Strategies and roadmaps for sustainable energy use transport

Overview

This document focuses on the advances in knowledge and technology required to mitigate the environmental impacts of transport and improve environmental sustainability highlighting omissions and apparent gaps in knowledge. It covers the use of bio-fuels and hydrogen as transport fuels as well as the improvements to more conventional fuels and technologies.

The document summarises key strategies and roadmaps for four transport modes: road vehicles; air transport; sea transport and rail. A further section lists roadmaps relevant to the use of hydrogen as a transport fuel. Hydrogen and fuel cells are covered fully in a separate section of the research atlas. The coverage is international but all the cited reports are relevant to the UK.

In some areas (e.g. air transport), nothing that can be considered a roadmap in a formal sense has been produced. We do however cite strategic documents which point to future research needs. .

1) Road vehicle development roadmaps
2) air transport development strategies
3) sea transport development strategies
4) rail transport development strategies and roadmaps
5) hydrogen roadmaps

1. Road vehicle development roadmaps (Table 1)

a. environmental impacts of energy use in road transport

Each of the roadmaps (except 2) acknowledges the contribution of tailpipe emissions to climate change and highlights the need to reduce them. The European Strategic Research Agenda (2004) (7) also recognises the need to reduce the impacts of surface run-off on water quality and the road transport system on natural habitats, but only the Foresight Vehicle Programme Technology Roadmap sets 'Environmental performance measures and targets [which] relate to the overall environmental burden of road transport, global warming, pollution, energy and material waste'.

b. advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

Most road vehicle development roadmaps (1, 2, 4, 5, 7) list the technical developments and innovations essential for improving engine performance, and increasing both cost-effectiveness and energy efficiency. These include development of fuel cells, hybrid engines, low viscosity lubricants and waste heat recovery systems. But only two roadmaps (1, 7) relate these advances directly to the environment and set targets for reducing the use of fossil fuels, generation of waste, emissions of GHG and other pollutants and enabling the utilization of biofuels and hydrogen. The European Strategic Research Agenda (7) provides an exhaustive assessment of essential advances in the areas of biofuel development, vehicle design, recycling, traffic management systems and road construction; a typical statement in this roadmap is 'Cost effective processes for large-scale hydrogen production from biomass, wind and other renewable energy sources are needed.' Greater detail of the research and technological 'break-throughs' required to achieve these advances is provided by the Foresight Vehicle Programme Technology Roadmap (1), which has the creation of an environmentally-sustainable road transport system as part of its 'vision'. This roadmap aims to achieve the specific targets for carbon dioxide emission reductions desired by the European Commission (to 140g/km new car fleet average in the EU by 2008 for passenger cars and to 120g/km by 2012). To meet these targets 'New sources of non-oil derived energy are required, which impacts the development of natural gas derived and bio-fuels as well as hydrogen. Improvements to conventional propulsion unit thermodynamic efficiencies will need continuing attention with the development of advanced, fuel efficient, high specific output, downsized engines a key. Advances in lubricants and tribological coatings are needed to reduce friction. Vehicle weight is also a factor in improving overall energy efficiencies. Lightweight materials and structures, whilst retaining or improving safety, are needed to enable gains to be realised.' Research priorities and challenges relating to each of these topics are described in detail. In contrast, Carbon to Hydrogen Roadmaps for Passenger Cars (updated November 2004) (2) aims to reduce well-to-wheels emissions of carbon dioxide, but it focuses on advances in vehicle technology alone and does not deal with the availability of sustainably-produced hydrogen.

Conflicts between technological developments contributing to different aspects of environmental sustainability are highlighted by two roadmaps (1, 6). The Foresight Vehicle Programme Technology Roadmap (1) notes that 'Engine efficiency improvements imply more, smaller particulates, with attendant post-combustion clean-up required.' And that 'The technologies required for pollutant reduction are generally at the expense of CO2 reduction, and continuing vigilance is required for prioritising the needs.' The 'A Roadmap for Sustainable Mobility' (6) highlights that reducing particulate emissions (by the installation of a particulate filter and the necessary adjustments to the engine management system) reduces fuel economy in diesel cars. Also that 'Fixed recycling quotas and bans on the use of certain materials, for example, render lightweight design concepts involving composite and hybrid materials more difficult to implement and prevent the potential for cutting weight – and thus fuel consumption – from being exploited to the full.'

Table 1. Road Vehicle Development Roadmaps

Roadmap	**Source**	**Environmental impacts highlighted**	**Research topics and targets proposed to address environmental sustainability issues**
1 Foresight Vehicle Programme Technology Roadmap Version 2	produced by Foresight Vehicle for the Department for Trade and Industry. 2004	Sets 'Environmental performance measures and targets (which) relate to the overall environmental burden of road transport, global warming, pollution, energy and material waste'. 'Reduction of emissions of greenhouse gasses, noxious substances and particulates is seen as a major challenge for the industry',	Sets '*Technological* performance measures and targets relate to energy and power, electronics and control, materials and structures, together with the processes and systems that support development of these technologies.' Details technological innovations required in each of these areas.

