AIR QUALITY EXPERT GROUP

ROAD TRANSPORT BIOFUELS: IMPACT ON UK AIR QUALITY

Advice Note prepared for:

Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Assembly Government; and Department of the Environment in Northern Ireland

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This is an Advice Note from the Air Quality Expert Group to the Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Assembly Government; and Department of the Environment in Northern Ireland, on the likely impact of road transport biofuels on air quality in the UK.

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AQEG report to the Secretary of State for Environment, Food and Rural Affairs, Scottish Ministers, the National Assembly for Wales and the Department of the Environment in Northern Ireland (the Government and Devolved Administrations).

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- to give advice on levels, sources and characteristics of air pollutants in the UK;
- to analyse trends in pollutant concentrations;
- to assess current and future ambient concentrations of air pollutants in the UK; and
- to suggest potential priority areas for future research aimed at providing a better understanding of the issues that need to be addressed in setting air quality objectives.

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Executive summary and recommendations

This Advice Note, prepared by the Air Quality Expert Group (AQEG) for Defra and the Devolved Administrations, looks at recent trends in biofuel consumption in the UK and summarises the effects of biofuels on vehicle emissions and air quality based on current evidence. The Advice Note addresses only the direct effects of consumption of biofuels on air quality in the UK resulting from end of tailpipe emissions. The Note recognises that this is only one of many aspects which need to be considered in the full context of biofuel production and use and is not meant to diminish the importance of wider sustainability issues, both in the UK and globally.

The Advice Note addresses several questions posed by Defra and the Devolved Administrations. This summary outlines AQEG's responses and recommendations, with further details and supporting evidence given in the main body of the report.

Question 1: What are the likely biofuels within the UK context?
&
Question 2: What combinations and blends are likely to be implemented?

When considering the impact of biofuels on air quality, it is necessary to differentiate between the consumption of biofuels in neat and diluted forms. At present, biofuels are mainly consumed in the UK as low strength blends (<5%) of biodiesel from a variety of plant and vegetable oils and bioethanol from sugar cane and sugar beet. The feedstocks for biodiesel are varied and are likely to remain so, but consumption will be mainly as processed (esterified) oils from these feedstocks. In order to meet renewable targets, the same types of biofuels are likely to be used, with blends strengthened to up to 10% by 2020. Pure or high strength blends (up to 100% in the case of biodiesel) are likely to be consumed in lower quantities or remain as niche fuels. Very small quantities of biogas and more advanced second-generation fuels such as synthetic diesel produced from waste biomass feedstocks are currently consumed, however these may grow in availability in future depending on economic conditions and sustainability issues.

Question 3: What is the evidence that the use of biofuels changes vehicle exhaust emissions and thus has an impact on air quality? How do exhaust emissions vary with blend strength and source material?

Results from research studies on the effects of biofuels on vehicle emission are inconclusive and show a high degree of variability. This is partly because of differences in the test procedure used, for example the operational drive cycle, vehicle age and maintenance condition, quality of the base fuel, type of engine and exhaust after treatment technology.

Most evidence suggest that at low strengths bioethanol leads to no change in oxides of nitrogen (NO_x) emissions but a reduction in other regulated pollutant emissions (Carbon monoxide (CO), Hydrocarbons (HC), and Particulate Matter (PM)). It also leads to a reduction in other air toxics, but a significant increase in acetaldehyde emissions, an unregulated pollutant, but one considered a toxic air pollutant. The reductions in emissions may be more apparent for older vehicles and 2-stroke engines. For high strength blends of bioethanol (E85), the reductions in emissions are smaller for CO and HC probably because of the need to re-tune the engine while increased emissions of acetaldehyde ***and*** formaldehyde are evident. Adding ethanol to petrol at low strengths causes an increase in fuel volatility and can lead to an increase in evaporative emissions of volatile organic compounds (VOCs) unless the volatility of the base petrol fuel is reduced. The overall change in the composition of the fuel vapour when ethanol is added is small.

Most types of biodiesel from esterified vegetable oils lead to reductions in HC, CO and PM emissions, but lead to a small increase in NO_x emissions, with the effects getting stronger with increasing biodiesel strength in the fuel. Data on the effects of biodiesel on emissions from light duty vehicles are sparse and further research is required on the drive cycle and technology dependence of these biodiesel emission effects in light and heavy duty diesel vehicles. Overall, biodiesel may have a beneficial effect by reducing emissions of polyaromatic hydrocarbons (PAHs) and other air toxics. Emissions from virgin plant oil are more varied reflecting the need for engine re-calibration or conversion and show smaller reductions in CO, HC and PM emissions compared with esterified biodiesel fuels. The potential negative impact on NO_x emissions from modern engine and vehicle technologies running on biodiesel needs to be verified. In spite of uncertainty in the magnitude of the effects of biodiesel on emissions, sufficient research has allowed a rational explanation to be found on the directional changes in emissions observed and this has led to suggestions as to how engine conditions can be optimised to minimise increases in NO_x without compromising on levels of PM emitted. The reductions in PM are believed to be due to the presence of oxygen in biodiesel leading to more complete combustion. Biodiesel produced from saturated animal fats appear to show better emission performance than that derived from vegetable and plant oils.

There remains uncertainty on the effect of biodiesel on the particle number and size distribution of PM emissions although the majority of studies suggest a shift towards smaller particles when biodiesel is used. There is little known about the toxicity of particulate matter from biodiesel and the chemical speciation of volatile and semi-volatile organic compounds emitted from biodiesel consumption is not known indicating that their propensity to forming secondary organic aerosols cannot currently be assessed. There is no information on the impact of biodiesel on primary nitrogen dioxide (NO_2) emissions.

AQEG conclude that consumption of biofuels as low strength blends up to 15% has little effect on air quality, but further research on the effects of high strength blends on emissions is required if their consumption were to be encouraged. AQEG also recommends further research on the effects of different strengths of biodiesel fuels on mass emissions of NO_x, primary NO_2 and PM and the characterisation of particulate matter and chemical composition of organic compounds emitted from

modern diesel engines and vehicle technologies so that the full air quality impacts of biodiesel consumption can be assessed.

Although used on a small scale in the UK, biogas and synthetic diesel produced from gasification of waste biomass feedstocks show reductions in emissions of all air quality pollutants.

Question 4: What is the evidence from other countries for changes in atmospheric composition as a result of the use of biofuels

The UK still uses relatively small amounts of low strength bioethanol and biodiesel and consumption has only grown to current levels over the past few years. It is too soon to observe any trends in atmospheric concentrations that can be associated with biofuel use, **however roadside concentrations should be monitored as biofuel consumption grows to confirm any evidence for changes in vehicle emissions. This includes observations of potential biofuel "markers" such as acetaldehyde**.

More insight into the effects of biofuel consumption on the atmosphere can best be found in places which have been using biofuels for longer. Most of the evidence can be found in studies of ambient air pollution undertaken in parts of North and South America where gasoline containing ethanol or related oxygentated fuels have been used for several decades. There is clear evidence from studies in Brazil and the U.S. that the use of ethanol leads to higher concentrations of acetaldehyde and Peroxy Acetyl Nitrate (PAN). These compounds are toxic air pollutants as defined by the U.S. Clean Air Act. There is fairly strong evidence for increases in formaldehyde concentrations in regions of the world where high strength (E85) ethanol is used. Elevated levels of ozone seen in some districts of the U.S. have been attributed to higher NO_x emissions and evaporative losses of VOCs as a result of using 10% bioethanol, however this is far from certain.

Fewer places in the world have had prolonged experience in the use of biodiesel as a fuel so it is not possible to find any changes in the atmosphere that can be associated with biodiesel consumption.

Question 5: What is the likely impact on air quality in the UK of the change in emissions as a result of the increased use of biofuels?

Modelling and assessments on the future air quality impacts of biofuel consumption in the UK based on current evidence suggest traffic emissions of PM, CO and VOCs should fall for most probable biofuel uptake scenarios, while there may be very small increases in NO_x emissions. A more extreme scenario involving major uptake of virgin plant oil as a biodiesel option to meet renewable targets could lead to an increase in traffic emissions of PM. Higher emissions of acetaldehyde and evaporative losses of fuel vapour resulting from growth in consumption of bioethanol across Europe, consistent with renewable fuels targets, are expected to have a very small impact on ground-level ozone in the UK.

Modelling studies in the U.S. suggest the replacement of petrol by high strength 85% bioethanol (E85) could lead to higher ozone concentrations in some areas and lower concentrations in others with changes varying with time of year. The balance of evidence is largely against the widespread introduction of E85 from an air quality perspective. Given that bioethanol is mainly consumed in the UK and in most of the rest of Europe as low strength blends (<15%), the results from these U.S. studies are unlikely to be relevant to current ozone air quality in the UK. **However, any policy that would lead to more widespread use of bioethanol as high-strength E85 blends would need to consider the potential impacts on ambient concentrations of ozone and other pollutants including aldehydes. This will require further research on the effects of E85 on "real world" emissions including aldehydes.**

Introduction

1. Biofuel is a generic rather than a specific description of a fuel that is derived from a variety of renewable feedstocks as replacements for fossil fuel-derived petrol for spark-ignition engine vehicles and diesel for compression ignition engine vehicles. The feedstocks can broadly be categorized as first generation and second generation biofuels. First generation biofuels are produced from biomass such as sugar or starch crops (e.g. maize and wheat) for bioethanol as a replacement for petrol, and plant and vegetable oils and animal fats for biodiesel, using processes that are currently available and economic to run. First-generation biodiesel is usually as trans-esterified vegetable oils (e.g. rape seed, palm, sunflower oil etc) or pure vegetable oils (either neat or waste). Second generation biofuels refer to a range of fuels under development and include bioethanol from lignocellulosic biomass feedstocks such as wood and straw, biobutanol, Fischer-Tropsch diesel and hydrogen. They are not yet produced commercially on a large scale, but offer a wider range of feedstocks including, for example, agricultural and forestry waste. Their introduction is thought to be necessary in order to meet the more challenging EU conditional target of 10% share of biofuels by 2020. Engines can also run on biogas (biomethane) which can be produced from any organic feedstock that is suitable for anaerobic digestion.

2. Biofuels are superficially highly attractive as a means of offsetting greenhouse gas emissions through combusting materials which have derived their carbon content from contemporary atmospheric carbon dioxide. However, as noted by a number of organisations including the Royal Society (Royal Society, 2008) biofuels have a range of environmental and societal implications which render them less sustainable than might appear the case at first sight. Indeed, the problems associated with first generation biofuels such as those derived from corn (ethanol for use in gasoline) rapeseed and palm oil (for incorporation in diesel fuels) may wholly outweigh their potential benefits. A report for Defra prepared by AEA (Defra, 2008) lists key indicators and sustainability criteria against which biofuel crops may be assessed. These include the following:

   - *Land use change*. Crops grown on otherwise marginal land are the most beneficial with those displacing food crops likely to be least satisfactory. Clearing rainforest to plant biofuel crops reduces carbon sinks.

