



EU Transport GHG: Routes to 2050?

Technical Options to reduce GHG for non-Road Transport Modes (Paper 3)

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Partners



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Executive Summary

In recent years the GHG emissions from the transport sector in Europe have continued to rise whilst the GHG emissions from other sectors have stabilised or begun to fall. Unless action is taken, transport GHG emissions alone will exceed an 80% reduction target for all sectors or make up the vast majority of a 60% reduction target. This illustrates the scale of the challenge facing the transport sector given that it is unlikely that GHG emissions from other sectors will be eliminated entirely. In this context the overarching aim of the project is to provide guidance and evidence on the broader policy framework for controlling greenhouse gas (GHG) emissions from the transport sector.

The main objective of Paper 3 is to review the technical options (excluding alternative powertrains and fuels which are covered in Paper 2) for reducing Greenhouse Gases (GHG) from the main motorised non-road transport modes in the short term (i.e. until 2020) and the longer term (i.e. between 2020 and 2050). It forms part of a suite of papers covering the full range of technical and non-technical options for reducing GHG from transport.

Paper 3 covers the rail, inland shipping, maritime shipping and aviation sectors. It utilises data and analysis from existing studies rather than undertaking new research. As well as considering the magnitude of the GHG emissions savings that could be achieved by each option the paper also reviews the evidence on costs, timescales for implementation, barriers and secondary benefits. A draft version of paper was presented to stakeholders during a technical focus group in July 2009. Stakeholders' comments have been taken account in this revised version.

The European **rail sector** can be characterised as a highly complex system comprised of a multitude of actors including infrastructure operators, rolling stock owners, train operating companies, regulators and passengers. In addition, there are hundreds of classes of rail vehicles of varying ages (brand new to 35 years old) in operation on a patchwork of networks. As a result it is very challenging to make accurate estimates of the carbon savings or costs associated with technical options without undertaking a detailed engineering feasibility study. Furthermore, due to the long lifetimes of rail infrastructure and rolling stock, there will be limited opportunities to renew the asset base with more energy efficient stock.

The main technical options for reducing GHG emissions from the rail sector are summarised in Table 1. It is important to note that these measures cannot be implemented simultaneously so the total GHG reduction potential cannot be calculated by simply summing the individual values.

Table 1 – GHG emissions reduction potential of the technical rail options

Technical option	Current GHG reduction potential on rail vehicle level where applicable
Mass Reduction	
Double deck trains	>10%
Aluminum railcar body	2% to 5%
Wide-body trains	>10%
Articulated trains	2% to 5%
Lightweight coach interior equipment	2% to 5%
Regenerative Braking	
AC network	10% to 15%
DC network	0% to 5%
Electrification	
Electrification	20% to 40%

Aerodynamic and friction	
Aerodynamic optimisation of pantographs	<1%
Aerodynamic ordering of freight cars	<1%
Bogie farings	6% to 7%
Covers for open freight cars	<1%
Streamlining of head and tail	<1%
Streamlining of train sides and underfloor areas	<1%
Improved air conditioning	
Improved air conditioning	4%
Driver support	
Driver training and in-cab displays	5% to 15%
Traffic management	Not available

Inland shipping is one of the most energy-efficient means of transporting goods over long distance inland. However, there are many additional options for reducing energy demand and GHG emissions that are yet to be exploited, or could be exploited to a greater extent. Although the project team were not able to identify any systematic studies on GHG-reduction options for inland shipping some relevant information sources were identified. However, explicit evaluation in terms of GHG-reduction potential is often lacking or very difficult to extract from such highly specialized studies. The Netherlands together with Germany has the largest share in inland waterway transport in Europe (more than 80 percent of total tonnekm moved). This is probably the main reason that much of the information relating to inland shipping has its origin in Germany or the Netherlands.

The main technical options for reducing GHG emissions from the inland shipping sector are summarised in Table 2. As above the total GHG reduction potential cannot be calculated by simply summing the individual values.