		but the roadmap does not compare or prioritise different fuels in this, or in any other, respect.	
2 Carbon to Hydrogen Roadmaps for Passenger Cars updated	produced by Ricardo Consulting Engineers Ltd. for the UK DTI November 2002 November 2004	'The report focuses on vehicle technology, and does not deal with … the availability of sustainably-produced Hydrogen.'	Details advances required in vehicle technology to reduce well-to-wheel emissions of CO2. Notes that hydrogen storage needs improvement.
3 CARS 21: A Competitive Automotive Regulatory System for the 21st century	produced by CARS 21 High Level Group for the European Commission. December 2005	Highlights need to reduce CO2 emissions, and airborne particulates and ozone as being the pollutants of most concern from road transport. Also mentions GHG produced by mobile air conditioning systems.	Proposes changes in policy and areas for technological development, for example, 'The Commission is considering reducing limits of pollutant emissions.' 'To maximise the potential for road transport CO2 emissions' reduction, the group strongly endorses applying an integrated approach involving vehicle manufacturers, oil/fuel suppliers, repairers, customers/drivers and public authorities. The integrated approach should aim at producing clear and quantifiable reductions in CO2 along the lines of the Community target through a range of options (e.g. vehicle technology, alternative fuels, taxation, eco-driving, gear shift indicators, consumer information and labelling, consumer behaviour and congestion avoidance). One of the recommendations is to 'Develop policy to encourage use of biofuels which offer greater greenhouse gas savings and support research and development efforts into 2nd generation biofuels'. 'Hydrogen should receive major research and development effort as a promising opportunity for the longer-term.' 'Alternative fuels should always be assessed on a comprehensive well-towheel basis, looking at cost-effectiveness and at all environmental consequences.'

4 Fuel Cell Vehicles: Race to a New Automotive Future	Office of Technology Policy, Technology Administration, US Department of Commerce. January 2003	Mentions CO_2 and pollutant emissions reduction as being one of the drivers for fuel cell vehicle development.	Details the major advances required in fuel cell technology to achieve cost-effectiveness. Notes that 'Fuel cell vehicles could eventually be powered by hydrogen derived from distributed domestic sources of energy, such as wind, solar, biomass, and hydro' but does not describe the technological advances required to generate hydrogen from these sources.
5 Pathways for Natural Gas into Advanced Vehicles	International Association for Natural Gas Vehicles. September 2002	Mentions CO_2 and pollutant emissions reduction as being one of the drivers for fuel cell vehicle development. But notes that if the electricity used by the electrolysis process to generate hydrogen is produced in a natural gas-fired power plant then CO_2 and low levels of other GHG are emitted, and that conversion of biomass to hydrogen requires combustion of fossil fuels and so also generates CO_2.	Describes current technologies in detail, with some examples of essential future improvements, but these are not related to the issue of environmental sustainability, except that this 'would call for the use of renewable primary energy. This could be biomass, biogas, solar energy, hydropower etc. Hydrogen production via gasification of biomass in centralised units would fulfil this requirement, as well as the use of biomethanol in decentralised systems.'
6 A Roadmap for Sustainable Mobility	DaimlerChrysler	This is a 'strategy for reducing CO_2 and tailpipe emissions'.	Highlights conflicts in technological developments eg reducing particulate emissions reduces fuel economy in diesel cars, eg, 'Fixed recycling quotas and bans on the use of certain materials, for example, render lightweight design concepts involving composite and hybrid materials more difficult to implement and prevent the potential for cutting weight – and thus fuel consumption – from being exploited to the full.'
7 Strategic Research Agenda Based on Vision 2020 and Challenges	European Road Transport Research Advisory Council December 2004 June 2004	Recognises the need to reduce GHG emissions, and to reduce the impacts of surface run-off on water quality and the road transport system on natural habitats.	Very environment–focused. Sets specific environment and energy-related research targets to be achieved by 2020. Provides an exhaustive and detailed description of all technological advances required to meet the goals of reducing GHG emissions, energy use and many other environmental impacts of road transport. Research areas include biofuel development, vehicle design, recycling, traffic management systems and road construction.

2. Air transport development strategies (Table 2)

The documents included in Table 2 are strategies, not roadmaps; no roadmaps towards the environmentally-sustainable use of energy for aviation have been identified during this study. The Environmental Effects of Civil Aircraft in Flight (November 2002), produced by the Royal Commission on Environmental Pollution, states that 'the ambitious targets for technological improvement in some industry announcements are clearly aspirations rather than projections'. This indicates that the gap between current knowledge and technology and that required for environmental-sustainability is too great for any organisation or government to envisage bridging on a 5-20 year timescale. However, for this study, the strategies listed in Table 2 do serve the same purpose as roadmaps.

There are other documents (not included in the table) which also describe the environmental impacts of aviation and explore the technological improvements which might offset these impacts; these include The Environmental Effects of Civil Aircraft in Flight (2002), produced by the Royal Commission on Environmental Pollution and The Potential for Renewable Energy Sources in Aviation (August 2003), produced by the Imperial College Centre for Energy Policy and Technology.

a. environmental impacts of energy use in air transport

Each of the four air transport development strategies (8, 9, 10, 11) highlight that aircraft emissions (CO2, NOx, soot and other particulates) have a major impact on the environment, contributing to climate change and also reducing air quality, particularly in the vicinity of airports. These studies also recognise that condensation trail (contrail) and cirrus cloud formation are major contributors to the radiative forcing effect of aviation. The Environmental Effects of Civil Aircraft in Flight states that 'the total radiative forcing due to aviation is probably some three times that due to the carbon emissions alone'. But all the strategies note that the impact of aircraft exhaust gases on the climate is not fully understood.

b. advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

Two of the strategies (8, 9) highlight that the most important environmental research priority in this field is elucidating in detail the effects of aircraft emissions (particularly water vapour, particulates and NOx) on the atmosphere and on climate. The Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK (11) concludes that this knowledge is essential to direct effective technological development and that, currently, 'the technology mitigation potential remains largely uncertain and unverified. This study recognises that contrail and cirrus cloud formation are identified as major contributors to the radiative forcing effect of aviation. Whilst operational procedures and to certain extent technology developments are being developed to mitigate contrail formation, specific information from technology developers on these options remain vague and the levels and certainty of the mitigation potential remain largely un-quantified.'