   - *Biodiversity management*. Extending monocultured crops across a greater land area can have deleterious consequences for ecosystems.

   - *Water use*. Biofuel crops may require irrigation in locations where natural water supplies are stretched or inadequate.

   - *Water pollution*. Biofuel production may cause pollution of local ground or surface water.

- *Soil health*. Increasing the intensity of agriculture may have deleterious impacts on soil fertility or contribute to erosion.

- *Effects on food crops*. Displacement of food crops may lead either to food shortages or increases in price which put them out of the range of some consumers.

- *Emissions*. This includes a range of possible adverse consequences including the generation of allergenic pollens, release of reactive volatile organic compounds which contribute to ozone and particle formation, and the possible generation of combustion products if land is burnt to clear for cultivation.

- *Greenhouse gas emissions*. Intensification of agriculture is likely to lead to increased releases of nitrous oxide, a potent greenhouse gas, from soils and some crops are a source of methane releases to the atmosphere. Additionally, before use, many biofuels require extensive processing which will be a direct or indirect cause of greenhouse gas emissions.

3. The Royal Society report highlighted the complexity of the issues surrounding the sustainability of biofuels and recommended both extensive further research and a reconsideration of current polices. In the latter context, the House of Commons Environmental Audit Committee (EAC, 2008) echoed many of these concerns and indicated that “in the absence of such (appropriate sustainability) standards, the government and EU has moved too quickly to stimulate the use of biofuels” and that “the stimulation of biofuels production by the government and EU is reckless in the absence of effective mechanisms to prevent the destruction of carbon sinks internationally. The government must ensure that carbon sinks are effectively protected before providing incentives for the use of biofuels”.

4. Notwithstanding these important sustainability issues, consumption of biofuels by road transport in the UK is growing, driven by domestic targets and EU directives aimed at accelerating growth in the share of fuel derived from renewable sources in order to meet commitments aimed at tackling climate change by reducing CO_2 emissions and to ensure the security of energy supplies. The EU Biofuels Directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for transport includes ‘reference’ biofuel targets of 5.75% of energy content by 2010. The target is raised to 10% for the share of biofuels by the end of 2020 in Directive 2009/28/EC which also provides a set of sustainability criteria for biofuel production and a system for monitoring and reporting life cycle greenhouse gas emission reductions and for demonstrating compliance with the sustainability criteria. The UK has a domestic Renewable Transport Fuels Obligation (RTFO) which requires suppliers of fossil fuels to ensure that a specified percentage of the road fuels they supply in the UK is made up of renewable fuels. The current target for 2009/10 is 3.25% by volume, rising to 5.26% by April 2013. As well as obliging fuel suppliers to meet targets for the volumes of biofuels supplied, the RTFO requires companies to

submit reports on the carbon and sustainability of the biofuels and the programme is administered by the Renewable Fuels Agency[1].

5. The RTFO is built around seven sustainability principles; five environmental and two social. These largely followed the 'Gallagher Review' of 2008 which identified the importance of addressing the indirect effects of biofuel production[2]. However, the impact of the consumption of biofuels on air quality was not addressed in the Gallagher Review. Studies have been undertaken on the impacts of biofuel use on emissions from road vehicles and air quality, but compared with research covering other sustainability criteria the findings have not been so well documented and are generally not conclusive. A chapter on air quality and emissions from use of biofuels by transport was included in the AEA review for Defra in 2008. This gave a qualitative assessment of potential air quality impacts including those arriving from the production as well as use of biofuels in a global context.

6. This Advice Note addresses only the direct effects of consumption of biofuels on air quality in the UK resulting from end of tailpipe emissions. As indicated above, this is only one of many aspects which need to be considered in the full context of biofuel production and use and is not meant to diminish the UK's contribution to life-cycle emissions arising from the production and transport of biofuels from overseas and the UK's share of the responsibility to air quality problems in other countries, and more globally, arising from "upstream" production of biofuels. A brief mention will be given to these impacts in this report, but reference to these occurring in major biofuel producing countries around the world were discussed in the Defra (2008) review. These impacts include the emissions of particulate matter from the burning of fields and peatlands in parts of China, Indonesia and Brazil.

7. The Note looks at recent trends in biofuel consumption in the UK and building on earlier work carried out for Defra and the Department for Transport (DfT), summarises the effects of biofuels on vehicle emissions and air quality based on current evidence. The aim of the Advice Note is to answer the following questions:

   - What are the likely biofuels within the UK context?
   - What combinations and blends are likely to be implemented?
   - What is the evidence that the use of biofuels changes vehicle exhaust emissions and thus has an impact on air quality? How do exhaust emissions vary with blend strength and source material?
   - What is the evidence from other countries for changes in atmospheric composition as a result of the use of biofuels?

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[1] Hhttp://www.renewablefuelsagency.gov.uk/

[2] Hhttp://www.renewablefuelsagency.gov.uk/sites/renewablefuelsagency.gov.uk/files/_documents/Report_of_the_Gallagher_review.pdf

- What is the likely impact on air quality in the UK of the change in emissions as a result of the increased use of biofuels ?

8. The focus is on first-generation bioethanol and biodiesel, although brief mention is given to biogas and second-generation Fischer-Tropsch biodiesel. Odours from consumption of certain biofuels are a nuisance problem which has been recognised, but is not discussed in this report. Similarly, soil and ground contamination from environmental releases of biofuels have been a concern in countries where significant consumption occurs, but are not addressed in this report.

Biofuel consumption in the UK

This section addresses the questions:

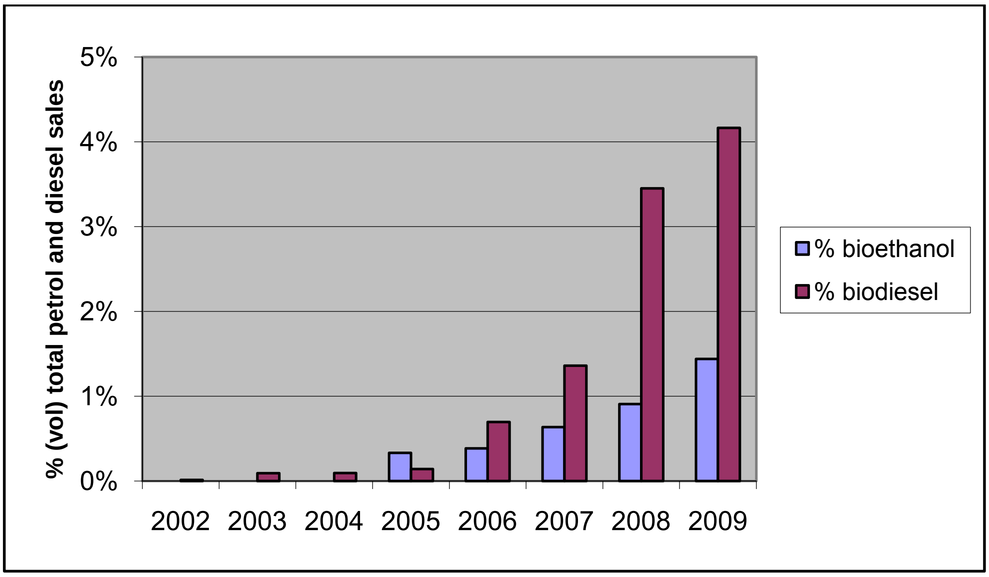
What are the likely biofuels within the UK context?

What combinations and blends are likely to be implemented?

Trends in total consumption of bioethanol and biodiesel

9. The main source of national statistics on the consumption of biofuels in the UK is the UK Revenue & Customs (HMRC). HMRC produces monthly statistics in their hydrocarbon oils bulletin[3] on the volume of bioethanol and biodiesel released for consumption, as well as volumes of fossil fuel petrol and diesel. Figure 1 shows the trend in consumption of bioethanol and biodiesel by calendar year up to 2009 based on these statistics expressed as the percentage by volume of total petrol and diesel consumed. The data show there has been a marked increase in biofuel consumption since 2005, particularly biodiesel. Consumption of biodiesel was 4.2% of all diesel consumed in 2009, while bioethanol consumption was 1.4% of all petrol consumed. The figures also show that of all the biofuel consumed in 2009, 77% was biodiesel and 23% was bioethanol on a volume basis.

Figure 1: Biofuel consumption in the UK as a percentage of total petrol and diesel consumption (source: HMRC Hydrocarbon Oils Bulletin, April 2010)



[3] Hhttps://www.uktradeinfo.com/index.cfm?task=bulloil&hasFlashPlayer=true

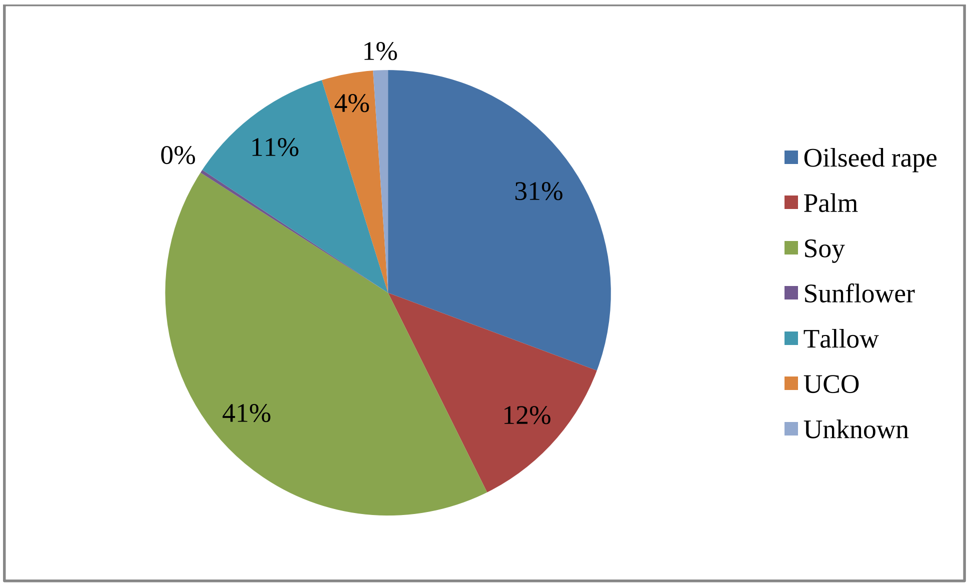
10. The figures from HMRC do not, however, reveal what type of feedstocks the biofuels are derived from nor in what mixture strengths the biofuels are consumed. This matters when considering the air quality implications of biofuel consumption because the impact on emissions of various pollutants can depend on how the biofuels are consumed, i.e. whether in neat or diluted form. In the UK, the majority of biofuels are consumed as weak blends with conventional fossil fuel-based petrol and diesel and the changes in air quality pollutant emissions that occur relative to emissions from fossil fuels depends on mixture strength in some cases in a non-linear fashion. The effect on emissions can also vary with biofuel feedstock as this defines the chemical structure of the fuel.