Table 2: GHG emissions reduction potential of the technical inland shipping options

Technical option	Current reduction potential on ship level where applicable
Power train	
More efficient engines	15% to 20%
Diesel-electric propulsion	10%
LNG optimized engines	20%
Reduction of required propulsion	
Larger units (economy of scale)	Up to 75% depending on difference in scale
Improved propeller systems	20% – 30%
Improved hull design	10% – 20%
Computer assisted trip planning and speed management	5% -10%
Lightweight hulls	5% -15%
Air lubrication	10%
Whale tail/experimental propulsion systems	25%

On **maritime vessels**, the technical abatement options are mainly related to the hull, the propeller, the superstructure of the vessel, to the vessels' power and propulsion systems. The options can either be retrofit or non-retrofit measures. Since the lifetime of vessels is relatively high (about 30 years), retrofit measures are important to realise CO₂ reductions in the short-term and medium-term. Thus it is only in the long run that design optimisation measures will be effective. For most of the measures there is still uncertainty as to the costs and the reduction potentials. Costs of the measures vary with the ship types and whether they are retrofitted or applied to a new ship. Cost data is often not available at all or only available for a certain ship type. The abatement potentials vary not only with the ship types but also with the routes these take, as well as with the respective weather conditions. Thus long-term field tests on a large scale are needed to produce reliable estimates. Tests in towing tanks have their place but only deliver data for still-water conditions.

The main technical options for reducing GHG emissions from the maritime shipping sector are summarised in Table 3. As above the total GHG reduction potential cannot be calculated by simply summing the individual values.

Table 3: GHG emissions reduction potential of the technical maritime shipping options

Technical option	Current reduction potential on ship level where applicable
Hull	
Design optimization	
Hull form	5 – 20% in still water
Weight reduction	< 7%
Retrofit	
Transverse thruster opening (grids, optimization of flow)	1 – 5 %
Surface (reduction resistance)	
Hull coatings	< 5%
Air cavity system	10 – 15 %
Propeller	
Design optimization	Unknown
Upgrade	
Installation of new propeller	5 – 10%
Propeller/rudder upgrade	< 4%
Recovering energy	5 – 10%
Propulsion/Engine	
Engine upgrade	1 – 2%
Recovery energy	< 10%
Alternative systems	
Sails	10 – 25 % at 10 knots
Towing kite	10 – 35% at 10 knots
Flettner rotors	Unknown
Superstructure	1 – 5%

In a similar vein to the rail sector, there are a number of generic challenges associated with making GHG emissions reduction in the **aviation sector**. Many of these challenges cut across a number of technical options. For instance, aircraft often remain in service for 30 years or more. Therefore, many new technologies can only ever be phased in over a lengthy period. In addition, the aviation sector is rightly very risk averse with any new technology. The stringent tests than any new technology is subjected to can act as a barrier. Payload limitations can also be a factor in the aviation sector.

Despite these challenges there is a broad range of research being undertaken to reduce the GHGs from the aviation sector. This research is being undertaken against a background of ambitious GHG reduction targets. For example, The Advisory Council for Aeronautical Research in Europe's (ACARE) targets for aerospace manufacturers include a 50% reduction in CO₂ emissions by 2020 relative to their year 2000 counterparts.

The main technical options for reducing GHG emissions from the aviation sector are summarised in Table 4. As above the total GHG reduction potential cannot be calculated by simply summing the individual values.

Table 4: GHG emissions reduction potential of the technical aviation options

Technical option	Current GHG reduction potential at a plane level
Open rotors	25-30%
Advanced aircraft materials	
Composites	20%
Winglets	4-6%
Laminar Flow	10-20%
Riblets	2%
Electric Aircraft systems	2-5%
New aircraft design	
Blended wing	20-30%
Pro-green aircraft	25%

