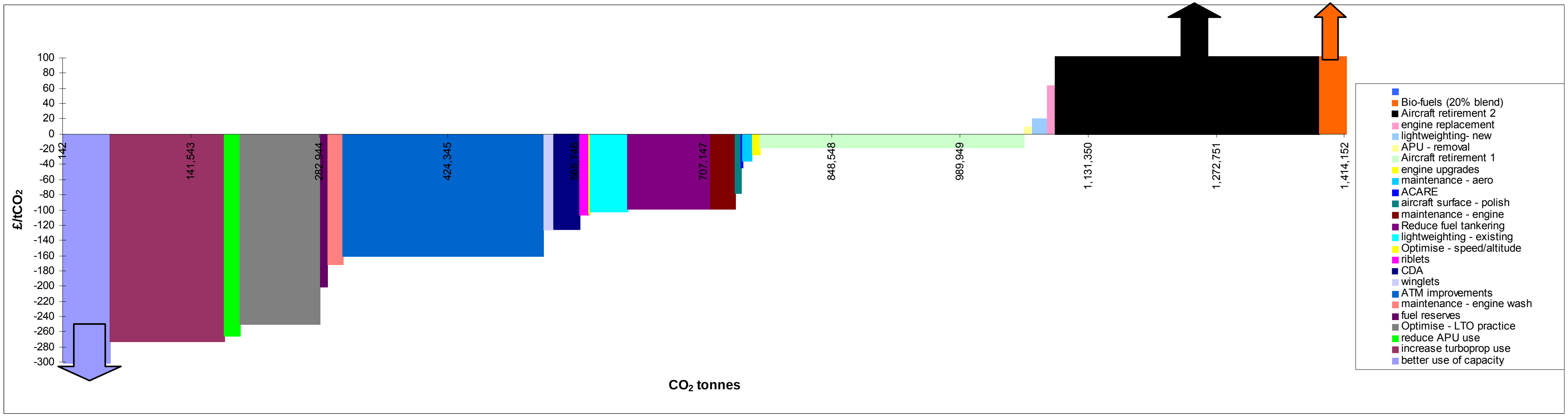


Figure 5.4 - UK Domestic Aviation MAC, 2020 for Central and Very High Oil and Fuel Price Scenarios.

(b) Very High: US$150/bbl, £0.69/ltr aviation fuel



5.5 UK Domestic Aviation MAC for 2050

It was not possible to produce an internally consistent estimate of MAC for 2050. Beyond 2020, most improvement in aviation fuel efficiency is perceived to be linked to operational improvements and technologies embedded within ACARE compliant airplanes. These are commonly assumed to each deliver about 25% savings in fuel consumption per SKO; 50% in total by about 2030.

Thus, many of the abatement options identified for 2020 continue through to 2050 in the form of operational and ACARE type improvements. A number of long term technological options, including synthetic fuels, fuel cell technologies, composite materials, enhanced engine designs, new propeller technologies and new airframe/engine configurations are particularly suited to the short haul UK domestic sector. Some of these options were explored, including the scope for the development of new families of engines, including improved turbo propeller units. It has not been possible to derive reliable estimates of development costs and of likely capital and operating costs for these long term options.

5.6 Sensitivity of Interventions to Fuel Prices

As already shown, the cost of abatements is very sensitive to oil and fuel prices. Table 5.9 shows the percentage change in fuel prices from the central estimate required to make the cost of an intervention equal to zero, that is breakeven. A doubling of oil and fuel prices from their 2007 levels, as experienced during 2008, makes technological and fleet management options associated with early replacement/retirement much more attractive.

Table 5.9 - Sensitivity of Abatement Options to Changes in Oil and Aviation Fuel Prices

ID	Intervention	% change in central fuel cost to breakeven 2007	2020
Technology			
T1	winglets	15%	10%
T2	riblets		25%
T3	lightweighting- new		120%
T4	lightweighting - existing	-15%	30%
T6	aircraft surface - polish	40%	45%
T7	engine replacement		155%
T8	engine upgrades	120%	85%
T10	APU - removal	160%	170%
T12	Bio-fuels		positive
Operational			
O1	ATM improvements		-20%
O2	CDA	3%	10%
O3	Optimise - speed/altitude	20%	25%
O4	Optimise - LTO practice	-90%	-90%
O5	Reduce fuel tankering	-80%	-75%
Fleet Management			
F1	Aircraft retirement 1	80%	90%
F2	Aircraft retirement 2	310%	380%
F3	maintenance - engine	30%	30%
F4	maintenance - aero	90%	80%
F5	maintenance - engine wash	-60%	-30%
F6	fuel reserves	-65%	-50%
F7	increase turboprop use	-75%	negative
F8	better use of capacity	negative	negative
F9	reduce APU use	negative	negative
F10	ACARE		70%

Central fuel price		
oil price	$/barrel	67
aviation fuel price	£/litre	0.33

NB negative = always negative cost
positive = always positive cost

5.7 Summary of Main Points

Numeric estimates of MAC have been derived for the UK domestic aviation sector for 2007, 2012 and 2020, together with a qualitative assessment of options for 2050. A combination of methodological issues and limited data on which to reliably predict the performance and cost of abatement measures requires that the estimates must be regarded as indicative at this stage. The key points arising are:

- A range of interventions could, when considered individually, enable the UK aviation sector to abate up to 14% of its CO_2 emissions at negative or zero cost by 2012, up to 17% if fuel prices rise to 'very high' levels. After this point, MAC appear to rise steeply, with limited opportunity at central oil price forecasts to achieve abatement at costs below £20/ t $CO_{2,}$ the benchmark provided by the current price of CO_2 ETS permits (and the prevailing social cost of carbon).
- By 2020, assuming no major technological breakthrough in airframe or engine performance, the potential for abatement at or below zero cost, with intervention abatement calculated individually, appears to be about 24% of the annual sector total at central fuel prices, with improvements in ATM providing a large share of these benefits.
- These estimates of reductions in emissions consider interventions individually. Emissions savings will necessarily decrease when additivity and overlapping effects between abatement options are taken into account.
- The most cost effective intervention measures in the short to medium term appear to be those associated with: increasing the use of capacity (through for example increased occupancy and consolidation of flights), reducing take-off weight, adopting in flight fuel-saving practices, matching airplanes to the short hauls of the UK sector (through for example increasing use of turbo-prop planes), employing in-situ engine wash maintenance technologies and, by 2020, introducing European-scale ATM improvements that reduce travel distance.
- High fuel prices are likely to encourage early retirement and replacement of airplanes with those that incorporate improved airframe and engine design for fuel efficiency.
- It is difficult to predict the efficacy of intervention measures beyond 2020 that are associated with ACARE compliant standards.
- The estimates derived here should be re-examined for robustness, engaging the aviation community in the process.

6.0 Case Study: MAC for the European International Aviation Sector

This chapter derives estimates of the Marginal Abatement Costs (MAC) for the reduction of emissions from aviation for European based airlines, using the information on aviation activities from the Association of European Airlines (AEA). The AEA includes 36 operators from EU member states and beyond. It includes operators such as Air France, British Airways and Lufthansa operating long haul flights, as well as mainly regional operators. It excludes so-called low-cost operators such as easyJet and Ryanair which were included in the UK domestic case. The AEA-based assessment of European airlines provides insights into MAC for a wider range of aircraft types and journey lengths than that of the UK case.

6.1 Methods

The methods used to derive estimates of MAC of interventions are similar to that described in Chapter 4, with some changes to reflect differences in scale and data availability. Emission estimates were obtained using CORINAIR sources. Estimates of emissions include non-CO_2 species. Aircraft journeys which begin and/or end within the countries of the AEA members, including within country flights are considered. These exclude the journeys of non-AEA member ‘cost operators’. The term European here relates to the AEA member fleets.

Table 6.1 shows the main aircraft categories and airplanes selected to “represent” particular types in the global fleet and European fleets. Selection of representative airplanes was influenced by data availability.

Table 6.1 – Representative aircraft applied to the European aviation sector

Category of Aircraft	Model of Aircraft	global fleet average age (years)	% of category, global fleet	% of category, euro fleet
Turboprop	Bombardier Dash400	N/A	N/A	18%
Regional Jet	Fokker 100	16.4	9%	6%
Single aisle 90-175	A320	7.8	18%	19%
Single aisle 90-175	B737-400	N/A	N/A	8%
Single aisle > 175	B757-200	13.8	60%	55%
Twin-aisle small	B767-300ER	10.97	31%	70%
Twin-aisle medium	A330-300	N/A	N/A	3%
Twin-aisle large	B747-400	13.13	51%	62%

Aircraft activity profiles were derived from AEA sources to show average block hours per year, average journeys per year, average journey time and average journey length (Table 6.2). Estimates of future growth in air traffic and changes in fleet size and composition for the European fleet drew on projections by the UK Department for Transport for estimates of regional and international traffic (Dft, 2007), also taking into account projections made by major aircraft manufacturers.

6.2 European Aviation Fleet MACs for 2007

Drawing on review of scientific literature and industry sources, including stakeholder consultation, Table 6.3 shows the range of abatement options considered and their assumed potential takeup for 2007 for the European fleet, categorised by type of aircraft. The reductions in fuel consumption and emission of CO_2, NO_x and other species was estimated using data and methods from CORINAIR modelled estimates and ICAO test reports.