Types of biofuels consumed in the UK

11. The Renewable Fuels Agency (RFA) produces an annual report on the RTFO which summarises the volumes of biofuel supplied in the UK by feedstock and country of origin. The most recent report is for the year 2008/09.[4]

12. The report shows that the majority of biodiesel supplied in the UK was from soy (41%) sourced mainly from the U.S., followed by oilseed rape (31%) sourced mainly from Germany, palm oil (12%) sourced mainly from Malaysia and Indonesia and tallow (11%) sourced mainly from the U.S. The UK supplied 6% of its own biodiesel mainly in the form of used cooking oil (UCO, 3.4%), where it was by far the largest supplier, and oilseed rape (2.5%). Figure 2 shows the share of feedstocks used to supply biodiesel in the UK in 2008/09.

Figure 2: Feedstocks of biodiesel supplied in the UK in 2008/09. Source: RFA, 2010.



[4] Hhttp://www.renewablefuelsagency.gov.uk/yearone

13. These feedstocks can be consumed as virgin plant oils in diesel engines, but are usually trans-esterified into products such as Rapeseed Methyl Ester (RME) and Soybean Methyl Ester (SME) to improve their physical characteristics.

14. Bio-petrol is almost completely supplied with a discrete chemical identity in the form of ethanol. The large majority of bioethanol (80%) is supplied from sugar cane sourced from Brazil. The next major source is sugar beet supplied from within the UK (19%).

15. Vehicle engines can be adapted to run on biogas which can be produced from any organic feedstock that is suitable for anaerobic digestion. It can be produced from renewable sources such as sewage, landfills and agricultural waste materials. Biogas makes up 0.03% of all biofuels currently supplied in the UK and is mainly sourced from municipal solid waste.

16. It is difficult to predict how the supply of biofuels may change in the future. At the moment, the supply of biodiesel exceeds that of bioethanol, but both are expected to grow in the future to meet the EU and domestic renewable fuel targets. The proportions of various feedstocks for biodiesels may change according to socio-economic and political factors and sustainability requirements, but at least in the next few years biodiesel supplies are likely to continue to be based on esterified plant and vegetable oils. Second generation lignocellulosic biomass feedstocks such as wood and straw may emerge as sources of biodiesel in the future. A production plant is being planned in East London for the production of jet biofuel derived from waste biomass via a thermal gasification and Fischer-Tropsch (F-T) process to power part of British Airways' fleet of aircraft.[5] Plans like this might stimulate the production of high volumes of F-T biodiesel for the road transport sector. Fuels made from algae and other simple microscopic living organisms have attracted attention, but are still at a development stage.

17. Bioethanol from sugar crops will continue to dominate as a substitute for petrol in the near term. However, other types of oxygenated fuels such as biobutanol and various types of ethers may be preferable if these can be produced economically and sustainably, especially as these alternative fuels may offer better physical properties than ethanol which can be problematic at high strengths.

Strength of biofuel blends consumed in the UK

18. Although biodiesel and bioethanol can be used neat or as high strength blends in engines, they are usually consumed as low to medium strength blends with fossil fuel petrol and diesel. Use in strengths up to around 10% v/v generally pose few

[5] Hhttp://www.renewableenergyfocus.com/view/7343/british-airways-to-use-biofuel/H

problems in most engines and with widespread adoption would achieve the renewable transport fuel targets.

19. Until recently, there have been difficulties with the supply of biofuels of strengths higher than 5%. EU Directive 2003/30/EC on the promotion of biofuels included a requirement for Member States to ensure specific labelling at sales points. This specified a labelling scheme where more than 5% biofuel was supplied, meaning filling stations would require separate tanks for fuels containing >5% biofuel. Many vehicles require their computer controlled fuel metering system to be re-mapped to accommodate the different physical and thermodynamic properties of higher strength blends and some car manufacturers provided a warranty that is only valid provided that <5% biofuel mixtures are used. However, the limits on biofuel content of commercially available fuel have been increased in the recent Directive 2009/30/EC to 7% for fatty acid methyl ester (FAME) in diesel and 10% for ethanol in petrol.

20. Diesel engines can run on 100% esterified biodiesel (B100) and even on virgin plant oil, though some engines require conversions using retrofit systems or re-calibrations for the vehicle to run. This alone can lead to changes in emission performance. Virgin plant oil has less superior physical and combustion properties and can be of variable quality. Some diesel engine manufacturers will allow their engines to run on B100, while others will not. Larger heavy duty engines may be better suited to run on B100.

21. High strength bioethanol fuels (e.g. 85%, E85) are used extensively in some parts of the world, but not in the UK. E85 is more of a niche fuel in Europe, though it is more widely used in some countries such as Sweden, and vehicles require engine re-tuning and other adaptations to run. Flexible-fuelled vehicles are on the market that can run on both normal petrol and E85 using just one fuel tank, but these are sparse in the UK. Many cars can run on bioethanol strengths up to 10% (E10), though some cannot. There are several adverse effects that can occur with even low strength bioethanol blends that provide a challenge for manufacturers and can lead to increases in emissions. One is the fact that ethanol is hydroscopic. It can affect plastic and rubber materials leading to an increase in fuel vapour permeation. Adding ethanol to petrol at low strengths increases the fuel vapour pressure leading to higher evaporative losses unless the volatility of the base petrol is reduced by taking out lighter fractions. Ethanol can affect the performance of carbon canisters used for controlling evaporative emissions. Engines running on bioethanol at higher strengths can show different behaviour during cold starts.

Effect of biofuels on vehicle emissions

This section addresses the questions:

What is the evidence that the use of biofuels changes vehicle exhaust emissions and thus has an impact on air quality?

How do exhaust emissions vary with blend strength and source material?

22. There has been a fair amount of research on the effect of biofuels on vehicle emissions though the results are not always comparable and in some cases they are contradictory making it dangerous to generalise and difficult to draw overall conclusions on the relative effects of biofuels on emissions compared with fossil fuels. This is partly because of differences used in test procedure, for example the operational drive cycle, vehicle age and maintenance condition, quality of the base fuel, type of engine and exhaust after-treatment technology and many other conditions all affecting emissions. Much of the research carried out stands alone, addressing a specific issue and only a few studies are of major coordinated campaigns aiming to cover a range of fuels, vehicles and test cycles under comparable conditions. However, some very useful literature reviews have been undertaken and these have been drawn upon for this report.

23. A literature review was carried out in the National Atmospheric Emissions Inventory (NAEI) programme during 2008 on the effects of different types and strengths of biofuels on vehicle emissions (Murrells and Li, 2008). This focused on large research programmes carried out at JRC Ispra, TNO in the Netherlands, AVL in Sweden, USEPA and a few other smaller studies in Europe and North America between 2002 and 2006. The NAEI review examined emissions data for bioethanol in strengths from 5-85%, biodiesel from esterified oils, virgin plant oil and biogas and considered the impacts on exhaust emissions of regulated pollutants nitrogen oxides (NO_x), particulate matter (PM), total hydrocarbons (HCs) and carbon monoxide (CO), as well as non-regulated pollutant emissions including certain air toxics and evaporative emissions.

24. Details of the review are given in Murrells and Li (2008), but the review led to a series of scaling factors representing the change in mass emissions (in grammes emitted per kilometre) for different types of biofuels and mixture strengths relative to base fossil fuel petrol and diesel. The aim was to produce factors that could be used in emission inventories and modelling studies. Where insufficient quantitative information was available for some of the non-regulated air toxics, only the directional change in emissions was highlighted.

25. The key findings from the NAEI review are discussed in the following sections, but it should be emphasised that there is a high degree of uncertainty in many of the scaling factors reflecting the variability in emission results especially for the low-strength blends where the changes are quite small. The scaling factors should be regarded as indicative rather than providing definitive quantitative answers to how biofuels affect tailpipe emissions and are principally to aid modelling and assessments of potential air quality impacts.

Bioethanol

26. Research has generally shown that **at low strengths** bioethanol leads to no change in NO_x emissions, but a reduction in other pollutant emissions. However, CO and PM are the only pollutants showing a clear reduction in all studies, with evidence for HCs and NO_x being rather mixed. The emission benefits are most apparent for older generation cars and 2-stroke engines without emission controls.

27. Research on emissions from **high strength** (E85) bioethanol is not conclusive, but tends to show rather different trends most probably resulting from the necessary re-tuning of the engine and different physical characteristics of the fuel. The evidence is largely based on fairly old vehicle technologies

28. Table 1 summarises emission scaling factors for different blends of bioethanol relative to base petrol concluded from various literature sources. Up to 15%, the effects are assumed to be linear with ethanol content, but there is considerable uncertainty, difficult to quantify, in all these scaling factors. For NO_x, a scaling factor of 1.0 (i.e. no change in emissions) is shown because it is difficult to discern with any certainty even the directional change in emissions, with some studies suggesting a small increase in emissions and others a decrease. The figures for E85 for other pollutants break the trend apparent at low strengths, but are much more uncertain.

Table 1: Emission scaling factors for different blends of bioethanol relative to base petrol

	HC	CO	NO_x	PM	Benzene	1,3-butadiene	Acetaldehyde
E5	0.975	0.9	1.0	0.8	0.9	0.925	2.5
E10	0.95	0.8	1.0	0.6	0.8	0.85	5.0
E15	0.925	0.7	1.0	0.4	0.7	0.775	7.5
E85	1.0	1.0	1.0	0.8	0.1	0.2	10

29. One pollutant which shows a significant increase in emissions is acetaldehyde. The evidence for this is unequivocal. Although emitted in very small quantities, and

largely controlled by catalytic converters, emissions can increase 5 fold for E10. Acetaldehyde is considered a toxic air pollutant as defined by the U.S. Clean Air Act and is one of the precursor volatile organic compounds involved in ground-level ozone formation. It is emitted through incomplete oxidation of ethanol in the engine. The NAEI estimates that traffic is responsible for 25% of primary acetaldehyde emissions in the UK on the basis of conventional fuels. Higher emissions of ethanol have also been observed, but the effect on formaldehyde is more uncertain with mixed evidence on the effects of low strength blends of bioethanol. For E85, there is more evidence for an increase in formaldehyde emissions together with increased emissions of acetaldehyde (Niven, 2005). Low strength blends of bioethanol appear to have little effect on acetone emissions (Niven, 2005).