Greater understanding of the different impacts of the components of aircraft exhaust gases is also crucial for resolving conflict between the measures taken to reduce NOx emissions and CO2 production, for example. As explained by Air Travel – Greener by Design, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities (8), "It is clear that total environmental impact can be reduced by setting different priorities in design. For example, NOx emission can be reduced by reducing engine pressure ratio and ozone generation by NOx might be reduced by optimising designs to cruise at lower altitudes. In both cases, the result is likely to be an increase in fuel burn, CO_2 emission and operating cost. Contrail and cirrus cloud formation and ozone creation might also be reduced by operational measures, but at the expense of an increase in fuel burn.' A strategy towards sustainable development of UK aviation (9) states that 'technology measures to reduce noise at source can have a negative impact on fuel efficiency; operational measures such as flying lower to avoid formation of cirrus cloud would lead to increased carbon dioxide (CO_2) production because of the reduced fuel efficiency at lower altitudes.' This strategy also points out that whilst hydrogen-powered aircraft produce no CO_2 they would generate significant quantities of water vapour. Another potential dilemma is that the development of higher pressure ratio engines will increase fuel efficiency but will lead to more NO_x per unit of fuel burnt (11).

Each of the strategies describes in detail future developments and new technologies proposed for reducing emissions and increasing fuel efficiency of kerosine-fuelled engines. The majority of these relate to improving engine and airframe design (including the use of light-weight, high-strength materials) and propulsion efficiency. Only one strategy (11) explores the potential of hydrogen-powered aircraft (the Cryoplane), and the aviation industry expresses little enthusiasm or optimism concerning biofuels. Air Travel – Greener by Design, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities (8) states that 'further research in alternative fuels was … not seen by the Sub-Group as a priority for aviation' whilst A strategy towards sustainable development of UK aviation (9) states that 'it is unlikely that alternative fuels will play a significant role in aircraft propulsion in the foreseeable future. Nonetheless, the industry will support and encourage research projects to find possible replacements for kerosene'. More positively, The Strategic Research Agenda (10) predicts that 'The next step will be the availability of alternative fuels (e.g. liquid H_2, bio fuels, synthetic fuels, LNG) or power sources (e.g. fuel cells), provided that it is demonstrated that they can reduce radiative forces.' Consequently, these strategies do not provide information concerning the technological advances (for example, in engine design) essential for the use of alternative fuels (other than hydrogen). There have been studies which explore the feasibility of renewables for aviation, for example The Potential for Renewable Energy Sources in Aviation (August 2003), produced by the Imperial College Centre for Energy Policy and Technology, which assesses the environmental impacts of different renewable fuels, and Transitioning to Biomass Fuels in General Aviation, produced by the Baylor Institute of Air Science, and The Present and Future Potential of Biomass Fuels in Aviation (June 2000), produced by the Renewable Aviation Fuels Development Centre, Baylor University. The latter concludes that ethanol is a viable aviation fuel for existing aircraft engines (in contrast with the Imperial College Centre for Energy Policy and Technology study which proposes only hydrogen, biodiesel and Fischer-Tropsch kerosine).

Three of the strategies (9, 10, 11) predict that targets for reducing CO_2 and NO_x emissions by 50% and 80%, respectively, by 2030 are achievable, even using kerosine as the sole aviation fuel. However, the Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK (11) points out that 'taken together these new technologies cannot offset the additional environmental impact associated with forecast growth in air traffic and therefore the net or overall environmental impact from aviation is predicted to increase from today's levels'.

Post-2020 technologies envisaged by The Strategic Research Agenda (10) include 'Creating propulsive power from new forms of energy; Solar Power, Nuclear Energy, Hydrogen from the sea, Beamed Energy devices using laser or micro-wave and ground-powered energy forms'; 'morphing the aircraft structure into different shapes or aerodynamic forms under computer control. Thrust may be vectored to give directional or lift control. Plasma jets may replace the burnt fuel exhaust as the means of delivering thrust. Lift mechanisms may use alternative forces to fluid dynamics to derive the vehicle lift.'