Table 6.2 - Representative aircraft performance : European operators

category	model	status	average hours/year (hrs)	average journeys/year	average journey time (hrs)	average sector length (km)	(nm)
turboprop	**Dash 400**	in prod.	2431	2181	1.11	448	241.9
regional jet	**Fokker 100**	prod. end 97	2073	1616	1.28	595	321.3
single aisle 90-175	**A320**	in prod.	3022	1725	1.75	965	521.1
single aisle 90-175	**B737-400**	prod. end 2000	3220	1712	1.88	1007	543.7
single aisle >175	**B757-200**	prod. end 2004	2957	1307	2.26	1338	722.5
twin aisle, small	**B767-300**	in prod.	4055	797	5.09	3594	1941
twin aisle, medium	**A330-300**	in prod.	5167	905	5.71	4291	2317
twin aisle, large	**B747-400**	in prod.	5014	570	8.79	7140	3855

Table 6.3 - Assumed potential take-up of abatement interventions, as % of aircraft fleet, by representative type, adopting options in 2007.

abatemment	Dash400	F100	A320	B737-400	B757-200	B767-300	A330-300	B747-400
winglets	0%	0%	0%	25%	25%	0%	0%	0%
riblets	0%	0%	0%	0%	0%	0%	0%	0%
lightweighting- new	0%	0%	0%	0%	0%	0%	0%	0%
lightweighting - existing	50%	50%	50%	50%	50%	50%	50%	50%
blended wing	0%	0%	0%	0%	0%	0%	0%	0%
aircraft surface - polish	10%	10%	10%	10%	10%	10%	10%	10%
engine replacement	0%	0%	0%	0%	0%	0%	0%	0%
engine upgrades	10%	50%	25%	50%	50%	25%	25%	25%
open rotors	0%	0%	0%	0%	0%	0%	0%	0%
APU - removal	50%	50%	50%	50%	50%	50%	50%	50%
APU - tech replacement	0%	0%	0%	0%	0%	0%	0%	0%
Bio-fuels	0%	0%	0%	0%	0%	0%	0%	0%
Alternative fuels	0%	0%	0%	0%	0%	0%	0%	0%
Optimised aircraft design	0%	0%	0%	0%	0%	0%	0%	0%
ACARE	0%	0%	0%	0%	0%	0%	0%	0%
ATM improvements	0%	0%	0%	0%	0%	0%	0%	0%
CDA	10%	10%	10%	10%	10%	10%	10%	10%
Optimise - speed/altitude	25%	25%	25%	25%	25%	25%	25%	25%
Optimise - LTO practice	50%	50%	50%	50%	50%	50%	50%	50%
Reduce fuel tankering	50%	50%	50%	50%	50%	50%	0%	0%
reduce APU use	50%	50%	50%	50%	50%	50%	50%	50%
Aircraft retirement 1	10%	50%	10%	50%	50%	10%	10%	10%
Aircraft retirement 2	10%	50%	10%	50%	50%	10%	10%	10%
maintenance - engine	80%	80%	80%	80%	80%	80%	80%	80%
maintenance - aero	80%	80%	80%	80%	80%	80%	80%	80%
maintenance - engine wash	0%	80%	80%	80%	80%	80%	80%	80%
fuel reserves	75%	75%	75%	75%	75%	75%	75%	75%
increase turboprop use	0%	80%	50%	50%	50%	0%	0%	0%
better use of capacity	80%	80%	60%	60%	60%	40%	40%	40%

Table 6.4 shows the MAC for CO_2 for the European aviation fleet in 2007, assuming the prevailing fuel price of £0.33/ltr (US$73/bbl). It shows, for the assumptions made, the incremental abatement of CO_2 for each successive abatement option introduced in order of increasing abatement cost (£/t CO_2). It is noted that each intervention is considered independently. Table 6.4 also

shows the potential annual abatement attributable to each intervention expressed as a percentage of total annual European aviation fleet CO_2 emissions considering each intervention independently.

Table 6.4 - European Aviation fleet illustrative MAC of CO_2 emission for 2007 (central fuel price £0.33/ltr)

ID	intervenion	tCO_2	£	£/tCO_2	individual abated CO_2 % yr total	cum. abated tCO_2	cum. abated CO_2 % yr total
F8	better use of capacity	1907828	-276085423	-144.7	2.01%	1907828	2.0%
F6	fuel reserves	276908	-26318015	-95.0	0.29%	2184736	2.3%
T4	lightweighting - existing	804296	-73024531	-90.8	0.85%	2989032	3.1%
F5	maintenance - engine wasł	575091	-48589816	-84.5	0.61%	3564123	3.8%
O6	reduce APU use	545316	-43538240	-79.8	0.57%	4109439	4.3%
O4	Optimise - LTO practice	1238490	-98668574	-79.7	1.30%	5347929	5.6%
F7	increase turboprop use	4575823	-268263407	-58.6	4.82%	9923751	10.5%
O3	Optimise - speed/altitude	42204	-1829125	-43.3	0.04%	9965956	10.5%
T1	winglets	106666	-1949694	-18.3	0.11%	10072621	10.6%
F3	maintenance - engine	932744	-7661950	-8.2	0.98%	11005366	11.6%
O5	Reduce fuel tankering	1020936	-8195908	-8.0	1.08%	12026302	12.7%
O2	CDA	40121	385062	9.6	0.04%	12066422	12.7%
T6	aircraft surface - polish	34978	603534	17.3	0.04%	12101400	12.7%
T10	APU - removal	283393	6098267	21.5	0.30%	12384793	13.0%
F4	maintenance - aero	357552	23111784	64.6	0.38%	12742345	13.4%
T8	engine upgrades	284893	24953184	87.6	0.30%	13027238	13.7%
F1	Aircraft retirement 1	2512437	322233720	128.3	2.65%	15539675	16.4%
F2	Aircraft retirement 2	2512437	1054898879	419.9	2.65%	18052112	19.0%

Eleven abatement options have potential to achieve emission abatements at negative net cost, that is offering overall financial benefit. Most are operational or fleet management interventions. Better use of capacity and increased turboprop use provide the greatest abatement potential, offering particular advantage for short haul traffic. As noted earlier for the UK domestic case, there is evidence from stakeholders that many of these interventions are now being introduced in response to high fuel prices. Abatement options when considered independently are associated with a reduction of up to 13% of the sector's 2007 CO_2 emissions. However, the cumulative effects are likely to be less.

Abatement options that reduce fuel burn and CO_2 emissions also have potential to reduce NO_x and other emissions. Table 6.5 shows MAC for NOx for the European aviation fleet in 2007 assuming a fuel price of £0.33/ltr (oil price of US$73/bbl). It shows, for the assumptions made, the incremental abatement of NO_x for each successive abatement option introduced in order of increasing abatement cost (£/kg NO_x)

Table 6.5 - European Aviation fleet illustrative MAC of NO_x emissions for 2007 (central fuel price £0.33/ltr)

ID	intervenion	kgNOx	£	£/kgNOx	individual abated NOx % yr total	cum. Abated KgNOx	cum. abated NOx % yr total
O4	Optimise - LTO practice	2186204	-98668574	-45.1	0.55%	2186204	0.6%
F8	better use of capacity	8068303	-276085423	-34.2	2.03%	10254507	2.6%
O6	reduce APU use	1478761	-43538240	-29.4	0.37%	11733268	3.0%
F6	fuel reserves	1179329	-26318015	-22.3	0.30%	12912597	3.3%
T4	lightweighting - existing	3488730	-73024531	-20.9	0.88%	16401327	4.1%
F5	maintenance - engine wasl	2449998	-48589816	-19.8	0.62%	18851326	4.7%
F7	increase turboprop use	18689037	-268263407	-14.4	4.71%	37540363	9.5%
O3	Optimise - speed/altitude	180842	-1829125	-10.1	0.05%	37721205	9.5%
T1	winglets	365022	-1949694	-5.3	0.09%	38086226	9.6%
O5	Reduce fuel tankering	4220612	-8195908	-1.9	1.06%	42306838	10.7%
F3	maintenance - engine	3972478	-7661950	-1.9	1.00%	46279316	11.7%
O2	CDA	446950	385062	0.9	0.11%	46726266	11.8%
T6	aircraft surface - polish	148968	603534	4.1	0.04%	46875234	11.8%
T10	APU - removal	1230686	6098267	5.0	0.31%	48105920	12.1%
F4	maintenance - aero	1522783	23111784	15.2	0.38%	49628703	12.5%
T8	engine upgrades	1170071	24953184	21.3	0.29%	50798775	12.8%
F1	Aircraft retirement 1	9657524	322233720	33.4	2.43%	60456299	15.2%
F2	Aircraft retirement 2	9657524	1054898879	109.2	2.43%	70113823	17.7%

Eleven interventions have potential to achieve NO_x emission abatements at negative net cost, and most of these are operational or fleet management interventions. Optimising LTO practice is the most cost effective intervention due to the weighting of NO_x emissions generation to LTO stage. Better use of capacity and increase in turboprop use provide the greatest abatement, with 2.3 and 4.71% of annual emission abated. These win-win NO_x abatements are achieved by same win-win CO_2 abatements, although the ordering is slightly different. However, this estimate is very uncertain. The main reason is the uncertainty associated with the relationship between fuel burn and NO_x emissions, although allowance has been made here for differential emissions of NO_x for different stages in the LTO-cruise cycle. It is noted that currently available cost effective interventions for NO_x do not involve major changes in engine technologies that lead to tradeoffs between CO_2 and NO_x.

6.3 MAC by Airplane Type

MACs can be estimated for individual categories of airplanes working particular routes. Table 6.6 shows MAC for CO_2 abatement for the Airbus 320 type aircraft of the European fleet in 2007, assuming the prevailing fuel price of £0.33/ltr (oil price of US$73/bbl). Nine interventions have potential to achieve emission abatements at negative net cost, and most of these are operational or fleet management interventions. Better use of capacity, optimised LTO practice and substitution by turboprops provide the greatest abatements at zero net cost, reflecting the relatively high use of A320 for short haul flights.