30. **Overall, low strength blends of bioethanol reduce or have little effect on emissions of air quality pollutants with the exception of acetaldehyde which shows a marked increase in emissions. For high strength blends of bioethanol (E85), the reductions in emissions are smaller for CO and HC and emissions of pollutants such as acetaldehyde *and* formaldehyde increase, however further research is required especially if consumption of high strength blends is encouraged**.

31. As well as emissions from the exhaust owing to incomplete combustion, hydrocarbons are also emitted from petrol vehicles due to evaporation of fuel vapour from the fuel tank and the vehicle's fuel delivery system, a process that depends on the vapour pressure of the fuel, ambient temperature conditions and whether the car is fitted with a carbon canister device for evaporative emission control. Fuel quality regulations in Europe and North America set maximum limits on the vapour pressure of petrol that can be sold during the summer months so as to reduce evaporative emissions which can be significant in hot climates. However, adding small quantities of ethanol to petrol (from 0 to ~8% by volume (v/v)) has the effect of increasing the vapour pressure of the fuel. Above around 8%, the vapour pressure decreases with increasing ethanol content.

32. A modelling study by AEA for the Department for Transport estimated that increasing fuel vapour pressure from 60 to 68 kPa during the summer months to allow the uptake of 10% bioethanol would increase total hydrocarbon emissions in Europe by 0.7% in 2010 and 0.35% in 2020 during the summer owing to the increase in evaporative emissions from vehicles (Li *et al.*, 2007). The same study reviewed evidence on the effect of ethanol on the chemical composition of hydrocarbons in the fuel vapour. Based on empirical observations and theoretical considerations it was concluded that adding 10% ethanol to a low volatility (60 kPa) base fuel would lead to:

- Ethanol being present at 1% by mass in the bioethanol fuel vapour

- The mix of hydrocarbons within each of the alkane, alkene and aromatic groups remaining unchanged
- The alkane/alkene mix remaining unchanged, but the (alkane + alkene) concentrations increasing relative to aromatics such that the (alkane + alkene)/aromatic ratio increases by 27%.

33. Based on these criteria and the default speciation profile of petrol fuel vapour emissions taken from Passant (2002), Table 2 indicates the VOC speciation profile for the base fuel and for 10% bioethanol. The enrichment in alkanes and alkenes relative to aromatics caused by adding 10% ethanol has a very small effect on the profile overall.

Table 2: Chemical speciation of non-methane VOC (NMVOC) emissions from evaporation of 10% ethanol-petrol fuel blends from road vehicles compared with base fuel values

Species	**% of total NMVOC**	
	Base fuel	**10% ethanol/petrol**
1-pentene	2.0%	2.0%
2-butene	2.0%	2.0%
2-methylbutane	25.1%	25.0%
2-methylpropane	10.1%	10.1%
2-pentene	3.0%	3.0%
n-butane	20.1%	20.0%
Benzene	0.3%	0.3%
m-xylene	0.3%	0.2%
n-pentane	15.1%	15.0%
Propane	1.0%	1.0%
p-xylene	0.2%	0.2%
Toluene	1.0%	0.8%
n-heptane	2.0%	2.0%
n-hexane	15.1%	15.0%
1-butene	1.0%	1.0%
1,3-hexadiene	1.5%	1.5%
Ethanol	0%	1.0%

Biodiesel

34. Studies on biodiesel have also shown a high degree of variability in emissions, although some consistent patterns are apparent. The majority of studies have been carried out on heavy duty vehicles and engines. The US Environmental Protection Agency (USEPA) carried out a comprehensive analysis on emission test results for a variety of biodiesel products based on studies made predominantly in the U.S. (USEPA, 2002). Results from this study were the basis of the scaling factors for biodiesel developed in the NAEI review. These are largely consistent with the conclusions of a more recent comprehensive review of biodiesel engine emissions carried out by Lapuerta *et al.* (2008). The available information indicated that emissions from light duty vehicles might respond differently to biodiesel than emissions from heavy duty vehicles for some pollutants. Furthermore, emissions from virgin plant oil are different to those from esterified vegetable oils.

35. Most types of biodiesel from esterified vegetable oils lead to reductions in HC, CO and PM emissions, but lead to a small increase in NO_x. Moreover, the changes in emissions become larger with increasing biodiesel strength in the fuel. The changes observed in most studies are consistent for CO and HC which is not surprising given that biodiesel contains a significant amount of oxygen in the fuel thus helping to oxidise unburnt fuel. The changes in NO_x and PM emissions are more uncertain and variable, however the weight of evidence in the reviews of the USEPA (2002) and Lapuerta *et al*. (2008) points to a slight increase in NO_x emissions and a reduction in PM emissions relative to conventional diesel. Most of the evidence points to a reduction in emissions of toxics such as polyaromatic hydrocarbons.

36. The USEPA study examined emissions data for different types of esterified biodiesel feedstocks. It found that animal fat based esterified diesel blends showed greater reductions in emissions of PM and smaller increases in emissions of NO_x compared with vegetable and plant oil based diesel blends and this again was consistent with the balance of evidence given by Lapuerta *et al*. (2008). The emission effects of different vegetable and plant oil-based biodiesel blends were quite similar.

37. The results from the USEPA study are largely consistent with the other major reviews undertaken in Europe since then , for example at the JRC Ispra and were used by Murrells and Li (2008) to develop scaling factors for esterified vegetable/plant oil biodiesel blends shown in Table 3 for different mixture strengths, from 5-15% and 100%. Table 3 refers to the change in emissions from heavy duty vehicles. The figures should be taken to be approximate.

Table 3: Emission scaling factors for different blends of esterified vegetable/plant oil biodiesel relative to base diesel: Heavy duty vehicles:

	HC	CO	NO_x	PM
B5	0.95	0.98	1.00	0.98
B10	0.89	0.96	1.01	0.95
B15	0.84	0.94	1.01	0.93
B100	0.31	0.66	1.08	0.62

38. Data on biodiesel emissions from light duty vehicles are much more sparse and the USEPA acknowledges that it cannot say for certain that their conclusions for heavy duty vehicles apply to light duty vehicles. In fact, data from the JRC on light duty vehicles sometimes conflicts with those of the USEPA on heavy duty vehicles. This may be in part be due to the dependence of the emission changes on drive cycle and diesel engine and exhaust after treatment technologies. These were discussed in detail in the review by Lapuerta *et al.* (2008). Table 4 refers to change factors in emissions from light duty diesel vehicles. These are based on considerations of evidence given in the USEPA and JRC reports and again are very approximate.

Table 4: Emission scaling factors for different blends of esterified vegetable/plant oil biodiesel relative to base diesel: Light duty vehicles:

	HC	CO	NO_x	PM
B5	0.97	0.99	1.00	0.95
B10	0.95	0.98	1.00	0.91
B15	0.92	0.97	1.00	0.86
B100	0.31	0.66	1.08	0.62

39. These change factors are assumed to apply to all driving cycles, but must be viewed with a high level of uncertainty. **Further research is required on the cycle and technology dependence of these biodiesel emission effects on light and heavy duty diesel vehicles.**

40. Virgin plant oil (without esterification) can be used in pure form or blended with petroleum-based diesel fuel. Far fewer studies have been made on the effects of virgin plant oil (VPO) on emissions and the results appear to be much more varied and different to those for esterified biodiesel fuels. This might reflect the need for engine re-calibration or conversion especially at high strengths. Results tend to show smaller reductions in emissions of CO and HC compared with esterified biodiesel fuels, while the effects on PM are especially uncertain with both increases and decreases in emissions being reported. Based mostly on the evidence from the

JRC study (JRC, 2006), Table 5 provides very approximate scaling factors for pure 100% VPO.

Table 5: Emission scaling factors for pure virgin plant oil (VPO) biodiesel relative to base diesel: all vehicles

VPO	HC	CO	NO_x	PM
100%	1.5	1.5	1.0	1.5

41. For the non-regulated pollutants, it is at best only possible to make qualitative statements on the effects of biodiesel. These are summarised in Table 6 for esterified and virgin plant oil biodiesel where a √ symbol indicates a reduction in emissions relative to conventional diesel, a X symbol indicates an increase in emissions and a O symbol indicates no effect. Emissions of overall toxics from virgin plant oil biodiesel are not known and cannot be even qualitatively assessed. Overall, biodiesel may reduce emissions of PAH, but increase emissions of benzene and 1,3-butadiene compared with conventional diesel.

Table 6: Directional change in emissions of non-regulated pollutants from esterified and virgin plant oil biodiesel relative to emissions from petroleum-based fuels

	All toxics	Benzene	1,3-butadiene	PAHs
RME	√	**X**	**O**	√
VPO	**-**	**X**	**X**	**O**

√ indicates a likely decrease in emissions relative to petroleum-based fuel (i.e. a beneficial effect)

O indicates weak effect or no clear trend, with equal evidence for increase and decrease in emissions relative to petroleum-based fuel (i.e. no clear effect)

X indicates a likely increase in emissions relative to petroleum-based fuel (i.e. negative effect)

RME refers to rapeseed methyl ester diesel

VPO refers to virgin plant oil diesel

42. The effects on biofuels on vehicle emissions summarised in this Advice Note are derived from the literature review carried out in 2008 for the NAEI (Murrells and Li, 2008). More recent emission factor reviews and compilations give similar overall conclusions on biofuel effects even though they do not specifically address biofuels. This includes the recent emission factor review carried out by the Transport Research Laboratory (TRL) on behalf of DfT (Boulter *et al*., 2009) and the most recent EMEP/CORINAIR emission inventory guidebook.

43. The recent comprehensive review by Lapuerta *et al* .(2008) not only brought together all the evidence on the effects on biodiesel fuels on emissions for each pollutant in turn, but also gave reasons for the changes observed and the effect of biodiesel characteristics.

44. For NO_x, Lapuerta *et al*. (2008) highlighted how the emission effects depend on the type of engine and operating conditions. The consensus is that NO_x emissions are slightly increased because the injection of biodiesel fuel is slightly advanced in the engine cycle relative to the injection of conventional diesel fuel because of the physical properties of the fuel and this leads to a higher mean peak combustion temperature. A reduction in heat dissipation by radiation as a consequence of lower soot yield leading to higher flame temperatures and other potential combustion chemistry effects have also been postulated for the increase in NO_x emissions. Because PM emissions from biodiesel exhausts are lower it has been suggested that delaying fuel injection could be used as a means to eliminate the increase in NO_x, paying a minor penalty in PM emissions from the engine which could be controlled by downstream exhaust abatement technologies such as particulate filters. Another approach may be to use more saturated biodiesel fuels derived from animal fats as opposed to vegetable oils in order to reduce NO_x. Increases in NO_x emissions could also be controlled by optimising Exhaust Gas Recirculation (EGR).