Table 2. Air Transport Development Strategies

Roadmap	Source	Environmental impacts highlighted	Research topics and targets proposed to address environmental sustainability issues
8 Air Travel – Greener by Design, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities	Greener by Design Science and Technology Sub-Group, DTI, UK July 2005	Reviews current understanding of the impact on the environment (particularly on climate) of air pollution around airports, and emissions at altitude, generated by civil aircraft operations. Notes that the three main contributors to aviation's impact on climate are contrails, CO_2 and NOx.	'assesses the potential for mitigating *environmental impacts* by advances in technology and changes in design priorities and operating procedures.... considers possible future research, technology demonstration and design studies and suggests priorities.' Describes in detail future developments and new technologies proposed for improving engine and airframe design (including the use of light-weight, high-strength materials) and propulsion efficiency, with the aim of reducing NOx and CO_2 emissions. Highlights that the most important environmental research priority should be 'the effect of aviation emissions on the atmosphere and on climate', particularly stresses the need for more research to assess 'the impact on climate of NOx, water vapour and of contrails and aviation related cirrus.' However, 'further research in alternative fuels was … not seen by the Sub-Group as a priority for aviation.'
9 A strategy towards sustainable development of UK aviation	Sustainable Aviation June 2005	Notes that 'Aircraft operations generate CO_2, a direct greenhouse gas, and lead to other effects in the atmosphere linked to ozone generation, methane reduction and cirrus cloud formation.' But 'impact of aircraft exhaust gases on climate is not fully understood.'	Targets for technology development include 'improve fuel efficiency and CO_2 emissions by 50% per seat kilometre' ('will be addressed through airframe, engine and air traffic management improvements'); 'reduce NOx emissions by 80%' ('to be achieved largely through aircraft and engine improvements')' Reduction of CO_2 should be a priority. No further detail is provided. Highlights that 'further research is necessary in order to understand fully the impacts that aviation's contrails, particle emissions and NOx emissions have on climate.' However, 'it is unlikely that alternative fuels will play a significant role in aircraft propulsion in the foreseeable future. Nonetheless, the industry will support' and encourage research projects to find possible replacements for kerosene'.

10 The Strategic Research Agenda (2nd Edition) arising from European Aeronautics: A Vision for 2020	Advisory Council for Aeronautics Research in Europe October 2004 European Commission January 2001	'Climate change…is a global issue and strongly linked to CO_2 and NOx emissions, but also to soot, particulate, water vapour, etc. …. In particular condensation trails created by water vapour and particulates are suspected to have a significant effect on global warming. … further work is needed in this area.'	Technological advances required are described in detail with timescale targets upto 2020. Reducing CO_2 emissions by 50 % by 2020 can be achieved by improving fuel efficiency 'through aerodynamic improvements, weight reduction and fuel efficient engines and systems.' NOx levels can be reduced (by 80%) via the development of 'new combustion and fuel injection systems'. 'The next step will be the availability of alternative fuels (e.g. liquid H_2, bio fuels, synthetic fuels, LNG) or power sources (e.g. fuel cells), provided that it is demonstrated that they can reduce radiative forces.' Post-2020 technologies envisaged include 'Creating propulsive power from new forms of energy; Solar Power, Nuclear Energy, Hydrogen from the sea, Beamed Energy devices using laser or micro-wave and ground-powered energy forms'; 'morphing the aircraft structure into different shapes or aerodynamic forms under computer control. Thrust may be vectored to give directional or lift control. Plasma jets may replace the burnt fuel exhaust as the means of delivering thrust. Lift mechanisms may use alternative forces to fluid dynamics to derive the vehicle lift.'
11 Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK	Arthur D. Little Limited for the Department for the Environment, Transport and Regions (DETR) December 2000	Notes that the three main contributors to aviation's impact on climate are contrails, CO_2 and NOx., and that emissions have a negative impact on air quality around airports. 'This study recognises that contrail and cirrus cloud formation are identified as major contributors to the radiative forcing effect of aviation'	Future critical technologies are 'development of technologies for improving aerodynamics, research on structures and materials to reduce weight, and development of new engine designs with improved efficiency' for reducing CO_2 emissions and 'Development of new combustor concepts to achieve substantial NOx reductions'. These should be sufficient to achieve targets of reducing individual aircraft emissions of CO_2 and NOx by 50% and 80%, respectively, by 2030. Furthermore 'This study has applied a screening methodology to identify and define the significant environmental benefit criteria for describing the environmental benefits of future aviation technologies'. Consequently, 'CO_2 and NOx emissions per passenger km are defined as the most significant environmental benefit criteria.' In contrast, the report notes that less is known about the impacts of contrail and cloud formation so for these impacts 'technology mitigation potential remains largely uncertain and unverified.' Relevant technological developments (including the Cyroplane concept) are described in great detail, each with an assessment of their environmental benefit and take-up potential. Alternative fuels are not explored.

3. Sea transport development strategies (Table 3)

Two (12, 13) of the four documents included in Table 3 describe strategies, not roadmaps and no detailed roadmaps towards the environmentally-sustainable use of energy for sea transportation have been identified during this study. However, all but one of these publications highlight environmental impacts and potential means of remediation. For example, one of the strategic objectives the Maritime Administration Strategic Plan for Fiscal Years 2003-2008 (13) (produced by the US Department of Transport) is to 'Promote maritime and intermodal transportation solutions that enhance environmental stewardship', and the outcome should be 'Reduced pollution and other adverse environmental effects of transportation and transportation facilities'. Remarkably, the Marine and Ocean Industry Technology Roadmap (15) (produced by the National Research Council, Canada) does not address environmental issues at all. However, following the publication of A European Union strategy to reduce atmospheric emissions from seagoing ships in November 2002, the European Commission is preparing a Green Paper for an all embracing Maritime Policy; it should be adopted in the first half of 2006.

There are other published strategies which encompass sea transportation, including 'An Ocean Blueprint for the 21st Century Final Report of the U.S. Commission on Ocean Policy' (2004), Canada's ocean strategy "our oceans, our future" (2002) and The Portuguese Oceans Strategy (2004). But these documents, whilst promoting the concept of environmental stewardship of the oceans in general terms, provide no useful information for this study; the latter document refers only 'in passing' to 'the urgent need for the oceans to be managed with an eye to conservation and sustainable utilisation'.