Table 6.6 - European operated Airbus 320 aircraft illustrative MAC of CO_2 emission for 2007 (central fuel price £0.33/ltr)

ID	intervenion	tCO2	£	£/tCO2	individual abated CO2 % yr total	cum. abated tCO2	cum. abated CO2 % yr total
F8	better use of capacity	700	-125547	-179	3.43%	700	3.4%
O6	reduce APU use	377	-40091	-106	1.84%	1077	5.3%
O4	Optimise - LTO practice	756	-79371	-105	3.70%	1833	9.0%
F5	maintenance - engine wasl	138	-13027	-94	0.68%	1971	9.6%
F6	fuel reserves	70	-6338	-91	0.34%	2041	10.0%
T4	lightweighting - existing	300	-26398	-88	1.47%	2340	11.5%
O2	CDA	133	-8294	-62	0.65%	2473	12.1%
F7	increase turboprop use	3866	-21303	-6	18.92%	6339	31.0%
O3	Optimise - speed/altitude	29	-67	-2	0.14%	6368	31.2%
O5	Reduce fuel tankering	761	2255	3	3.72%	7129	34.9%
F3	maintenance - engine	221	7371	33	1.08%	7349	36.0%
T10	APU - removal	105	4056	38	0.52%	7455	36.5%
T6	aircraft surface - polish	66	5920	89	0.32%	7521	36.8%
F4	maintenance - aero	85	11724	139	0.41%	7606	37.2%
F1	Aircraft retirement 1	2759	431844	157	13.50%	10364	50.7%
T8	engine upgrades	184	33146	180	0.90%	10548	51.6%
F2	Aircraft retirement 2	2759	1497006	543	13.50%	13307	65.1%

Table 6.7 shows MAC for CO_2 for the Boeing 747-400 type aircraft of the European aviation fleet in 2007, assuming the prevailing fuel price of £0.33/ltr (oil price of US$73/bbl). Ten interventions have potential to achieve emission abatements at negative net cost, and most of these are operational or fleet management interventions. Better use of capacity and light-weighting existing aircraft provide the greatest abatement at negative cost. The scope for

reducing fuel burn tends to be lower on long haul flights due the increased proportion of flight time in cruise mode and better matching of airplanes suited to long haul journeys.

Table 6.7 - European operated Boeing 747-400 aircraft illustrative MAC of CO_2 emission for 2007 (central fuel price £0.33/ltr)

ID	intervenion	tCO2	£	£/tCO2	individual abated CO_2 % yr total	cum. abated tCO_2	cum. abated CO_2 % yr total
F8	better use of capacity	5332	-864062	-162	3.81%	5332	3.8%
F6	fuel reserves	479	-59192	-124	0.34%	5810	4.2%
T4	lightweighting - existing	2124	-240453	-113	1.52%	7934	5.7%
F5	maintenance - engine wasl	945	-93358	-99	0.68%	8879	6.3%
O3	Optimise - speed/altitude	241	-17683	-73	0.17%	9119	6.5%
O4	Optimise - LTO practice	1000	-61945	-62	0.71%	10119	7.2%
O6	reduce APU use	381	-23324	-61	0.27%	10500	7.5%
T6	aircraft surface - polish	453	-15060	-33	0.32%	10953	7.8%
T8	engine upgrades	1259	-36085	-29	0.90%	12213	8.7%
F3	maintenance - engine	1511	-34745	-23	1.08%	13724	9.8%
T10	APU - removal	749	2498	3	0.54%	14473	10.3%
F4	maintenance - aero	579	12073	21	0.41%	15052	10.8%
O2	CDA	182	9651	53	0.13%	15234	10.9%
F1	Aircraft retirement 1	18891	1357579	72	13.50%	34125	24.4%
F2	Aircraft retirement 2	18891	2422741	128	13.50%	53016	37.9%

By way of example, Figure 6.1 contains (based on Table 6.4) a MAC curve for CO_2 for 2007 for the European (AEA) fleet showing the incremental cost of reducing emissions by successive amounts. The win-win opportunities under prevailing fuel prices are apparent. Marginal costs of abatement rise steeply beyond the point where the MAC curve crosses the breakeven point (at £0/t CO_2) indicating that achieving further reductions in CO_2 become relatively expensive.

Figure 6.1 - European Aviation fleet illustrative MAC diagram of CO_2 emission for 2007 (central fuel price £0.33/ltr)

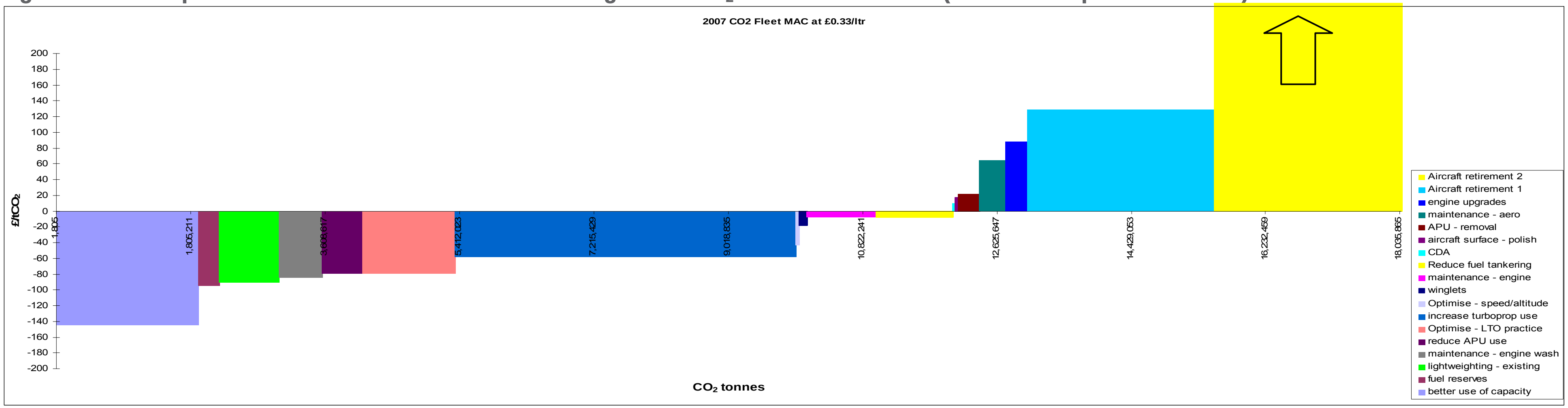


Figure 6.2 – European Aviation fleet illustrative MAC diagram of NO_x emission for 2007 (central fuel price £0.33/ltr)

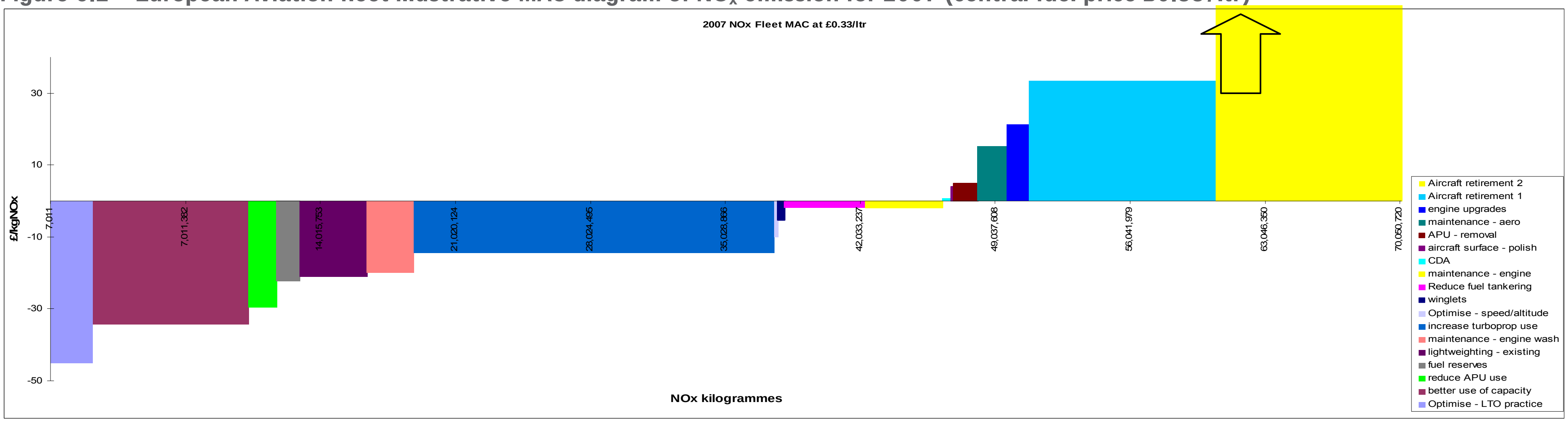


Figure 6.3 - European operated A320 aircraft MAC diagram of CO_2 emission for 2007 (central fuel price £0.33/ltr)