45. For PM, Lapuerta *et al.* (2008) highlighted that although agreement on a reduction in emissions is fairly unanimous, the magnitude of the effect is highly variable and dependent on engine conditions, load and exhaust after-treatment systems. Larger decreases appear to be shown under high engine load conditions and the benefits appear to be more evident on older engine technologies. However, under cold engine conditions during start-up, the advantages of biodiesel may be substantially reduced. The main reasons for the reduction in PM emissions are believed to be due to the higher oxygen content of biodiesel leading to more complete combustion, and the absence of aromatic compounds leading to a reduction in soot formation, as well as the advance in combustion timing. Again, saturated biodiesel fuels from animal fats may lead to lower PM emissions compared with those derived from vegetable and plant oils. Lapuerta *et al*. (2008) report that the majority of studies show a shift in the particulate size distribution towards smaller particles when biodiesel is used. This appears to be caused by a sharp decrease in the number of large particles with some studies showing this is compensated for by an increase in number of small particles (<40 nm) emitted though this and the overall effect on particle numbers emitted remains highly uncertain.

46. For HCs and CO, the fairly clear evidence for the reduction in emissions from biodiesel fuels is mainly because of their increased oxygen content leading to more complete combustion. The effect may be less pronounced in diesel vehicles equipped with diesel oxidation catalysts.

47. Lapuerta *et al*. (2008) summarise that the absence of polyaromatic hydrocarbons (PAHs) in biodiesel fuels is the main reason for the reduction in PAH emissions. The change in aromatic emissions such as benzene is less conclusive. The effect of biodiesel on oxygenated compound emissions such as formaldehyde is also unclear.

48. Evidence in the literature on the effects of biofuels on more modern engine and vehicle technologies is lacking and should be addressed. There is further, as yet unpublished evidence from engine and vehicle manufacturers that biodiesel does cause an increase in NO_x emissions. This can be corrected by SCR technology for low biodiesel blends, but may be a problem with high strength biodiesel.

49. As indicated by the reviews referred to in this report (USEPA (2002), Lapuerta *et al.* (2008), JRC (2006)), there is a fairly strong indication that biodiesel reduces PM mass emissions from most vehicles under most conditions, but there is no clear evidence on the impacts of biodiesel on the particle size distribution, on particle number and on characterisation of particulate matter in exhaust emissions. There is little known about the toxicity of particulate matter from biodiesel. It has been suggested that biodiesel may be more effective in reducing PM emissions from older diesel engines and that the effect on more modern vehicles is dependent on aftertreatment technologies. The chemical speciation of volatile and semi-volatile organic compounds emitted from biodiesel consumption is not known indicating that their propensity to forming secondary organic aerosols cannot be assessed.

50. There has been no research on the effect of biodiesel on primary NO_2 emissions. The possibility that biodiesel leads to higher primary NO_2 emissions from diesel engines should be examined given the higher oxygen content of the fuel and the difference in physical properties and combustion conditions.

51. **AQEG recommends further research on the effects of different strengths of biodiesel fuels on mass emissions of NO_x, primary NO_2 and PM and the characterisation of particulate matter and chemical composition of organic compounds emitted from modern diesel engines and vehicle technologies so that the full air quality impacts of biodiesel consumption can be assessed.**

Fischer-Tropsch biodiesel

52. The Fischer-Tropsch (F-T) process is a way of producing synthetic diesel fuel from gas derived from waste biomass feedstocks. Any type of biomass can be used as a feedstock, including woody and grassy materials and agricultural and forestry residues. The biomass is gasified to produce synthesis gas, which is a mixture of carbon monoxide (CO) and hydrogen (H_2). Prior to synthesis, this gas can be conditioned using the water gas shift to achieve the required H_2/CO ratio for the synthesis. The liquids produced from the syngas, which comprise various

hydrocarbon fractions, are very clean (sulphur free) straight-chain hydrocarbons with very low aromatic content, ideal for diesel engines.

53. The production of F-T biodiesel is still mainly on a small-scale development phase. However, recent research does suggest significant reductions in the regulatory pollutants, HC, CO and PM, relative to fossil-fuel diesel and pure soybean methyl-ester biodiesel fuel and reductions in NO_x emissions were seen under some conditions (Armas *et al*., 2010). However, further research is required to confirm this under real-world conditions.

Biogas

54. Biogas can be derived from a variety of renewable sources and comprises mainly methane and a mix of other gaseous impurities. These need to be removed to produce a product which is essentially biomethane that can be run on vehicles able to run on compressed natural gas (CNG). The effects of biomethane on emissions therefore largely mirror the effects of running a vehicle on CNG. These show reductions in emissions of all the air quality pollutants relative to their emissions from petrol or diesel equivalent vehicles. Biogas is still a niche fuel used largely on a trial basis in the UK as a replacement fuel for heavy duty vehicles, especially buses. Based on the review of biogas emissions in the GAVE research programme in the Netherlands (TNO, 2004), Murrells and Li (2008) developed approximate scaling factors for emissions from heavy duty vehicles running on biogas relative to fossil fuel diesel shown in Table 7. The larger reduction in NMVOC emissions compared with HC reflects the fact that most of the HC emissions are in the form of unburnt methane.

55. These factors refer to current diesel technologies. A potential negative impact of biogas could arise for more advanced diesel technologies relying on a NO_x storage catalyst system. These rely on HC reducing agents in the exhaust to regenerate the NO_x trap. A potential problem arises because methane, the main HC constituent of biogas, is a poor reducing agent so may not adequately regenerate the NO_x trap.

Table 7: Emission scaling factors for biogas emissions from heavy duty vehicles relative to base diesel

	HC	CO	NO_x	PM	NMVOCs
Biogas	0.65	0.83	0.5	0.3	0.065

Effect of biofuels on air quality

Evidence based on current consumption of biofuels

This section addresses the question:

What is the evidence from other countries for changes in atmospheric composition as a result of the use of biofuels?

56. The UK still uses relatively small amounts of low strength bioethanol and biodiesel and consumption has only grown to current levels over the past 2-3 years. Consumption is also likely to be well dispersed across the country, with no particular "hot spots" of biofuel consumption. For this reason, it is highly unlikely that there is any evidence for changes in atmospheric concentrations of pollutants directly emitted from consumption of biofuels by road transport or of those produced indirectly from emissions via secondary reactions in the atmosphere. This pattern is likely to continue, although there may be localised use of some biofuels by captive fleets in areas close to where they are produced. An example may be localised use of biogas for captive fleets of road and off-road vehicles in rural areas close to sites with anaerobic digestors, but it is unlikely that consumption would be high enough to observe any changes in ambient concentrations.

57. The likely continued growth in biofuel consumption in the UK means that evidence for any atmospheric change in pollutant concentrations should be monitored in parallel with direct measurements of biofuel emissions from road vehicles. As indicated in the previous section, any evidence for changes in NO_x, PM and primary NO_2 emissions from road vehicles running on biofuels should be coupled with observations of roadside concentrations providing supporting evidence.

58. Other atmospheric signatures of biofuel consumption could also be monitored. For example, increases in roadside acetaldehyde concentrations would be a signature for increases in bioethanol consumption. Increases in other oxygenated VOCs and products from their reactions in the atmosphere could be monitored. Any observed increases in concentrations of the toxic compound peroxyacetyl nitrate (PAN) may be inferred from increases in traffic emissions of acetaldehyde. PAN is a constituent of photochemical smog normally formed in stagnant air in warm summer climates causing eye irritation and respiratory problems.

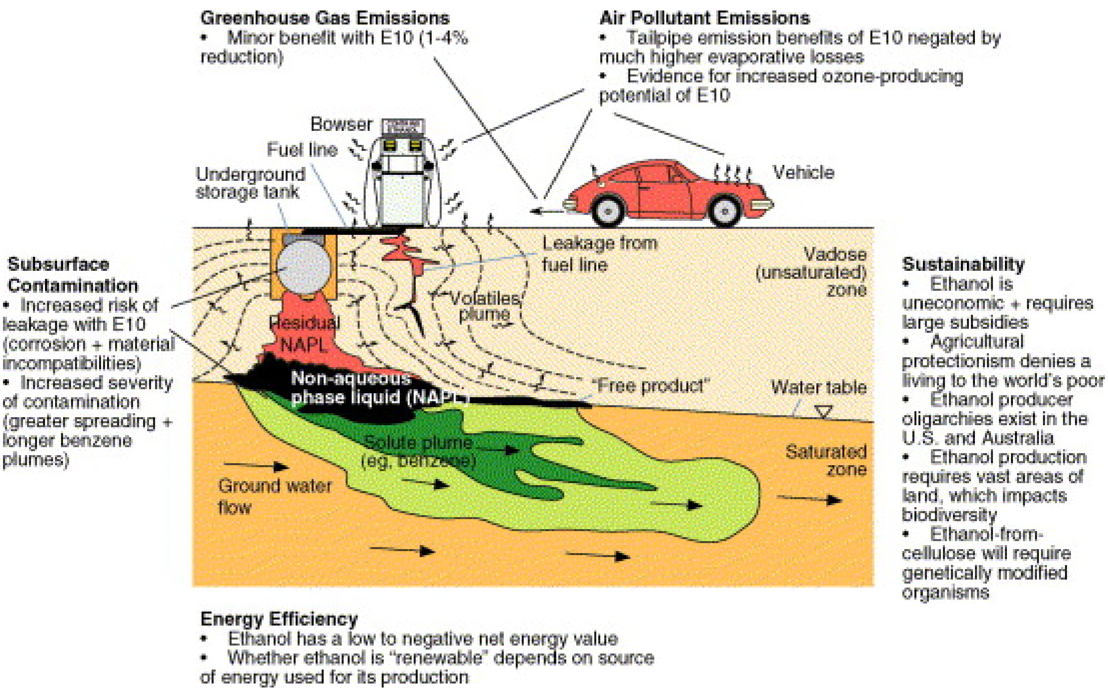
59. More insight into the effects of biofuel consumption on the atmosphere can best be found in places which have been using biofuels for longer. Most of the evidence can be found in studies of ambient air pollution undertaken in parts of North and South America where petrol containing ethanol or related oxygentated fuels have been

used for several decades. Fewer places in the world have had prolonged experience in the use of biodiesel as a fuel.

60. The environmental impacts of ethanol as a biofuel are controversial (Anderson, 2009; Niven, 2005). Some of the earliest measurements of the atmospheric impact of ethanol biofuels come from Grosjean *et al.* (Grosjean *et al*., 1998a; Grosjean *et al*., 1998b) from VOC measurements in Porto Alegre in Brazil showing enhanced ambient ethanol concentrations ascribed to the use of ethanol based biofuels. Of the 600,000 vehicles in the city 17% used ethanol fuel (hydrated ethanol ca. 5% water with small amounts of gasoline $\leq$ 5%) with many more using 15% methyl-tertiary butyl ether (MTBE)/gasoline fuels. Though ethanol was prominent by atmospheric concentration the authors show that it is not important in terms of ozone formation and may assist in the reduction of ozone and photochemical pollution.