'Sustainable shipping, progress in a changing world' was a conference was held on the 1st/2nd of February 2005 in London and was organised by the Maritime and Coastguard Agency in conjunction with the Institute of Marine Engineering, Science and Technology (IMAREST). Presentations included -
1. Sustainable Energy in Marine Transportation, by Lloyd's Register EMEA, which proposed a simple roadmap for a transition to electrical ships fuelled by hydrogen via duel fuel diesel engines, but with no timescale;
2. A Path to Sustainable Shipping, BSR's Sustainable Transport Initiative and Clean Cargo by 'Business for Sustainable Responsibility', merely promoted a shift to oceanic transportation from other methods and made the prediction that 'Ocean transportation may gain in importance in a sustainable transport network' due to the relatively high energy efficiency and relatively low GHG emissions of shipping.
3. Sustainable Shipping, the vision of the port of Rotterdam, by Edo Donkers (Rotterdam Port) was pessimistic in outlook, concluding that the shipping industry is not keen to innovate technologically, that there is little funding available for this, and that there is no R&D drive.

a. environmental impacts of energy use in sea transportation

Three of the publications (12, 13, 14) listed in Table 3 highlight the environmental impacts of SOx and NOx emissions. Sustainable Energy in Marine Transportation (14) notes that the Energy Intensity (KJ/t-km) of, and CO2 and NOx intensity (g/t-Km) from, shipping are low relative to other transport modes, but that SOx intensity is high (significantly more than rail transport, but less than from aviation).
The Maritime Administration Strategic Plan for Fiscal Years 2003-2008 (13) also highlights the role of ballast water in the transfer of 'nuisance species' between habitats. None of these publications mention the environmental consequences of wrecking and collisions of oil tankers.

b. advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

The Maritime Administration Strategic Plan for Fiscal Years 2003-2008 (13) notes that 'Historically, investment in research, development, and deployment of air pollution reduction technologies in the maritime sector (including port equipment and vessels) has been minimal. As a result, while landside transportation has seen vast improvements in pollution control technologies and processes, marine transportation has advanced slowly. Emphasis must be given to identifying technology transfer and adaptation opportunities'. 'Means and strategies' include 'research on marine applications of hydrogen technologies', evaluation and implementation of 'ballast water treatment technologies' and 'conduct research and identify, demonstrate, and promote energy efficient, alternative fuels, and air pollution reduction technologies for maritime applications.' Sustainable Energy in Marine Transportation (14), highlights current technological developments in areas of alternative fuels (eg low sulphur fuels), alternative technologies (eg fuel cells) and energy efficiency, and the need for new engine designs (principally, for employing low sulphur fuels) and conversion technology (for generating hydrogen). Neither of these documents provides any detail of current and future research priorities. A European Union strategy to reduce atmospheric emissions from seagoing ships (12) focuses on regulatory measures to reduce emissions, not on technological innovation. However, the Commission has funded a number of reports which describe in detail the technological solutions for abatement and their feasability, these are General Report, Shore-side electricity, NOx abatement, SOx abatement.

Other informative documents, not included in the Table 3, include the Environmental Information Portal for Maritime Industries which details environmental impacts of maritime emissions and remediation technologies and the Marine Sector Technology Plan (Version 1, September 2005), produced by the DTI Aerospace, Marine and Defence Unit. The latter provides an overview of key technologies and R&D requirements for the UK marine engineering sector, and highlights the key areas for technology development (eg renewable energy, improvements in exhaust systems, improvements in sealing technologies to minimise accidental spills) relevant to environmental concerns. These include navigation and traffic management, as there are 'significant fuel savings to be obtained through more accurate ship's course holding'. Improvements in this area should also reduce collisions at sea involving oil tankers, which is one of the aims of the Galileo satellite navigation system.

There are several innovative ships in service which are designed to have a reduced environmental impact eg Ecoship (NYK Line, Japan); Super Eco-Ship (National Maritime Research Insititute, Japan).

Examination of environmental issues can be found within other publications, including the Advisory Council for Waterborne Transport Research in Europe (WATER*BORNE* [TP]) publication Vision 2020. One of the aims of this document is 'safe, sustainable and efficient water transport' and it includes targets such as 'In 2020 the environmental impacts of air and water emissions will be reduced drastically', and it highlights the relevant 'innovation challenges' eg 'A 'zero emission' approach, notably on substances like SOx, NOx, CO2, PM, VOCs is an enormous technological challenge. Reducing one pollutant may well have a negative effect on other pollutants, while no single option will be suitable for all types of ships' but this document provides no details of essential technological advances.

It is apparent that, in common with the aviation industry, the shipping industry - and relevant governmental bodies - lack the vision and motivation for developing roadmaps towards environmental sustainability. But first, companies need to be able to calculate their environmental impact. The Clean Cargo Environmental Performance Survey enables shippers to gauge their carriers' environmental management performance and address the environmental impacts of their ocean-going transportation. The survey was developed by members of the Business for Responsibility's Clean Cargo Group, a worldwide committee consisting of multinational corporations who have voluntarily developed environmental guidelines for ocean transportation. Among its potential benefits, the survey will help ocean carriers and their customers assess options for increased fuel efficiency, which in turn will lower emissions and help improve air quality.