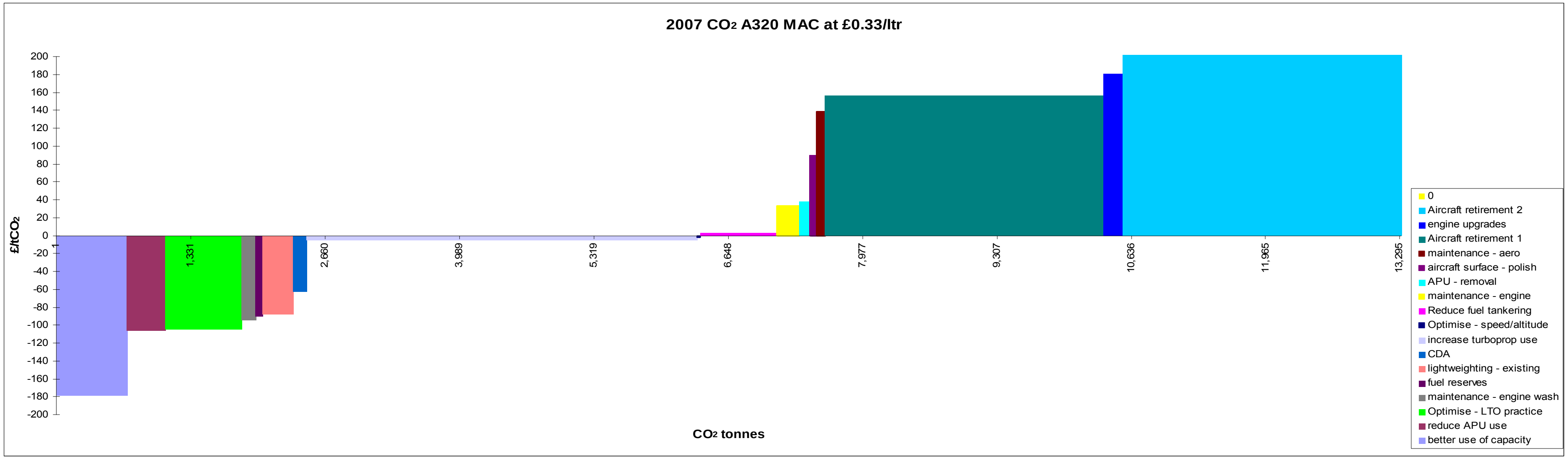
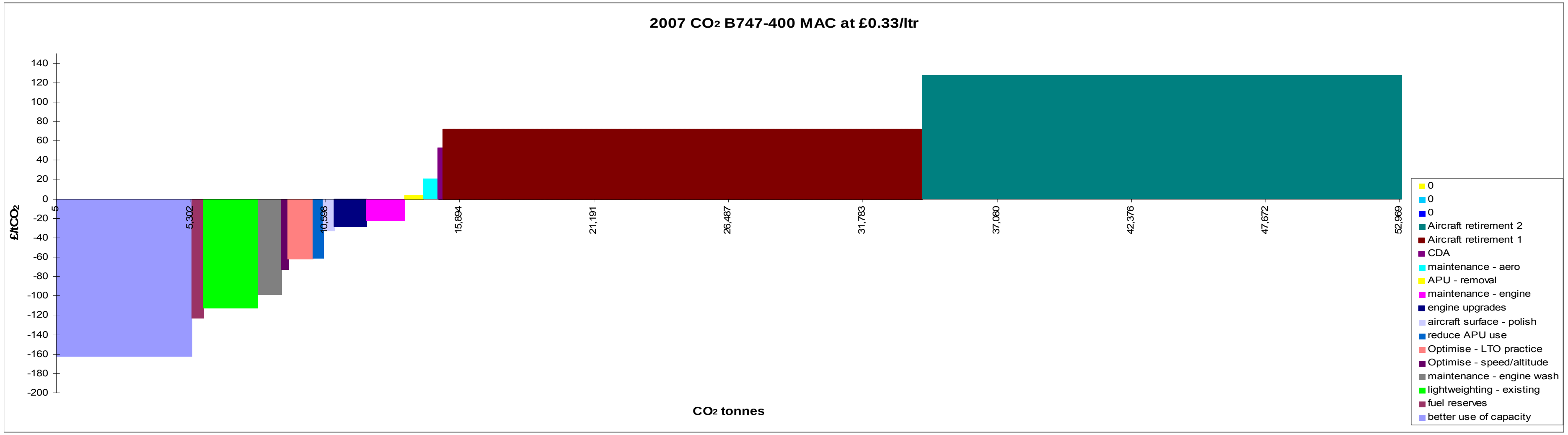


Figure 6.4 - European operated B747-400 aircraft MAC diagram of CO_2 emission for 2007 (central fuel price £0.33/ltr)



6.4 European Aviation fleet MAC's for 2012

Table 6.8 shows the MAC for CO_2 for the European aviation fleet in 2012 for assumed takeup of abatement options (detailed in Appendix 6) and the central fuel price estimate. Eleven abatement options have potential to achieve emission abatements at negative net cost, that is offering overall financial benefit. Most are operational or fleet management interventions. Better use of capacity and increased turboprop use provide the greatest abatement potential, offering particular advantage for short haul traffic. Abatement options when considered independently are associated with a reduction of up to 15% of the sector's 2007 CO_2 emissions. However, the cumulative effects are likely to be less.

Table 6.8 - European Aviation fleet illustrative MAC of CO_2 emission for 2012 (central fuel price £0.29/ltr)

ID	intervenion	tCO2	£	£/tCO2	individual abated CO2 % yr total	cum. abated tCO2	cum. abated CO2 % yr total
F8	better use of capacity	2749689	-364607961	-132.6	2.40%	2749689	2.4%
F6	fuel reserves	379467	-31358240	-82.6	0.33%	3129156	2.7%
T4	lightweighting - existing	1361520	-106689568	-78.4	1.19%	4490676	3.9%
F5	maintenance - engine wash	738832	-53276634	-72.1	0.64%	5229508	4.6%
O6	reduce APU use	791242	-54470064	-68.8	0.69%	6020751	5.2%
O4	Optimise - LTO practice	1797024	-122747525	-68.3	1.57%	7817775	6.8%
F7	increase turboprop use	6515647	-308170937	-47.3	5.68%	14333422	12.5%
T2	riblets	510315	-16731601	-32.8	0.44%	14843737	12.9%
O3	Optimise - speed/altitude	102063	-3140739	-30.8	0.09%	14945800	13.0%
O5	Reduce fuel tankering	1481358	-8849390	-6.0	1.29%	16427158	14.3%
T1	winglets	291120	-547165	-1.9	0.25%	16718278	14.6%
F3	maintenance - engine	1198317	5021324	4.2	1.04%	17916595	15.6%
T10	APU - removal	479731	11770860	24.5	0.42%	18396326	16.0%
T6	aircraft surface - polish	211468	6272017	29.7	0.18%	18607794	16.2%
O2	CDA	121280	4716128	38.9	0.11%	18729074	16.3%
F4	maintenance - aero	459355	35390397	77.0	0.40%	19188429	16.7%
T8	engine upgrades	636597	59335676	93.2	0.55%	19825026	17.3%
F1	Aircraft retirement 1	6000181	780867106	130.1	5.23%	25825207	22.5%
F2	Aircraft retirement 2	6000181	2299213452	383.2	5.23%	31825388	27.7%

Table 6.9 shows indicative MAC for NOx abatement for the European fleet, indicating a similar pattern and degree of abatement, for the assumptions made, to that of CO_2 abatement.

Table 6.9 - European Aviation fleet illustrative MAC of NOx emission for 2012 (central fuel price £0.29/ltr)

ID	intervenion	kgNOx	£	£/kgNOx	individual abated NOx % yr total	cum. Abated KgNOx	cum. abated NOx % yr total
O4	Optimise - LTO practice	3172139	-122747525	-38.7	0.66%	3172139	0.7%
F8	better use of capacity	11673668	-364607961	-31.2	2.43%	14845807	3.1%
O6	reduce APU use	2145653	-54470064	-25.4	0.45%	16991460	3.5%
F6	fuel reserves	1616118	-31358240	-19.4	0.34%	18607578	3.9%
T4	lightweighting - existing	5905758	-106689568	-18.1	1.23%	24513336	5.1%
F5	maintenance - engine wash	3147567	-53276634	-16.9	0.66%	27660904	5.8%
F7	increase turboprop use	26754753	-308170937	-11.5	5.57%	54415656	11.3%
T2	riblets	2186652	-16731601	-7.7	0.46%	56602308	11.8%
O3	Optimise - speed/altitude	437330	-3140739	-7.2	0.09%	57039639	11.9%
O5	Reduce fuel tankering	6124025	-8849390	-1.4	1.28%	63163663	13.2%
T1	winglets	1024037	-547165	-0.5	0.21%	64187701	13.4%
F3	maintenance - engine	5103530	5021324	1.0	1.06%	69291231	14.4%
O2	CDA	1351075	4716128	3.5	0.28%	70642306	14.7%
T10	APU - removal	2083319	11770860	5.7	0.43%	72725624	15.1%
T6	aircraft surface - polish	900623	6272017	7.0	0.19%	73626247	15.3%
F4	maintenance - aero	1956353	35390397	18.1	0.41%	75582601	15.7%
T8	engine upgrades	2659047	59335676	22.3	0.55%	78241648	16.3%
F1	Aircraft retirement 1	23978238	780867106	32.6	4.99%	102219886	21.3%
F2	Aircraft retirement 2	23978238	2299213452	95.9	4.99%	126198124	26.3%

Figures 6.5 and 6.6 contain indicative MAC curves for CO_2 and NOx respectively for 2012. An analysis of abatement options for short-medium haul A320 and long haul B747 representative aircraft for 2012 (Figures 6.7 and 6.8) show similar patterns of abatement to that for 2007. There appears to be considerable scope for low cost abatement for the short and medium haul sectors.