61. Niven (2005) concluded from review work that "E10 is of debatable air pollution merit (and may in fact increase the production of photochemical smog); offers little advantage in terms of greenhouse gas emissions, energy efficiency or environmental sustainability and will significantly increase both the risk and severity of groundwater contamination". These are summarised in Figure 3.

Figure 3: Schematic representation of the environmental impacts of ethanol in gasoline (Niven, 2005).



62. With respect to E85 he concludes that "E85 offers significant greenhouse gas benefits, it will produce significant air pollution impacts, involves significant risks to biodiversity and its groundwater contamination impacts and overall sustainability are

largely unknown". In this review, Niven (2005) pays particular attention to the air quality risks of higher evaporative losses arising from low-strength ethanol blends in regions such as Australia where fuel vapour pressure is not controlled and higher concentrations of acetaldehyde and PAN. A number of studies were reported by Niven (2005) showing levels of ethanol and acetaldehyde in several cities in Brazil substantially higher than elsewhere in the world, these being attributed to lack of control on fuel vapour pressure in Brazil leading to higher evaporative emissions. Martins and Arilla (2003) and Tanner *et al.* (2002) used a combination of field data and modelling to conclude that high acetaldehyde/formaldehyde concentration ratios and high PAN concentrations in Rio de Janeiro are due to the use of ethanol fuels.

63. Anderson (2009) reviews data from South America and concludes that there is clear evidence for enhancement of atmospheric concentrations of acetaldehyde and ethanol and that NO_X may well increase when ethanol based fuels are used. Gaffney and Marley (2009) have pointed out that the "combustion of renewable fuels may, in some cases, result in a reduction in the criteria pollutant, the emissions may contain significant amounts of unregulated yet equally important pollutants". There is little doubt that in the case of ethanol mixture combustion these may include ethanol and acetaldehyde.

64. In the U.S., oxygenated gasoline has been mandated for some years in several regions as a means to combat CO during winter months and ozone during summer. Niven's review quotes a study showing a significant increase in formaldehyde levels in the Denver metropolitan area when the fuel oxygen content was raised from 2.0 to 2.6 wt%. Another study found a five-fold increase in acetaldehyde and higher PAN concentrations in Albuquerque, NM, during one winter season relative to a summer reference which was attributed to consumption of E10 (Gaffney *et al*., 1997). Elevated levels of ozone seen in some districts of the U.S. using E10 have been attributed to higher NO_x emissions and evaporative losses of VOCs. However, it is unlikely this interpretation would be valid in the UK where fuel vapour and evaporative emissions are controlled by EU legislation and there is no evidence for any significant increase in NO_x emissions from petrol vehicles running on ethanol.

65. Niven's review makes a strong statement on the importance of life-cycle emissions of air quality pollutants from bioethanol suggesting that any tailpipe emission benefits may be negated by higher life-cycle emissions. This might be especially true for high strength E85 where "embodied" emissions of VOCs, CO, NO_x and PM may be higher than for fossil fuel petrol because of land clearance and harvesting practices.

66. A recent review by Liaquat *et al*. (2010) examines the potential emission reductions from the road transport sector from using biofuels in developing countries. It points a more positive picture stating that many developing countries in Asia are producing and exporting biofuels, but have not been utilising it themselves whereas if they did, it may help to reduce some of their own air pollution problems in major cities. It is the case that the emission benefits of biofuels may be stronger for older vehicle

technologies and 2-stroke engines which are more prevalent in these countries, especially as many are running on inferior quality petroleum-based fuels with high sulphur content. However, the review by Liaquat *et al.* did not consider whether the local air quality benefits achieved through consumption of biofuels leading to lower exhaust emissions outweigh the potential air quality disbenefits (and wider environmental damage) caused by the large scale production of these fuels in these countries.

67. In conclusion, it can be stated that there is no clear evidence of any benefits to air quality brought about by consumption of bioethanol in countries where consumption is significant, though some regions may have experienced improvements in CO that could be directly attributable to bioethanol consumption. There is fairly clear evidence of increases in acetaldehyde concentrations in all regions where ethanol is used as a fuel and increases in formaldehyde concentrations at least in regions where high strength (E85) ethanol is used.

Assessment of the future impact of biofuel consumption

This section addresses the question:

What is the likely impact on air quality in the UK of the change in emissions as a result of the increased use of biofuels?

68. Based on the emission change effects concluded by the NAEI and summarised in the previous section, the NAEI has predicted the future impact of biofuel consumption on emissions from the transport sector in the UK. Further assessments were carried out on the impacts of a Europe-wide increase in biofuel consumption on ground-level ozone concentrations in the UK.

69. As the precise mix of biofuel consumption in the UK cannot be predicted, the NAEI modelled a number of different biofuel uptake scenarios to quantify the effects each would have on projected UK traffic emissions of NO_x, PM, VOCs and CO (Murrells and Li, 2008). Seven illustrative uptake scenarios were modelled, differing in terms of the relative amounts of bioethanol and biodiesel consumed, but with all scenarios being consistent with the same overall energy content of the fuels displacing fossil fuel petrol and diesel according to current UK and EU renewable fuels targets. These imply a 5% biofuels by volume target for 2010 rising at a linear rate each year to reach 15% biofuels by volume target for 2020, the latter being consistent with the EU conditional target of 10% by energy content. The difference between each of the seven scenarios is the mix of different biofuels used to reach the target.

70. Some of the scenarios were quite extreme, by strongly favouring a particular type of biofuel, but were chosen deliberately to illustrate the maximum range of outcomes in terms of future emissions of air quality pollutants that can be expected within an overall strategy to boost consumption of biofuels consistent with current UK objectives and EU targets. All the scenarios are based on consumption of first-generation biofuels although it is recognised that second-generation biofuels might be necessary to meet the more ambitious EU conditional target for 2020. The scenarios are listed below and described in detail in Annex 1.

- **'Realistic' Scenario 1**
- **'Bioethanol Favoured' Scenario 2**
- **'Bioethanol Only' Scenario 3**
- **'Biodiesel Favoured' Scenario 4**
- **'Biodiesel Only' (RME) Scenario 5**
- **'Biodiesel Only' (VPO) Scenario 6**
- **'Realistic' with biogas consumption by HDV Scenario 7**.

71. The methodology, assumptions and emission factors used for calculating and forecasting future emissions from road transport are given in the methodology annex to the Greenhouse Gas Inventory report (Choudrie *et al.*, 2008[6]). The changes in future exhaust and evaporative emissions from UK road transport in years up to 2020 were calculated using other core assumptions underlying the NAEI's base emission projections at the time of the study, including future changes in traffic and the development of the vehicle fleet and penetration of new technologies.

72. Details of the assumptions made for the basecase and the biofuel scenarios together with the results are given in Murrells and Li (2008). Table 8 summarises the relative change in UK road transport emissions of NO_x, PM, CO and NMVOCs for each scenario relative to the base (no biofuels) from 2010 to 2020. A negative value indicates a decrease in emissions. The results for NO_x and PM are also shown graphically in Figures 4 and 5.

73. For NO_x, all the biofuel scenarios have very little effect on overall emissions. All the scenarios except the biogas scenario lead to a very small increase in emissions. In relative terms, the effects range from +0.3% to –0.7% of total road transport emissions predicted in 2010. As the uptake rate of biofuels increases further into the future, the impacts increase to +1.6% to –2.2% of total road transport emissions predicted in 2020. By this time, it is the RME-biodiesel only scenario (S5) which

[6]Hhttp://www.airquality.co.uk/archive/reports/cat07/0804161424_ukghgi-90-06_annexes_UNFCCCsubmission_150408.pdf

leads to the largest increase in NO_X as a result of the impact of pure RME-biodiesel on emissions from LDVs and HDVs. The beneficial effect of biogas on NO_X emissions from diesel vehicles leads to Scenario 7 showing the largest decrease in emissions by 2020. The 'more realistic' scenario (S1) involving equal uptake rates of low strength bioethanol and biodiesel blends leads to a 0.2 to 0.5% increase in road transport NO_X emissions from 2010 to 2020.

74. For PM, the effects of biofuels are more significant and all scenarios lead to a reduction in emissions except the scenario involving uptake of pure virgin plant oil biodiesel (S6). In 2010, the effects range from a decrease of 2.1% in emissions for the bioethanol favoured scenarios (S2 and S3) to a decrease of 7.1% for the biodiesel favoured and 'only' scenarios (S4-S6). By 2020, the range of outcomes between the different scenarios becomes much larger. The extreme 'biodiesel only scenario' involving the uptake of pure virgin plant oil leads to a 8.9% increase in PM emissions, reflecting the negative impact of this fuel on diesel vehicle emissions shown in Table 5. On the other hand any scenario that involves the widespread uptake of low strength blends of RME-biodiesel (S1, S2 and S4) in the fleet by 2020 leads to almost 17% reduction in predicted PM emissions for that year. The scenario leading to the largest reduction in emissions is the 'realistic with biogas' scenario (S7) leading to an 18.5% reduction by 2020. The 'more realistic' scenario (S1) involving equal uptake rates of low strength bioethanol and biodiesel blends leads to a 4.8 to 16.8% decrease in road transport PM emissions from 2010 to 2020.

Table 8: Percentage change in projected emissions of NO_x, PM, NMVOCs and CO from UK road transport for different biofuel uptake scenarios relative to the basecase. A negative number indicates a decrease in emissions.