Table 3. Sea Transport Roadmaps and Strategies

Roadmap	**Source**	**Environmental impacts highlighted**	**Research topics and targets proposed to address environmental sustainability issues**
12 A European Union strategy to reduce atmospheric emissions from seagoing ships	European Commission November 2002	Highlights the environmental impacts of SOx and NOx emissions	Focuses on regulatory measures to reduce emissions, not on technological innovation.
13 Maritime Administration Strategic Plan for Fiscal Years 2003-2008	US Department of Transport September 2003	Highlights the role of ballast water in the transfer of 'nuisance species' between habitats and the 'adverse contribution of maritime transportation activities to air quality'	Promotes 'research on marine applications of hydrogen technologies', evaluation and implementation of 'ballast water treatment technologies' and the need to 'conduct research and identify, demonstrate, and promote energy efficient, alternative fuels, and air pollution reduction technologies for maritime applications.' No detail provided.
14 Sustainable Energy in Marine Transportation	Lloyd's Register EMEA, presentation at IMarEST, February 2005	Notes that NOx intensity (g/t-Km) from shipping is significant and that SOx intensity is high.	Highlights technology developments in areas of alternative fuels (eg low sulphur fuels), alternative technologies (eg fuel cells) and energy efficiency, and need for new engine designs (for use of low sulphur fuels) and conversion technology (hydrogen). Proposes transition to electrical ships fuelled by hydrogen via duel fuel diesel engines. No detail provided, nor targets.
15 Marine and Ocean Industry Technology Roadmap	National Research Council, Canada	Does not address environmental issues	None

4. Rail transport development roadmaps and strategies (Table 4)

Only three documents (16, 17, 18) have been identified which promote the environmentally-sustainable use of energy for rail transport. Each of the documents refers to the lower environmental impact of rail transport compared to road and air but highlight the importance of reducing this further. Rail21: Sustainable rail systems for a connected Europe (17), produced by the European Rail Research Advisory Council (ERRAC) in March 2006, states that 'Railway transport is (and will remain) by far the most environmentally friendly form of motorised transport. Nevertheless, the railway does not rest on its green laurels but continuously strives to improve in order to meet the growing expectations of society and become an ever better, quieter and cleaner neighbour.' ERRAC believes that 'the most effective contribution to the greening of transport in Europe is to encourage a modal shift to rail. They also believe that for this to be possible environmental measures should not 'jeopardize the overall competitiveness of the railways.'

a. environmental impacts of energy use in rail transport

Rail21: Sustainable rail systems for a connected Europe (17) does not describe any environmental impacts. The Railroad and Locomotive Technology Roadmap (18) (produced for the US Department of Energy in December 2002) makes only indirect references to NOx and sulphur emissions, stating that railways 'transport freight efficiently because they require less energy and emit fewer pollutants than other modes of surface transportation.' But only the THE RAIL INDUSTRY – A WAY FORWARD ON SUSTAINABLE DEVELOPMENT (16) (produced by the UK Rail Safety and Standards Board in February 2006) points out that locomotive diesel engines create emissions which contribute to global warming. It also compares these emissions favourably with those from road and air transportation; railways produce 'Lower NOx and particulate emissions per passenger km or freight Tkm than road and air [but] higher SO2 emissions than road due to high Sulphur content of fuel. Two further key advantages of rail are the lower carbon dioxide emission per freight tonne and passenger kilometre and the contribution the rail network makes to managing road congestion.' This strategy points out that 'Diesel engine emissions have been the subject of new regulation from the EC and there is a threat of further tightening of these requirements. Key issues in this area are sulphur in fuel, exhaust emissions treatment and retrofitting cleanup technology.'

b. advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

Each of the documents listed in Table 4 highlight that the focus of technological development in this sector should be on increasing energy efficiency and reducing emissions.

Rail21: Sustainable rail systems for a connected Europe (17) proposes research in a number of areas; 'Help improve and deliver achievable standards for noise, emissions, diesel engines, etc. Develop new lightweight and low noise freight wagons; greening existing fleet'. Similarly, THE RAIL INDUSTRY – A WAY FORWARD ON SUSTAINABLE DEVELOPMENT only lists future research under general topics eg for reducing carbon emissions 'Future of grid distributed power technologies: power station efficiency, distribution loss, new materials technologies for power lines etc. Maglev [trains]'. Neither details nor targets are provided in either document. But THE RAIL INDUSTRY – A WAY FORWARD ON SUSTAINABLE DEVELOPMENT makes two very important points;-

1. It is taxation issues, not technological barriers, that are preventing the uptake of low sulphur fuels;
2. That the widespread implementation and retrofitting of technology currently-available - regenerative braking and

exhaust treatment systems - could significantly reduce carbon and NOx/particulates emissions, respectively.

In contrast, the Railroad and Locomotive Technology Roadmap (18) does describe in detail the advances in knowledge and technology required to reduce negative environmental impacts and to advance towards the environmental sustainability of rail transport. However, the principal driver for investment appears to be economics, not concern for the environment, nor for sustainability; 'U.S. railroads spend over $2 billion per year, or approximately 7% of their total operating expenses, on diesel fuel. New emission standards — to be implemented in stages between 2000 and 2005 — may reduce the fuel efficiency of new locomotives by as much as 10–15%. With the potential to substantially increase operating costs and further erode already tight net operating income, meeting those standards could become a major obstacle to the economic health of the industry.'