Figure 6.5 – European Aviation fleet illustrative MAC diagram of CO_2 emission for 2012 (central fuel price £0.29/ltr)

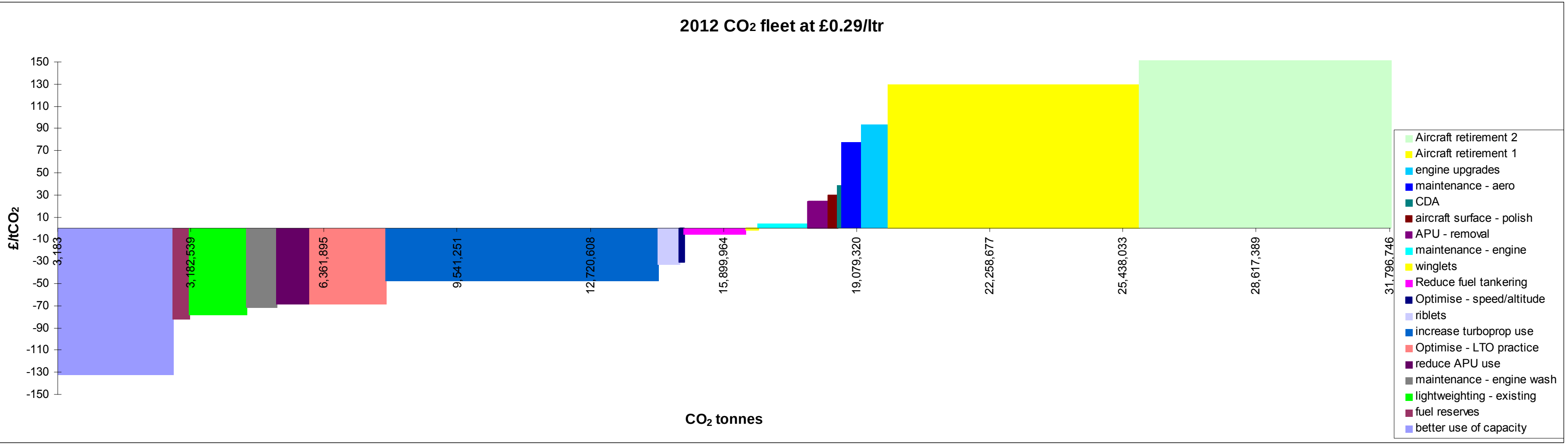


Figure 6.6 – European Aviation fleet illustrative MAC diagram of NOx emission for 2012 (central fuel price £0.29/ltr)

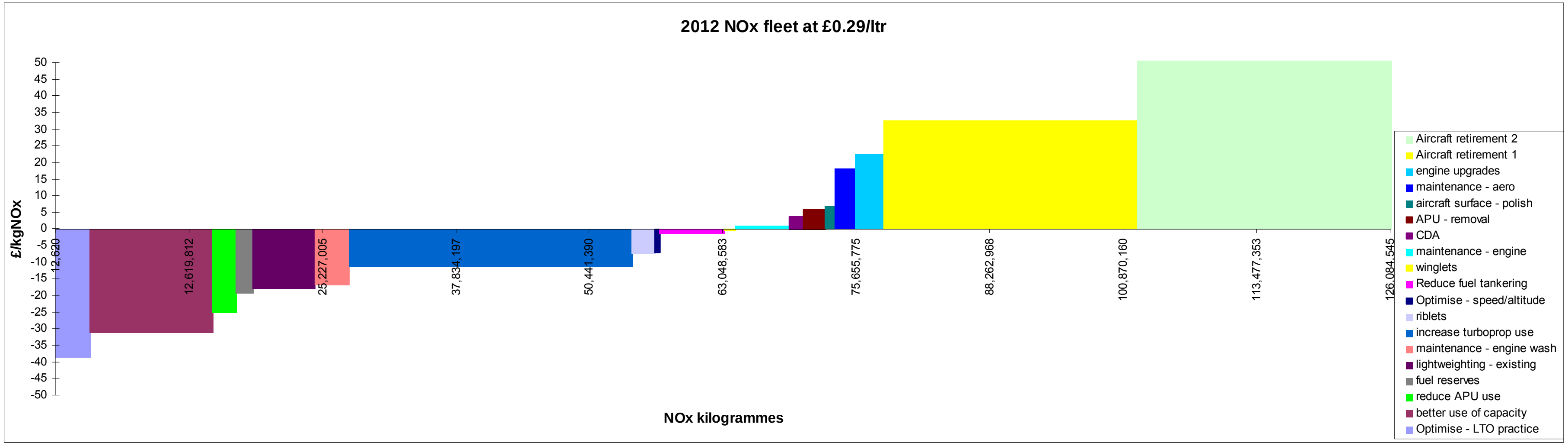


Figure 6.7 - European operated A320 aircraft MAC diagram of CO_2 emission for 2012 (central fuel price £0.29/ltr)

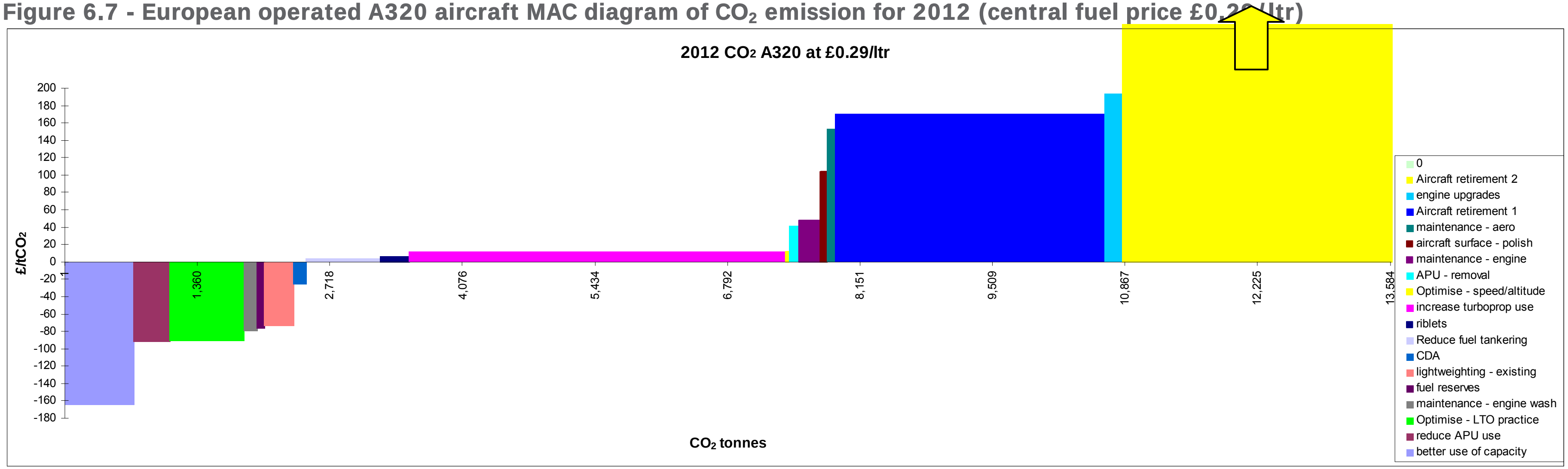
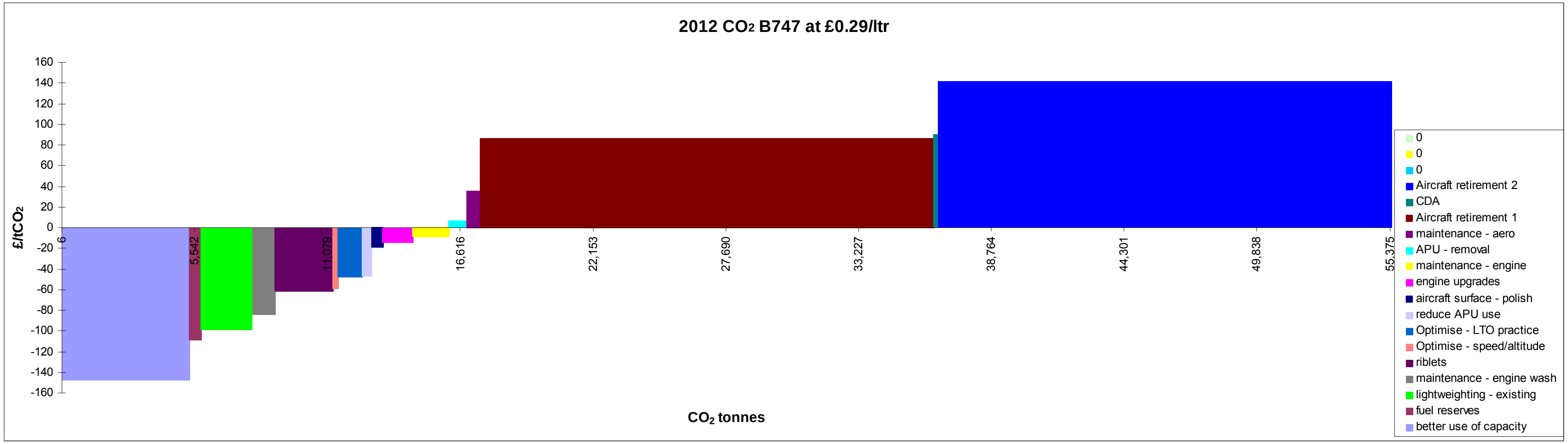


Figure 6.8 - European operated B747-400 aircraft MAC diagram of CO2 emission for 2012 (central fuel price £0.29/ltr)



MACs are sensitive to the price of aviation fuel. Table 6.10 indicates the likely impact of a "very high" estimate for fuel price on the MAC for CO_2 emissions in 2012 compared with the "central" fuel price. Abatement options become significantly more attractive and the boundary of win–win options is extended.

Table 6.10 - European Aviation Fleet Illustrative MACs for CO_2 emissions in 2012 by Oil Price Scenario

	oil price scenario	**central**		**very high**
	US$/brl oil	75		150
	£/l aviation fuel	0.33		0.68
ID	**intervenion**	**£/tCO2**	**ID**	**£/tCO2**
F8	better use of capacity	-132.6	F8	-196.820
F6	fuel reserves	-82.6	F6	-148.107
T4	lightweighting - existing	-78.4	T4	-143.977
F5	maintenance - engine wash	-72.1	F5	-137.456
O6	reduce APU use	-68.8	O4	-128.275
O4	Optimise - LTO practice	-68.3	O6	-126.893
F7	increase turboprop use	-47.3	O2	-115.693
T2	riblets	-32.8	F7	-115.020
O3	Optimise - speed/altitude	-30.8	O3	-97.099
O5	Reduce fuel tankering	-6.0	T2	-85.550
T1	winglets	-1.9	T1	-76.340
F3	maintenance - engine	4.2	F3	-61.279
T10	APU - removal	24.5	T6	-35.810
T6	aircraft surface - polish	29.7	O5	-16.814
O2	CDA	38.9	T10	8.610
F4	maintenance - aero	77.0	F4	11.574
T8	engine upgrades	93.2	T8	27.044
F1	Aircraft retirement 1	130.1	F1	62.282
F2	Aircraft retirement 2	383.2	F2	315.332

6.5 European Aviation fleet MACs for 2025

By 2025, it is expected that there will be considerably more scope for the take up of new technology, operational and fleet management options, such as light-weighting of new aircraft, optimising LTO cycles, improved air traffic management, improved LTO, replacement by new generation aircraft, and initial appearance of ACARE compliant airplanes (see Appendix 5).