		% Change in emissions		
		2010	2015	2020
Scenario 1 - Realistic	NOx	0.2%	0.3%	0.5%
	PM	-4.8%	-10.2%	-16.8%
	NMVOCs	-1.8%	-4.8%	-7.8%
	CO	-7.9%	-15.1%	-22.9%
Scenario 2 - Bioethanol favoured	NOx	0.0%	0.2%	0.5%
	PM	-2.1%	-9.5%	-16.8%
	NMVOCs	-1.4%	-4.1%	-7.8%
	CO	-16.4%	-22.1%	-22.9%
Scenario 3 - Bioethanol only	NOx	0.0%	0.0%	0.0%
	PM	-2.1%	-0.5%	-1.3%
	NMVOCs	-1.4%	0.0%	0.0%
	CO	-16.4%	0.0%	0.0%
Scenario 4 - Biodiesel favoured	NOx	0.3%	0.5%	0.5%
	PM	-7.1%	-11.3%	-16.8%
	NMVOCs	-3.0%	-6.1%	-7.8%
	CO	-0.4%	-4.7%	-22.9%
Scenario 5 - Biodiesel only (esterified)	NOx	0.3%	1.1%	1.6%
	PM	-7.1%	-5.4%	-6.7%
	NMVOCs	-3.0%	-5.6%	-8.8%
	CO	-0.4%	-1.3%	-2.0%
Scenario 6 - Biodiesel only (virgin plant oil)	NOx	0.3%	0.0%	0.0%
	PM	-7.1%	7.1%	8.9%
	NMVOCs	-3.0%	4.1%	6.4%
	CO	-0.4%	1.9%	3.0%
Scenario 7 - Realistic + 10% HDVs with biogas	NOx	-0.7%	-1.4%	-2.2%
	PM	-5.2%	-11.1%	-18.5%
	NMVOCs	-2.4%	-6.2%	-10.1%
	CO	-7.9%	-15.1%	-23.1%

Figure 4: Change in UK road transport emissions for different biofuel uptake scenarios: NO_x

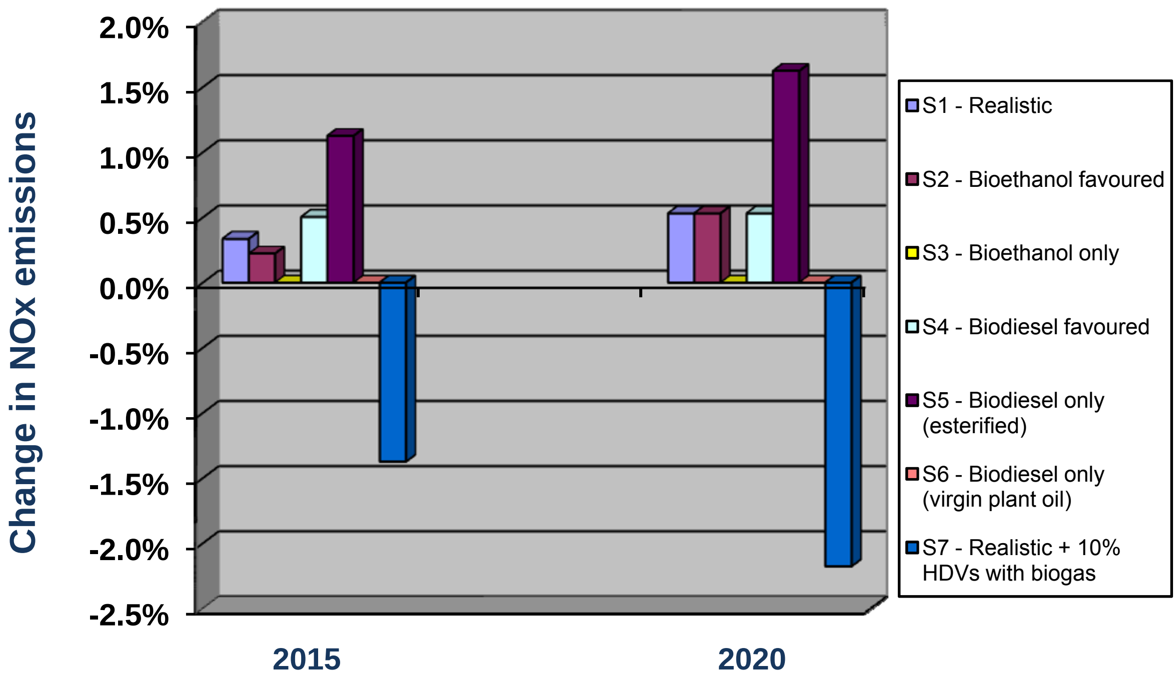
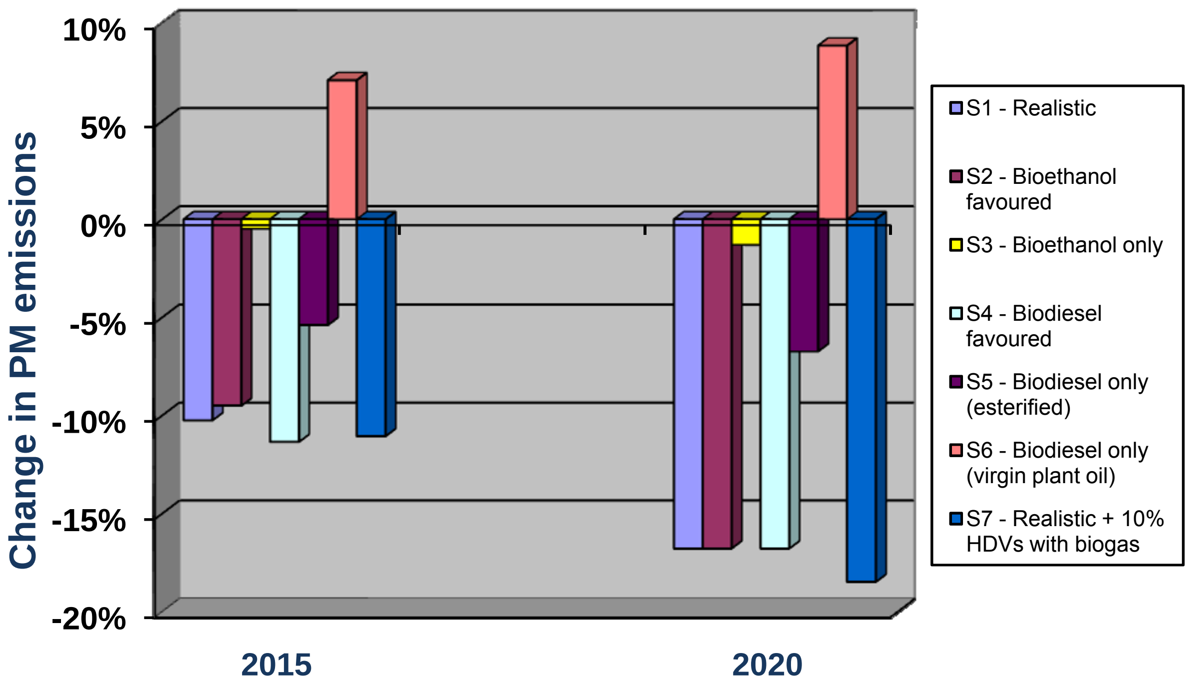


Figure 5: Change in UK road transport emissions for different biofuel uptake scenarios: PM



75. Table 9 summarises the range of outcomes in emission changes occurring in 2020 for the seven scenarios investigated and that for the "more realistic" scenario. The only scenario leading to increases in PM, CO and VOCs is the extreme one concentrated on the uptake of pure virgin plant oil biodiesel.

Table 9: Effect of biofuel uptake scenarios on UK road transport emissions in 2020 (Source: Murrells and Li, 2008)

	"Realistic" scenario	**Range over scenarios**
NOx	0.5%	-2% to +2%
PM	-16.8%	-19% to +9%
NMVOCs	-7.8%	-10% to +6%
CO	-22.9%	-23% to +3%

76. Two modelling and assessment studies were carried out specifically on the effect of bioethanol uptake on VOC emissions and their impact on ground-level ozone concentrations in the UK. The first study was undertaken for the Department for Transport and considered the increase in evaporative emissions of VOCs that would occur across Europe if the vapour pressure of fuel was increased by the addition of bioethanol to petrol. It was estimated that the overall increase in evaporative emissions during the summer period (May to September) in 2015 would be around 17% in 2015 and around 0.5% in terms of total emissions of VOCs from all sources in Europe (Li *et al.*, 2007). Taking into account the ozone forming potential of the VOCs emitted in fuel vapour using the Photochemical Ozone Creation Potential (POCP) concept, the increase in the POCP-weighted emissions of VOCs in Europe was also estimated to be around 0.5%. This gives an indication of the increase in episodic ozone along a trajectory reaching the UK caused by the increase in fuel volatility.

77. Another study for Defra examined the effect on ozone of increases in vehicle exhaust emissions of acetaldehyde and evaporative emissions of fuel vapour due to increased consumption of bioethanol in Europe. The Ozone Source Receptor Model was used to model the effect on ozone concentrations at 41 receptor sites in the UK in 2010, 2015 and 2020 (Murrells *et al.*, 2008). The study assumed that all petrol consumed in Europe would contain 10% bioethanol by 2020. The impact on ozone concentrations in the UK was found to be extremely small. This is mainly because of the small contribution made by vehicle evaporative emissions to overall VOC emissions in Europe beyond 2010 and because of the relatively small baseline

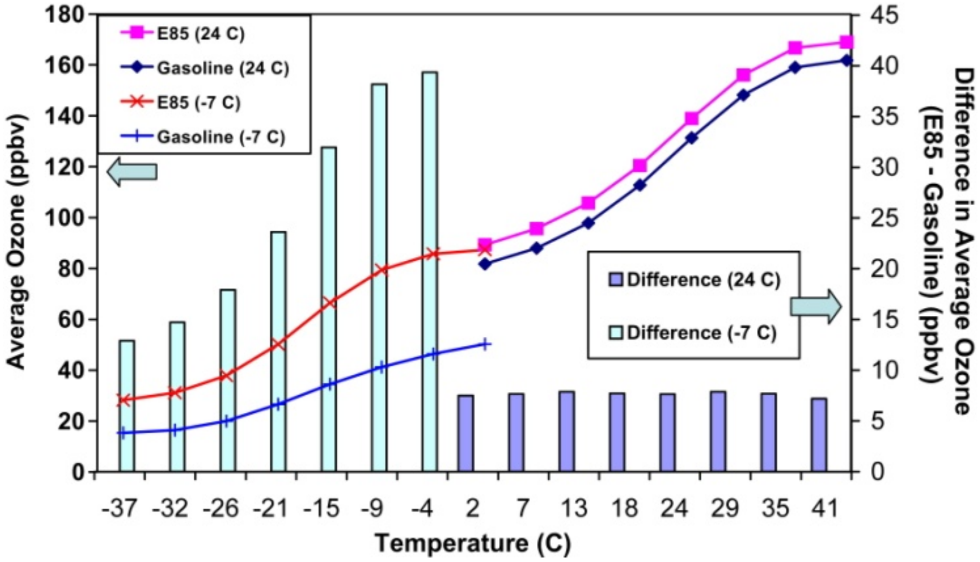
contribution of acetaldehyde to exhaust emissions of VOCs. Other environmental consequences of higher acetaldehyde emissions were not considered.

78. Other studies on the effects of biofuels on air quality have been undertaken in the U.S. focusing on the potential effects of high-strength E85 bioethanol on ozone concentrations. A modeling study by Jacobson (2007) suggests that ozone levels could increase in some urban areas in the U.S. like Los Angeles and decrease in other urban areas in the southeastern U.S. if vehicles start using E85 instead of gasoline. The study concluded that the population-weighted ozone exposure over the whole U.S. would likely increase.