This roadmap highlights that 'Some of the technologies that could be employed to meet the emission standards may negatively affect fuel economy — by as much as 10–15% when emissions are reduced to Tier 2 levels. Achievement of all Tier 2 (2005 and later) standards for locomotives may require exhaust-gas recirculation (EGR), very low sulfur diesel fuels, and possibly aftertreatment devices (such as particulate traps and oxidation catalysts). Unfortunately, most of the techniques for reducing NOx also decrease the fuel efficiency of the engine and raise PM [particulate matter] emissions. This decrease in fuel efficiency would have a serious negative effect on the financial stability of the railroads and, thus, provides an additional urgency to finding ways to improve fuel efficiency. Cooled EGR may help recover some of the losses in engine efficiency and power density caused by retarded injection timing but may adversely affect engine durability. Furthermore, cooled EGR is difficult on a locomotive because of the lack of ram air.'

It also describes other research challenges -

'Trains have much less freedom in choice of speed because their schedules must be coordinated with those of many other trains on the same track. In addition, locomotives must be able to pass through long tunnels, limiting the size of mechanisms that can be attached to the exterior and producing special challenges with respect to thermal management.
On-road trucks have large exposed radiators in the front, and with speeds usually maintained above 50 mph, ample air (ram air) is available for both engine and aftercooler cooling. In contrast, locomotives usually run in consists (i.e., groups) of two or more, often run in "reverse" or in the middle of the train, and spend most of their time at speeds below 45 mph. The radiators are mounted in the roof and cooling fans are required to remove engine heat. Airto- air aftercooling is difficult; consequently, engine air temperatures (which affect NOx formation) are much higher than ambient.
Locomotive engines, which have up to 6,000 horsepower, are, of course, much larger than truck engines. Their larger bores and lower speeds mean that fuel-system modifications developed for trucks cannot be directly transferred to locomotives, although many of the approaches (e.g., higher pressures, multiple injections, shaped injections) could be used in modified form. Also, locomotives have considerably less power per ton carried than do trucks.
Diesel fuel for locomotives can contain 10 times more sulfur than diesel fuel for trucks contains. Sulfur contributes to formation of engine-out particulate matter, corrosive exhaust gases, and rapid poisoning of some aftertreatment devices.'

This document identifies and describes in detail 'critical research and development (R&D) needs for reducing fuel consumption and emissions while maintaining or enhancing system performance.' These needs are in the following four areas;-

- Train Systems – Aerodynamics, Wheel/Rail Friction, Rolling Resistance;
- Locomotive Systems - Idle Reduction, Energy Recovery, Motors and Drives;

- Locomotive Engines - High-Efficiency Turbo, Sensors and Controls, Fuel Injection/Combustion, NOx Adsorber, PM Trap;
- Advanced Powerplants and Fuels – HCCI [homogeneous-charge compression ignition], Alternative Fuels, Fuel Cells.

Consequently, they predict that 'A focused research and development program could enable the locomotive diesel engine to achieve thermal efficiencies of 50̃55%, resulting in a reduction in specific fuel consumption of about 20%.' Concerning alternative fuels, 'most alternative fuels, with the exception of biodiesel and oxygenated diesel (oxydiesel), cannot be used directly without substantial modifications to engine and locomotive systems, as well as to the refueling infrastructure'. But, more positively, they also point out that much of the alternative fuel technology developed for the automotive and trucking industries may be transferable to the railroad industry. 'Natural gas — either as compressed natural gas (CNG) or liquefied natural gas (LNG) — or Fischer-Tropsch fuel and other renewable fuels (such as ethanol, biodiesel, and oxydiesel) might find application to locomotives. Additional research is needed.'

Again, 'The primary barriers for alternative fuel use are not technical — they are cost, market acceptance, reliability, and deployment. The primary barrier for biodiesel, oxydiesel, and water/diesel emulsions is high production costs. Additionally, untreated biodiesel has issues related to oxidation, high viscosity, and thermal stability, and oxydiesel has issues related to lower lubricity, corrosion, and high vapor pressure. For example, the lower lubricity of oxydiesel, in excess of 5% ethanol, has shown to contribute to abrasive wear and cavitation in high-pressure fuel injectors in durability testing. Long-term stability of water/diesel emulsions is considered a barrier, as is the durability of fuel-injection-system components.'
'Unmodified diesel engines can be operated on the various liquid fuels, such as Fischer-Tropsch, biodiesel, oxydiesel, dimethyl ether, dimethoxy methane, and diethyl ether, as well as various blends thereof. However, there has been relatively little basic research and optimization with regard to locomotive engines using these or other alternative fuels.'
The roadmap lists the R&D activities that 'would need to be undertaken to determine which of these fuels offer the benefits in emission control and support aftertreatment device development.' These activities include 'basic research on liquid fuels and blends to better understand the combustion process.'