Figures 6.9 and 6.10 show indicative MAC for 2025 for the European Fleet. ATM improvements, better use of capacity and increased use of turbo props offer potential win-win options. Considered individually, win-win and relatively low interventions could abate about 30% of C02 emissions.

The sensitivity of MAC to fuel prices in 2025 is shown in Table 6.11. The very high fuel price scenario considerably extend the range of interventions that are potentially win-win options.

Table 6.11 - European Aviation Fleet Illustrative MACs for CO_2 emissions in 2025 by Oil Price Scenario

	oil price scenario	central		very high
	US$/brl oil	75		150
	£/l aviation fuel	0.33		0.68
ID	**intervention**	**£/tCO2**	**ID**	**£/tCO2**
F8	better use of capacity	-148	O2	-279
F6	fuel reserves	-96	F8	-268
F5	maintenance - engine wash	-85	F6	-218
O6	reduce APU use	-82	F5	-206
O4	Optimise - LTO practice	-81	T1	-195
O1	ATM improvements	-79	O4	-194
F7	increase turboprop use	-63	O6	-191
T1	winglets	-58	F7	-189
T2	riblets	-44	O1	-173
O3	Optimise - speed/altitude	-43	O3	-167
T4	lightweighting - existing	-33	T4	-155
T3	lightweighting- new	-23	T3	-147
O5	Reduce fuel tankering	-8	T2	-141
F3	maintenance - engine	-7	F3	-129
T5	blended wing	10	T5	-127
O2	CDA	11	T9	-122
T9	open rotors	15	T6	-104
T6	aircraft surface - polish	18	T15	-86
T10	APU - removal	22	F4	-56
T15	ACARE aircraft	51	T8	-49
T14	Optimised aircraft design	57	T7	-47
F4	maintenance - aero	66	F1	-39
T8	engine upgrades	72	T14	-29
T7	engine replacement	73	O5	-28
F1	Aircraft retirement 1	83	T10	-9
T12	Bio-fuels	163	F2	83
F2	Aircraft retirement 2	205	T12	336

6.6 Sensitivity of MAC to Fuel Prices –breakeven analysis

As previously shown, MAC are sensitive to fuel prices. Table 6.12 indicates the degree to which fuel prices would need to change from their central estimate

Figure 6.9 - European Aviation fleet illustrative MAC diagram of CO_2 emission for 2025 (central fuel price £0.33/ltr)

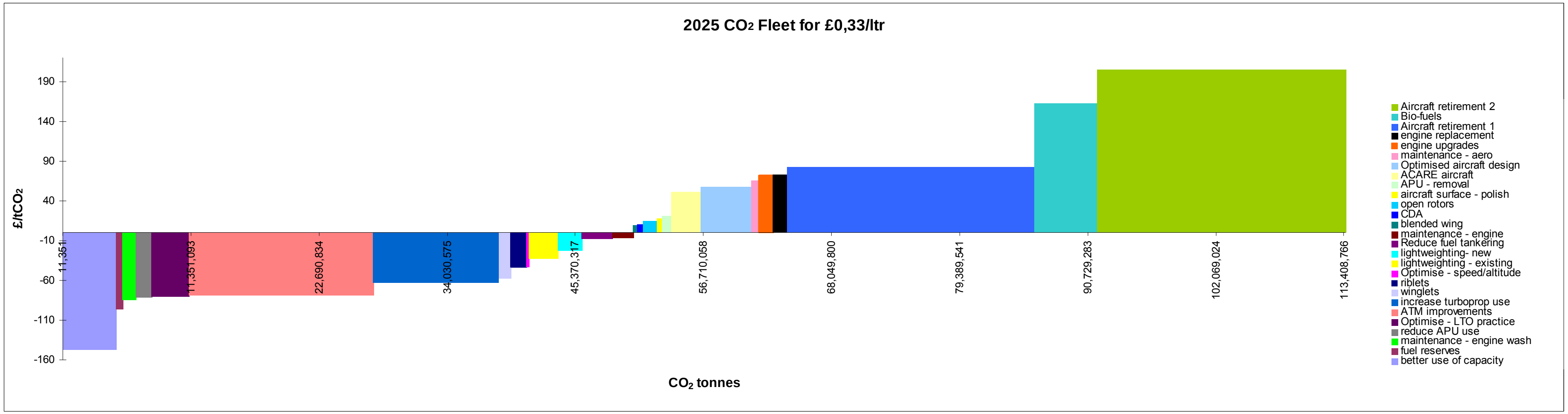
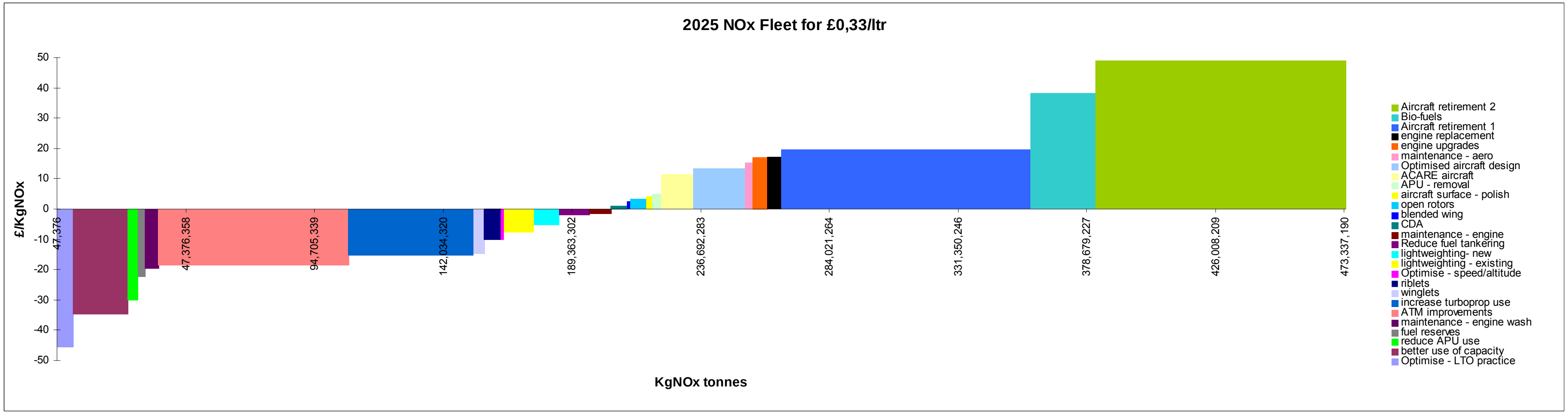


Figure 6.10 - European Aviation fleet illustrative MAC diagram of NOx emission for 2025 (central fuel price £0.33/ltr)



to make MAC breakeven (that is equal zero). For example, a 15% decrease in fuel prices would make winglets breakeven compare to their estimated win-win potential in 2007. A 79% increase in fuel prices would be needed to make APU removal worthwhile. The very high price scenario for fuel is about twice that of the central price scenario.

Table 6.12 - Sensitivity Analysis based on CO_2 fleet emissions and fuel price

ID	Intervention	% change in central fuel cost to break even	
		2007	2025
Technical			
T1	winglets	-15%	-45%
T2	riblets	~	-48%
T3	lightweighting- new	~	-21%
T4	lightweighting - existing	-80%	-27%
T5	blended wing	~	9%
T6	aircraft surface - polish	15%	15%
T7	engine replacement	~	64%
T8	engine upgrades	76%	65%
T9	open rotors	~	12%
T10	APU - removal	79%	73%
T11	APU - tech replacement	~	~
T12	Bio-fuels	~	positive
T13	Alternative fuels	~	~
T14	Optimised aircraft design	~	70%
T15	ACARE aircraft	~	42%
Operational			
O1	ATM improvements	~	-82%
O2	CDA	3%	3%
O3	Optimise - speed/altitude	-36%	-32%
O4	Optimise - LTO practice	-76%	-76%
O5	Reduce fuel tankering	-42%	-45%
O6	reduce APU use	-79%	-85%
Fleet management			
F1	Aircraft retirement 1	106%	73%
F2	Aircraft retirement 2	348%	179%
F3	maintenance - engine	-6%	-6%
F4	maintenance - aero	58%	58%
F5	maintenance - engine wash	-75%	-73%
F6	fuel reserves	-85%	-85%
F7	increase turboprop use	-48%	-52%
F8	better use of capacity	negative	negative

Central fuel price			
	oil price	$/barrel	73
	aviation fuel price	£/litre	0.33

NB

negative = always neagtive cost
positive = always positive cost

6.7 Summary of Main Points

The preceding example derived estimates of indicative MAC for a range of interventions to reduce aviation emissions from European national and international carriers. It is based on the profile of AEA members and therefore does not provide complete coverage of all European operators. This is not a major concern for the purposes of the study, given that the methods can be applied at a range of scales. A number of points arising from the case are note worthy.

- A range of interventions could, when considered individually, enable the UK aviation sector to abate up to about 15 % of its CO_2 emissions at negative or zero cost by 2012, up to 17% if fuel prices rise to 'very high' levels. After this point, MAC appear to rise steeply, with limited opportunity at central oil price forecasts to achieve abatement at costs below £20/ t CO_2, the benchmark provided by the current price of CO_2 ETS permits (and the prevailing social cost of carbon).
- It was not possible, for the purpose here, to derive a meaningful composite CO_2 equivalent which combined CO_2 and NOx for aviation. Hence MACs were derived separately for CO_2 and NOx abatement. It is noted however that for the most part for the interventions considered, the two are positively correlated. Further research is needed to provide a better understanding of the interrelationships between the costs and effectiveness of measures to abate CO_2 and NO_x.
- There are differences in the MAC of interventions for short-medium and long haul traffic. There appears to be considerably more scope for win-win and low cost interventions in the short-medium haul sectors where landing and take-off account for a larger proportion of fuel and emissions, and capacity utilisation and matching of airplanes to journey length are less efficient than in the long haul sector. It is noted that the low cost airlines, which demonstrate higher than average capacity utilisation, are not included in the assessment here.
- By 2025, assuming no major technological breakthrough in airframe or engine performance, the potential for abatement at or below zero cost, with intervention abatement calculated individually, appears to be about 30% of the annual sector total at central fuel prices, with improvements in ATM providing a large share of these benefits.