79. More recently, a chemical modelling study by Ginnebaugh *et al*. (2010) simulated the effect of E85 bioethanol on urban air pollution using Los Angeles in 2020 as a basecase for two different ambient temperature conditions. The study used the Master Chemical Mechanism in a 3-D box model using species-resolved vehicle emissions data characteristic of warm summer conditions (using exhaust and evaporative emissions at $24^{o}C$) and cold winter conditions (using exhaust emissions at $-7^{o}C$) for E85 and base gasoline fuel to determine how atmospheric chemistry is affected by temperature. Higher ozone concentrations were produced from E85 compared with gasoline at all temperature conditions, but the difference was much greater in the simulated winter conditions than in the simulated summer conditions for an area with a high NO_x/VOC ratio (see Figure 6). Formaldehyde, acetaldehyde and PAN levels were also all higher with E85 than with gasoline. The enhancement of these tracers is in agreement with experimental data from Brazil where there is much larger usage of ethanol-based fuels (Anderson, 2009).

80. The authors of these studies strike a note of caution with respect to the air quality impacts of the widespread introduction of E85. Given that bioethanol is mainly consumed in the UK and in most of the rest of Europe as low strength blends, the results from these U.S. studies are unlikely to be relevant to current ozone air quality in the UK. **However, any policy that would lead to more widespread use of bioethanol as high-strength E85 blends would need to consider the potential impacts on ambient concentrations of ozone and other pollutants including aldehydes. This will require further research on the effects of E85 on "real world" emissions including aldehydes.**

Figure 6: Two day average ozone concentration from E85 and gasoline (left axis) and its difference (right axis) versus temperature using emission data at −7 °C and 24 °C (Ginnebaugh *et al*., 2010).



Annex 1: Biofuel uptake emission scenarios modelled by the National Atmospheric Emissions Inventory

81. The National Atmospheric Emission Inventory (NAEI) has predicted the future impact of biofuel consumption on emissions from the transport sector in the UK for the following biofuel uptake scenarios. This is taken from the NAEI report of Murrells and Li (2008) where further details are given.

Scenario 1 – "Realistic" scenario

82. This scenario assumes equal uptake rates of bioethanol displacing normal petrol and RME-biodiesel displacing normal diesel. In other words, by 2010, 5% of volume of petrol sold is bioethanol (as E5) and 5% of volume of diesel sold is RME-biodiesel (as B5). By 2020, 15% of volume petrol sold is bioethanol (as E15) and 15% of volume diesel sold is RME-biodiesel (as B15). The scenario is referred to as 'Realistic' simply because it implies moderate uptake of both low strength blends of bioethanol and biodiesel with neither being strongly favoured. The scenario, however, takes into account the overall growth in diesel consumption relative to petrol consumption as a result of the increased penetration of diesel cars into the fleet implied in the base emission projections of the NAEI. Hence, overall more biodiesel than bioethanol would have to be sold to meet this requirement. This scenario assumes a higher Reid Vapour Pressure (RVP) of the low strength bioethanol fuel relative to the petrol fuel it is displacing and hence an increase in evaporative emissions occurs during the summer months.

Scenario 2 – "Bioethanol favoured" scenario

83. This scenario assumes that the biofuel targets are met initially by the sale of 15% bioethanol (E15) only and once the sale of E15 reaches 100% of all petrol sales (i.e. saturates the petrol market, which it must do very quickly to maintain the overall biofuel target), then further growth of biofuel sales are met through sale of 15% RME-biodiesel to achieve the correct overall biofuel target. Again, the scenario takes into account the overall growth in diesel consumption relative to petrol consumption as a result of the increased penetration of diesel cars into the fleet implied in the base emission projections of the NAEI. The overall sales of biodiesel could be met by a mixture of sales of 5% (B5), 10% (B10) and 15% (B15) biodiesel at rates required to meet the overall biofuel volume equivalence defined by the sales of B15 given in Table A1. This scenario assumes a higher Reid Vapour Pressure (RVP) of the low strength bioethanol fuel relative to the petrol fuel it is displacing and hence an increase in evaporative emissions occurs during the summer months.

Table A1: Consumption-equivalence of 15% bioethanol and 15% RME-biodiesel as percentages of overall petrol and diesel sales necessary to meet definitions of Scenario 2 used in emission model

	2010	2015	2020
Sales of E15 as % of all petrol sales	71%	100%	100%
Sales of B15 as % of all diesel sales	0%	44%	100%

Scenario 3 – "Bioethanol only" scenario

84. This scenario assumes that the biofuel targets are met solely by the sale of bioethanol in all years. No biodiesel is consumed. It is assumed that this is initially met by the sale of 15% bioethanol (E15), but once the sale of E15 reaches 100% of all petrol sales (i.e. saturates the petrol market, which it must do very quickly to maintain the overall biofuel target), then further growth of biofuel sales are met through sale of 85% bioethanol (E85) to achieve the correct overall biofuel target. Again, the scenario takes into account the overall growth in diesel consumption relative to petrol consumption as a result of the increased penetration of diesel cars into the fleet implied in the base emission projections of the NAEI. In the initial years, when E15 is sold, this scenario assumes a higher Reid Vapour Pressure (RVP) of the low strength bioethanol fuel relative to the petrol fuel it is displacing and hence an increase in evaporative emissions occurs during the summer months. But once E15 saturates the petrol market and E85 is sold, the RVP of this fuel reduces back to the same level as the petrol fuel it is displacing and so no increase in evaporative emissions occurs during the summer months relative to the basecase. The scenario is represented in the model in terms of percentage sales of 15% and 85% blends (E15 and E85) as shown in Table A2 for this scenario.

Table A2: Consumption-equivalence of 15% bioethanol and 85% bioethanol as percentages of overall petrol sales necessary to meet definitions of Scenario 3 used in emission model. No biodiesel is sold in this scenario

	2010	2015	2020
Sales of E15 as % of all petrol sales	71%	0%	0%
Sales of E85 as % of all petrol sales	0%	29%	47%
Sales of biodiesel as % of all diesel	0%	0%	0%

Scenario 4 – "Biodiesel favoured" scenario

85. This scenario assumes that the biofuel targets are met initially by the sale of 15% RME-biodiesel (B15) only and once the sale of B15 reaches 100% of all diesel sales (i.e. saturates the diesel market, which it will eventually to maintain the overall biofuel target), then further growth of biofuel sales are met through sale of 15% bioethanol to achieve the correct overall biofuel target. Again, the scenario takes into account the overall growth in diesel consumption relative to petrol consumption as a result of the increased penetration of diesel cars into the fleet implied in the base emission projections of the NAEI. The overall sales of bioethanol could be met by a mixture of sales of E5, E10 and E15 at rates required to meet the overall biofuel volume equivalence defined by the sales of E15 given in Table A3. This scenario assumes a higher Reid Vapour Pressure (RVP) of the low strength bioethanol fuel relative to the petrol fuel it is displacing and hence an increase in evaporative emissions occurs during the summer months.

Table A3: Consumption-equivalence of 15% RME-biodiesel and 15% bioethanol as percentages of overall diesel and petrol sales necessary to meet definitions of Scenario 4 used in emission model

	2010	**2015**	**2020**
Sales of B15 as % of all diesel sales	63%	100%	100%
Sales of E15 as % of all petrol sales	0%	17%	100%

Scenario 5 – "Biodiesel only" scenario (RME)

86. This scenario assumes that the biofuel targets are met solely by the sale of biodiesel in all years. No bioethanol is consumed. It is assumed that this is initially met by the sale of 15% RME-biodiesel (B15), but once the sale of B15 reaches 100% of all diesel sales (i.e. saturates the diesel market, which it will eventually to maintain the overall biofuel target), then further growth of biofuel sales are met through sale of 100% RME-biodiesel (B100) to achieve the correct overall biofuel target. Again, the scenario takes into account the overall growth in diesel consumption relative to petrol consumption as a result of the increased penetration of diesel cars into the fleet implied in the base emission projections of the NAEI. The scenario is represented in the model in terms of percentage sales of 15% and 100% blends (B15 and B100) as shown in Table A4 for this scenario.

Table A4: Consumption-equivalence of 15% RME-biodiesel and 100% RME-biodiesel as percentages of overall diesel sales necessary to meet definitions of Scenario 5 used in emission model. No bioethanol is sold in this scenario

	2010	2015	2020
Sales of B15 as % of all diesel sales	63%	0%	0%
Sales of B100 as % of all diesel sales	0%	17%	24%
Sales of bioethanol as % of all petrol	0%	0%	0%

Scenario 6 – "Biodiesel only" scenario (VPO)

87. This scenario assumes that the biofuel targets are met solely by the sale of biodiesel in all years. No bioethanol is consumed. It is assumed that this is initially met by the sale of 15% RME-biodiesel (B15), but once the sale of B15 reaches 100% of all diesel sales (i.e. saturates the diesel market, which it will eventually to maintain the overall biofuel target), then further growth of biofuel sales are met through sale of 100% virgin plant oil (B100) to achieve the correct overall biofuel target. This scenario is therefore the same as Scenario 5 except that 100% virgin plant oil is favoured instead of 100% RME-biodiesel. Again, the scenario takes into account the overall growth in diesel consumption relative to petrol consumption as a result of the increased penetration of diesel cars into the fleet implied in the base emission projections of the NAEI. The scenario is represented in the model in terms of percentage sales of 15% and 100% blends (B15 and B100) as shown in Table A5 for this scenario.

Table A5: Consumption-equivalence of 15% RME-biodiesel and 100% Virgin Plant Oil as percentages of overall diesel sales necessary to meet definitions of Scenario 6 used in emission model. No bioethanol is sold in this scenario.

	2010	2015	2020
Sales of B15 as % of all diesel sales	63%	0%	0%
Sales of B100 as % of all diesel sales	0%	17%	24%
Sales of bioethanol as % of all petrol	0%	0%	0%

Scenario 7 – "Realistic" scenario with biogas consumption by HDVs

88. This scenario is the same as Scenario 1 except that 10% of the energy that would have been consumed by heavy duty vehicles (hence distance travelled) using RME-biodiesel is consumed using biogas instead. Hence, by 2010, 5% of volume of petrol sold is bioethanol (all as E5) and 5% of volume of diesel sold is RME-biodiesel (all as B5) for light duty vehicle consumption, but 4.5% of diesel consumed by heavy duty vehicles is RME-biodiesel (all as B5) and a remaining 0.5% of diesel that would have been consumed by heavy duty vehicles is displaced with biogas. By 2020, 15% of volume petrol sold is bioethanol (all as E15) and 15% of volume diesel sold is RME-biodiesel (all as B15) for light duty vehicle consumption, but 13.5% of diesel consumed by heavy duty vehicles is RME-biodiesel (all as B15) and a remaining 1.5% of diesel that would have been consumed by heavy duty vehicles is displaced with biogas.

89. As for Scenario 1, this scenario assumes a higher Reid Vapour Pressure (RVP) of the low strength bioethanol fuel relative to the petrol fuel it is displacing and hence an increase in evaporative emissions occurs during the summer months.

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