Table 4. Rail Transport Roadmaps and Strategies

Roadmap	**Source**	**Environmental impacts highlighted**	**Research topics and targets proposed to address environmental sustainability issues**
16 THE RAIL INDUSTRY – A WAY FORWARD ON SUSTAINABLE DEVELOPMENT	Rail Safety and Standards Board February 2006	'Energy used by rail creates emissions which contribute to global warming.' 'Rail has higher SO2 emissions per passenger km or freight Tkm than road due to high Sulphur content of fuel.' 'Lower NOx and particulate	Carbon emissions – 'grid distributed power technologies: power station efficiency, distribution loss, new materials technologies for power lines', Maglev trains. 'research on future power technology'. 'implementation of regenerative braking technology'. SO2 – 'Treasury address taxation issues currently preventing the uptake of low sulphur fuels'. NOx and particulates – 'Retrofitting exhaust treatment system to diesel

		emissions per passenger km or freight Tkm than road and air.'	engines'. No details or targets provided.
17 Rail21: Sustainable rail systems for a connected Europe	European Rail Research Advisory Council (ERRAC) March 2006	None highlighted	Propose research topics - 'Help improve and deliver achievable standards for noise, emissions, diesel engines, etc'; 'Develop new lightweight and low noise freight wagons; greening existing fleet'. No details or targets provided.
18 Railroad and Locomotive Technology Roadmap	Argonne National Laboratory, for the US Department of Energy December 2002	Only indirect references - in the USA 'Locomotives currently emit over one million tons of NOx each year'. 'Diesel fuel for locomotives can contain 10 times more sulfur than diesel fuel for trucks.'	Potential research topics;- Train Systems – 'Aerodynamics, Wheel/Rail Friction, Rolling Resistance' Locomotive Systems – 'Idle Reduction, Energy Recovery, Motors and Drives' Locomotive Engines – 'High-Efficiency Turbo, Sensors and Controls, Fuel Injection/Combustion, NOx Adsorber, PM [particulate matter] Trap' Advanced Powerplants and Fuels – 'HCCI [homogeneous-charge compression ignition], Alternative Fuels, Fuel Cells'. These are described in detail, but with no targets. Notes that 'Some of the technologies that could be employed to meet the emission standards may negatively affect fuel economy'.

5. Hydrogen roadmaps

Hydrogen roadmaps are listed as follows but are not evaluated here as they have been assessed in another study.

Hydrogen Roadmaps:

UK Fuel Cell Development and Deployment Roadmap (2005), produced by Synnogy Ltd for the UK Department of Trade and Industry (DTI).

DTI (UK) Sustainable energy technology route map - Hydrogen

DTI (UK) Sustainable energy technology route map - Fuel Cells

Hydrogen Energy and fuel Cells - A vision for our future (June 03), produced by the High Level Group for Hydrogen and Fuel Cells for the European Union Community Research programme.

A National Vision of America's Transition to a Hydrogen Economy (February 2002) and the National Hydrogen Energy Roadmap (November 2002), both produced by the U.S. Department of Energy.

Hydrogen from Natural Gas and Coal: The Road to a Sustainable Energy Future (June 2003), produced by the Hydrogen Coordination Group of the Office of Fossil Energy for the U.S. Department of Energy.

Hydrogen Posture Plan (2006), produced by the U.S. Department of Energy.

Hydrogen Futures: Toward a Sustainable Energy System (August 2001), produced by the U.S. Worldwatch Institute.

Research, Development, Demonstration, & Deployment Roadmap for Hydrogen Vehicles & Infrastructure to Support a Transition to a Hydrogen Economy (October 2005), produced by the U.S. Department of Transport.

Getting to Hydrogen: The Road to Sustainable Transportation, produced by INFORM, Inc. in the U.S., (INFORM Inc. is an independent research organization that examines the effects of business practices on the environment and on human health).

Fuel cell technology road map (2005), produced by Ballard Power Systems, U.S.

Canadian Fuel Cell Commercialization Roadmap (March 2003), produced by Industry Canada, Fuel Cells Canada and PricewaterhouseCoopers for the Government of Canada.

Canada - Charting the Course: A Program Roadmap for Canada's Transition to a Hydrogen Economy (2004), produced by the Government of Canada's Hydrogen and Fuel Cell Committee.

Roadmap towards a sustainable hydrogen economy in Mexico, published by Joel Ramírez-Salgado and Arquímedes Estrada-Martínez in the Journal of Power Sources 129 (2004) 255–263.

National Hydrogen Energy Roadmap (2005), produced by the Steering Group on Hydrogen Energy for the Government of India.

Nordic H2 Energy Foresight Roadmaps (March 2004) and Building the Nordic Research and Innovation Area in Hydrogen (January 2005), produced for the Nordic Energy Research Programme and the Nordic Innovation Centre.

Icelandic Hydrogen Energy Road map, prepared for the Icelandic Ministry of Industry and Commerce.

A Vision and Roadmap for Hydrogen Energy in China (May 04), produced by Energetics Inc. for the Chinese Ministry of Science and Technology.

New York State Hydrogen Energy Roadmap (October 2005), prepared by Energetics Inc. for the New York State Energy Research and Development Authority.

A roadmap to achieving the state's goal of moving to hydrogen as an increasing source of fuel for Minnesota's energy needs (February 2004), produced by the Minnesota Renewable Hydrogen Initiative.

Hydrogen Roadmaps in preparation –

Towards a European Hydrogen Energy Roadmap (May 2004) Preface to HyWays – the European Hydrogen Energy Roadmap Integrated Project, and Hyways - a roadmap for hydrogen energy in Europe, produced by HyNet Partners. Completion expected in March 2007.

Roadmap for the installation of a hydrogen infrastructure in Germany, begun in 2002, produced by the German Hydrogen and Fuel Cell Association.

Thailand Hydrogen and Fuel Cell Roadmap (November 2005).