- As for the UK case, the most cost effective intervention measures in the short to medium term appear to be those associated with: increasing the use of capacity (through for example increased occupancy and consolidation of flights), reducing take-off weight, adopting in flight fuel-saving practices, better matching of airplanes to short hauls sectors (through for example increasing use of turbo-prop planes), employing in-situ engine wash maintenance technologies and, by 2020, introducing European-scale ATM improvements that reduce travel distance.
- As for the UK case, high fuel prices are likely to encourage early retirement and replacement of airplanes with those that incorporate improved airframe and engine design for fuel efficiency.
- The estimates derived here should be re-examined for robustness, engaging the aviation community in the process.

7.0 Conclusions and Recommendations

The broad purpose of this study is to help inform cost effective strategies to control the environmental effects of aviation, through the development and use of an accounting framework to assess the feasibility and cost-effectiveness of measures to reduce the emissions to the environment of aviation. This chapter summarises the main conclusions of the study against its objectives, interprets the findings with respect to policy and makes recommendations for further work with respect to enhancing knowledge to enable the aviations sector to meet its environmental goals.

7.1 Conclusions

Conclusions are drawn with respect to the following study objectives.

Objective 1 sets out to identify the relationship between the characteristics of aviation and environmental emissions, and the scope for improving the environmental performance of the aviation sector.

Representative aircraft. The study used selected representative aircraft to present larger groupings of aircraft types and categories of use for the purpose of linking aviation activities with emissions. These representative aircraft are indicative of generic categories of size (passenger numbers) and journey length, whether short, medium or long haul. Data sets are available to construct regional and global profiles of aviation activity, although the degree of detail varies. A range of air traffic forecasts, available from international, government and industry sources, can be used to determine aviation activity at different scales. All of these predict continued growth in aviation traffic.

Estimates of emissions from aircraft in use were obtained from three major sources, namely ICAO, manufacturers estimates and modelled results. These vary in the coverage of emissions and the different stages of the LTO and cruise cycle, and in suitability for estimating MAC for specific interventions. Although various organisations predict that the aviation sector will be able in future to achieve considerable improvements in fuel efficiency, reduce CO_2 emissions and meet more stringent NO_x emissions standards, it is not clear whether such improvements are technically or commercially feasible. Much depends on the inducements provided by fuel prices and environmental regulation.

Data limitations. It was found that, although there is considerable interest in estimating MACs for aviation, there are considerable gaps in data and methods to enable this to be done with confidence. It is particularly difficult to estimate MAC for medium to long term technological changes that require considerable upfront investment in research and development and possible changes in behaviour, both by service providers and users.

Categories of abatement measures. The study identified three broad categories of abatement measures with scope to improve the efficiency of fuel consumption and reduce CO_2 and other emissions, notably NO_x. These comprise airframe and engine technology, operational improvements and fleet management.

Consultation with stakeholders confirmed that they apply a range of criteria to assess the feasibility and acceptability of these abatement options. These include effectiveness, costs, operational convenience and compatibility with business models and practices. It is clear that actions to reduce emissions have been driven directly by regulatory limits on emissions and indirectly by increases in fuel prices that promote fuel efficiency. While there is some agreement amongst stakeholders on the potential theoretical saving in fuel and reduction of emissions that can be achieved by these interventions, there is considerable uncertainty regarding their operational practicability and cost.

Changing emphasis. Most interventions in the past have focussed on meeting local air quality and noise standards that are set either internationally or at specific airports. Concern about climate change, however, has reoriented attention towards reducing CO_2 mainly by promoting increased fuel efficiency. Fuel efficiency has always been a critical commercial driver of technology change, but now concerns of global warming provide an added impetus.

Objective (ii) set out to determine, in broad terms at this stage, the cost effectiveness of alternative 'programmes of measures' to control environmental effects, and thereby the marginal costs of abatement

An analytical framework was developed that systematically determines the relative cost effectiveness of alternative measures to reduce emissions from aviation, notably CO_2, NO_x and a range of other species. The framework combines information on aviation activity profiles and baseline 'no-intervention' emissions, now and into the future, against which the efficacy of interventions can be assessed. The framework comprises a series of linked spreadsheets that contain data and estimation routines to calculate marginal abatement costs for a range of interventions to control emissions. Estimates are applied to specific types of aircraft operating specific types of journeys, allowing for the differential effect of abatements on different stages of the LTO-cruise cycle.

Case Studies. The application of the framework was demonstrated using two case studies. The case of the UK domestic sector focuses on reduced CO2 emissions. The case of the European-based sector includes long distance international traffic and covers CO_2, NO_x and selected other species. Numeric estimates of MAC have been derived for these cases for 2007, 2012/15 and 2020/25, together with a qualitative assessment of options for 2050. A combination of methodological issues and limited data requires that the estimates must be regarded as indicative at this stage.

Scope for abatement. The cases revealed that a range of interventions could enable the aviation sector to abate about 12-15% of its CO_2 (and related) emissions at negative or zero cost by 2012, and more than this if fuel prices rise to 'very high' levels. Analysis suggests, however, that after this point MAC rise steeply, with limited opportunity at central oil price forecasts to achieve abatement at costs below £20/ t CO_2, the benchmark provided by the current price of CO_2 ETS permits (and the prevailing social cost of carbon). By 2020/5 the UK and EU aviation cases reported here suggest that the potential for abatement at or below zero cost is about 25% of the annual sector total at central fuel prices, with improvements in ATM providing a large share of these benefits. These estimates of reductions in emissions consider interventions individually. Emissions reductions will be lower once overlapping effects between abatement options are taken into account.

Cost-effective abatement options. Analysis showed that the most cost-effective intervention measures in the short to medium term appear to be those associated with: increasing the use of capacity (through for example increased occupancy and consolidation of flights), reducing take-off weight, adopting in flight fuel-saving practices, matching airplanes to the short hauls of the UK and European sectors (through for example increasing use of turbo-prop planes), employing in-situ engine wash maintenance technologies and, by 2020, introducing European-scale ATM improvements that reduce travel distance. High fuel prices are likely to encourage early retirement and replacement of airplanes with those that incorporate improved airframe and engine design for fuel efficiency. There is too much uncertainty regarding the development costs for new technologies to construct MAC beyond 2020. This includes uncertainty about achieving ACARE compliant standards. In conclusion, it is considered that objective (ii) has been met though the development and demonstration of an accounting framework for MAC for aviation.

Objective (iii) set out to determine the main technical trade-offs and interdependencies amongst different environmental emissions, and the implications for assessing the cost effectiveness of interventions which affect different emissions in different ways.

Searching for a unified metric. A review of research and industry literature, combined with stakeholder consultation, identified interdependencies amongst emissions, and hence amongst abatement measures. It was hoped to derive a meaningful single unified metric, such as the CO_2 equivalent (CO_2e) used in GHG accounting, to represent the range of emissions species from aviation. However, this was not possible because many of the emissions from aviation, such as NOx, produced by exhaust gases, have secondary effects that are not well defined, especially as they occur at different altitudes. Furthermore, some emissions, such as NO_x, hydrocarbons and particulates have primary effects on Local Air Quality (LAQ) rather than (or as well as) on global atmospheric conditions, such that a common metric is inappropriate. Furthermore, a common metric between these LAQ-related emissions would itself need to cover the wide range of impacts on human health. It was not possible to find research evidence that measured aviation-related emissions reliably in this way. There is scope, however, for integrating these diverse emissions by estimating the combined costs of their effects

Interdependencies: CO_2 and NO_x. The study explored evidence of the trade-off and synergies amongst options to abate emissions. In most cases abatement measures designed to reduce fuel burn and CO_2 emissions result in corresponding reductions in NO_x emissions at both ground level and cruise altitude, with little or no impact on noise. But there are a few potential exceptions. Interdependencies may arise with major changes to engine technology designed to improve fuel efficiency. There is some evidence, for example, of a CO_2: NO_x trade-off in engine design, though the scale of this relationship is unclear and could be small. It was concluded that CO_2: NO_x trade-offs are likely to be of limited relevance for the engine technology abatement options identified in this study. This could, however, be an issue for new generation engines (and airframes) and will require attention.

CO_2 and Contrails. There is a potential trade-off between more fuel efficient engines and the production of water vapour contrails produced by very hot exhaust interacting with ambient humidity. However, they have not been considered here because their incidence and effects are very uncertain given the current state of knowledge.

CO_2 and Noise. There is some evidence of CO_2: noise trade-offs in engine or airframe design, particularly where an increase in drag and weight arises from measures to reduce noise. There is some evidence of CO_2: noise trade-offs in engine or airframe design, particularly where an increase in drag and weight arises from measures to reduce noise. Open rotor technology, which offers the prospect of considerable fuel benefits for short haul operations, may be noisier than new generation turbo fans.

The European case study considered the effect of interventions on a range of emissions, especially CO_2 and NO_x. It did not apply a common metric for reasons stated above. For the abatement options considered, there appeared to be more synergy than conflict amongst most measures to control major emissions, although information is not available to firmly support this argument.

In conclusion, although this objective has been addressed, it has not been possible to apply a common metric for the range of emissions species in the derivation of MAC for abatement options. This is a topic for further research.

Objective (iv) set out to identify the main knowledge gaps and uncertainties that need to be addressed to determine least-cost strategies for environmental abatement in the aviation sector, thereby making recommendations for further research on this topic.

This study set out to draw on available knowledge to meet the study objectives, rather than engage in primary research. The study identified the type and detail of information required to construct MAC curves. Previous work on the appraisal of environmental abatement options for aviation had identified limited data and methods. In many respects the current study confirms this position. There are degrees of uncertainty in all aspects of the analysis reported here, namely regarding the estimation of baseline emissions, the effectiveness of abatement under given operating conditions, and costs.

Baseline emissions. There is moderate uncertainty with respect to the estimation of baseline emissions from aviation activities given the inherent variation in aircraft types, and maintenance and operating conditions. Baseline estimates assume standard emission rates for given airframe; engine configurations and typical patterns of utilisation. It is not known how far actual emissions vary due to variations in the condition and use of aircraft.

Furthermore, standard estimates are mainly based on ground-based testing and modelling of emissions. Calibration of these estimates by in-service monitoring is limited, suggesting a need for this to be done.

Efficacy of abatement options. There is limited objectively verifiable data to confidently assess the efficacy of abatement options under the variety of real operating conditions. Information, where available, typically relates to very specific aircraft or operating circumstances such that generalisation is either not possible or requires great caution. It would be useful for test and monitoring results to report on the range of operational conditions to which results can reliably apply. There is a need for this to be done.

The two cases explored here used a combination of published ICAO/CORINAIR sources and estimates from PIANO and FAST simulation models. The former sources were found to be insufficiently complete in coverage of aircraft and/or of the full LTO-cruise cycle to support full appraisal of abatement options. The latter models in their present form cannot accommodate detailed changes in technology and practices required for the appraisal of abatement options on existing aircraft. There is need for the assembly of a coherent data base as well as new data and methods to support the technical appraisal and development of abatement options to control aviation emissions.

Costs of abatement options. There is considerable uncertainty about the costs of developing and implementing abatement options. Indeed, obtaining information on the actual baseline costs of operating aircraft is itself challenging due to a combination of inherent variation in costs, variations in accounting methods and restrictions imposed by commercial confidentiality. Obtaining information on the actual or likely costs of adopting abatement measures is equally problematic, partly for the same reasons. Capital costs, such as engine and airframe refits, are identifiable but in practice unit costs vary considerably according to contractual arrangements which may include discounts, financing and lease agreements. Furthermore, unit costs can fall considerably as particular technologies become widely adopted. There is limited hard information to assess the impact of individual interventions on operating costs other than fuel, requiring informed, reasoned assumptions which need verification in practice.

Information on Cost of abatement is particularly uncertain for longer term developments such as new engine and airframe technologies, in-flight monitoring and control systems, synthetic fuels and novel air traffic management systems. It proved particularly difficult to ascertain likely research and development costs, and how these costs translate into unit costs for users implemented over a future time period at an appropriate scale. There is a need to significantly enhance the knowledge base to verify the feasibility and cost effectiveness of new developments such as those associated with ACARE-type targets, and to direct research and development effort.

Asymmetry of information. The challenges experienced here draw attention to the fragmented and asymmetrical distribution of information amongst the different agents in the aviation sector. This might be expected in what has become a fiercely contested sector, such that information is not readily placed in the public domain. However, as the industry faces the prospect of further regulation, there is merit in greater exchange of information and knowledge amongst the various parts of the industry in order to promote industry scale responses to the management of environmental risk. In particular scope for greater knowledge exchange between the industry, its representative organisations and the government regulator (and sponsor) as they seek to determine mutually satisfactory strategies for balancing intended social, economic and environmental outcomes. It is strongly recommended that this exchange be further enhanced, incorporating a wide range of stakeholders.

Responses to drivers. The analysis here confirmed the critical influence of fuel price and regulatory policies as these provide incentives change. There remains considerable uncertainty how the various agents in the industry will respond to these drivers. It is clear that recent spikes in fuel prices renewed interest in fuel efficiency, indirectly helping to reduce fuel related emissions, and rekindling interest in fuel saving technologies. It is not clear how the more recent global economic downturn in late 2008, exacerbated for UK operators by falling £:US$ exchange rates, will continue to encourage fuel and emission saving practices. An analysis of current and historic drivers of changes in technology and practices in the industry, including trends in fuel efficiency and environmental performance, is needed to inform possible future prospects and behaviour. Such an analysis, including historical scientific reviews and participation of key stakeholders, would help to map out plausible future scenarios for aviation to which the industry, international agencies and governments could respond.

An integrated approach. The study here focussed mainly on 'supply side' technology and flight –based operational practices by airlines and supply organisations as they determine emissions. It is clear that analysis of the cost-effectiveness assessment of abatement technologies must be placed in the wider context of the aviation industry as a whole, including aspects of business strategies and models, demand management, customer behaviour, air transport management, airport management, research management, and regional and industrial planning. This is a call for an integrated approach to managing the environmental performance of the sector as a whole, of which the derivation of MAC is one part. Similarly, the relationship between emissions and impacts, whether environmental social or economic, are complex, diverse and often context specific. In some cases, controls on emissions from aviation could result in costs which are disproportionate to the environmental benefits obtained. This moves into the realms of cost:benefit analysis and a broader perspective than that taken here.

7.2 Potential for Informing Policy

This study has focussed on estimating the cost effectiveness of policy measures introduced by the aviation industry and the key drivers influencing them. The projected baseline trends in emissions reflect current policies and expected responses to them, but do not include possible future interventions at the national, regional and global levels.

The Policy Relevance of MAC. MAC indicate the costs that would be imposed on an industry by a mandatory regulation on emissions. MAC also indicate the likely response by industry to the introduction of pollution taxes or tradeable emission permits by defining the scope for cost-effective abatement, including negative cost, win-win opportunities. The analysis here suggests there is some scope for the industry to achieve negative cost, win-win abatement and to undertake some relatively low cost measures to avoid emission taxes or purchase of carbon credits. A tax on aviation fuel increases the attraction of and further induces self abatement, as do increased fuel prices as shown by historical and recent trends. In this respect the analysis here confirms the theoretical aspects of MAC referred to in Chapter 2, whereby higher fuel prices (due to market or policy mechanisms) dynamically induce the adoption and further development of abatement technologies.

Potential policy measures that might be taken by government and regulators have not been included here in the list of abatement measures. However, the findings of this study may have potential to inform policy on the management of environmental impacts from aviation in the future, including:

- Changes to the EU ETS, for example auctioning of permits and tightening the level at which aviation emissions are "capped"
- Flanking policy measures to the EU ETS under consideration to tackle the climate change impact of NO_x emissions
- Changes to fuel taxes or emission charges, charges for air traffic management , airport and/or passenger services
- Further consolidation of beyond compliance, 'best available technologies' as a basis for industry standard permitting
- The dissemination of information on the scope for and cost effectiveness of emissions abatement options
- Funding of research into airframe and engine technology
- Measures to assist in removing barriers to implementation identified for some abatement measures eg Single European Skies and to encourage the adoption of voluntary targets such as ACARE
- Abatement measures that could be influenced by Government initiatives, for example the introduction of bio-fuels and fuel-tankering
- Attitudes of government and regulators where trade-offs arise from some abatement measures, for example if the fuel efficiency improvements from the introduction of open rotors come at the cost of a noise penalty (or at least a slower pace of improvement in the noise climate over time).

7.3 Recommendations for Further Research

Following the conclusions from the study. especially regarding knowledge gaps, the following recommendations are made.

Stakeholder review of data and methods. Drawing on this exploratory study, it is recommended that consideration be given to a joint government-industry study to further develop and scrutinise the data and methods used here to assess the efficacy and costs of measures to reduce emissions with potential to cause environmental damage. It is important that such as study draws on the best available science, as currently reviewed by the Omega Programme, and critically, engages the full breadth of stakeholders in the aviation sector. This study should be designed to overcome some of the fragmentation and asymmetry of information that is evident in the industry in ways that help promote efficiency and best practice without compromising perceptions of competitive advantage.

Science Review: It is recommended that the outputs of the current Omega Programme, together with the results of other ongoing research, are assembled to produce a state of science review that specifically supports the identification, appraisal and, where appropriate, promotion of abatement technologies. This study should include aspects of behavioural science that can explain inertia and barriers to change by various stakeholders, including customers of air services.

Guidance: It is recommended that data and methods required to support the consistent estimation of the technical performance of different abatement measures are developed and made available, again drawing on available science. These should accommodate variations in real world circumstances and practices.

Exemplars: It is recommended that families of case studies are produced, drawing on practical experience, to demonstrate feasibility, costs and benefits of abatement options suited to particular user groups and situations. These should also demonstrate the participation of a range of service providers including SMEs.

Policy aspects: It is recommended, therefore that the study of abatement options is extended to include a broader assessment of policy options, taking into account the possible responses of the industry to a range of policy and commercial scenarios.

Integration: Finally, it is recommended that the aforementioned initiatives with respect to abatement are embedded within an integrated approach to managing the environmental performance of the aviation sector as a whole.

7.4 Epilogue

There is currently much interest in the concept of MAC both from the industry's viewpoint as it responds to environmental and commercial pressures, and from the governments viewpoint as it seeks to design environmental policies which achieve overall regulatory efficiency.

The derivation of Marginal Abatement Costs reported here represents a small part of a complex process that seeks to identify, prioritise and facilitate the development of effective options to improve the environmental performance of aviation. An understanding of the synergies and trade-offs amongst different technological, operational and policy approaches to managing the environmental effects of aviation is an important part of that process. Work elsewhere within Omega is exploring how engineering, physical and social sciences, including economics, can be integrated to help provide this improved understanding and a basis for policy and positive actions by a range stakeholders. Future work within Omega should examine how partnership work, in some cases at the feasibility level, on models and assessment processes can be developed into mutually beneficial broadly-applied decision support for the aviation sector

8.0 References

(Additional references are contained in the supporting Appendices)

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