1 Introduction

1.1 Topic of this paper

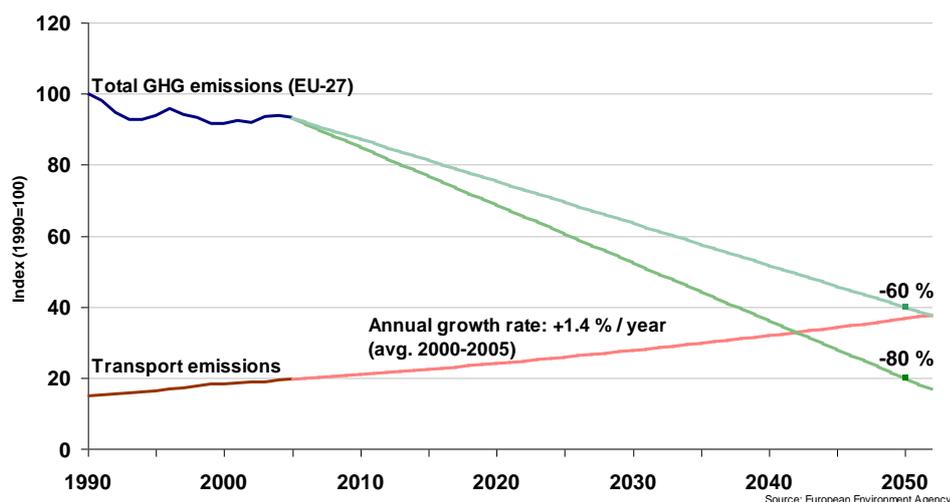
This paper is one of five papers on GHG reduction options for transport drafted under the *EU Transport GHG: Routes to 2050?* Project. These papers review the options – technical and non-technical – that could contribute to reducing transport's GHG emissions, both up to 2020 and in the period from 2020 to 2050. This paper focuses on the technical options for reducing Greenhouse Gases (GHG) from the main motorised non-road transport modes. The papers aim to provide a high-level summary of the evidence based on existing studies.

This paper was presented in draft form to a Technical Focus Group meeting (at which stakeholders were present) in July 2009 after which it has been updated on the basis of the discussion at the meeting and the comments and further evidence that were received.

1.2 The contribution of transport to GHG emissions

The EU-27's greenhouse gas (GHG) emissions from transport have been increasing and are projected to continue to do so. The rate of growth of transport's GHG emissions has the potential to undermine the EU's efforts to meet potential, long-term GHG emission reduction targets if no action is taken to reduce these emissions. This is illustrated in Figure 1 (provided by the EEA), which shows the potential reductions that would be required by the EU if economy-wide emissions reductions targets for 2050 of either 60% or 80% (compared to 1990 levels) were agreed and if GHG emissions from transport continued to increase at their recent rate of growth. The figure is simplistic in that it assumes linear reductions and increases. However it shows that unless action is taken, by 2050 transport GHG emissions alone would exceed an 80% reduction target for all sectors or make up the vast majority of a 60% reduction target. This illustrates the scale of the challenge facing the transport sector given that it is unlikely that GHG emissions from other sectors will be eliminated entirely.

Figure 1: EU overall emissions trajectories against transport emissions (indexed)¹

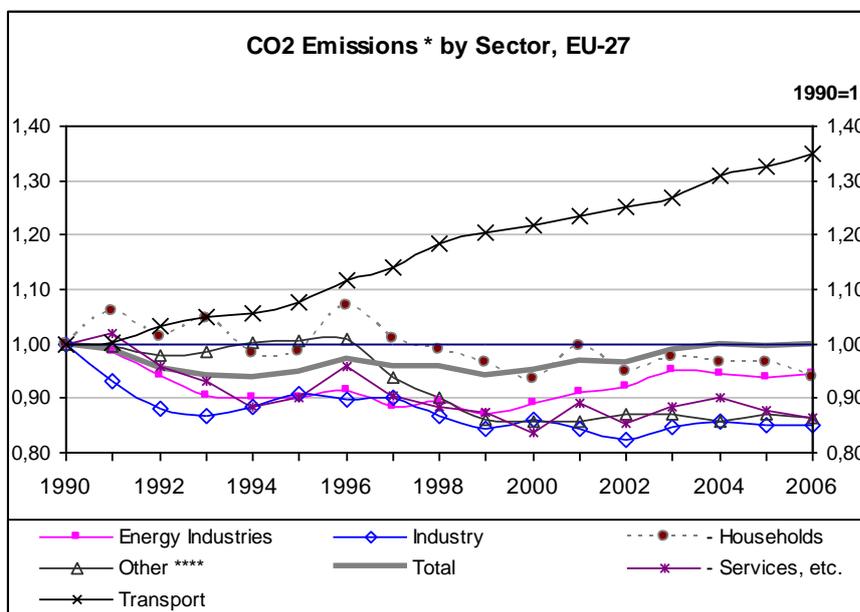


The extent of the recent growth in transport emissions is reinforced by Figure 2, which presents a sectoral split of trends in CO₂ emissions over recent years. Whilst the CO₂ emissions from other sectors have levelled out or have begun to decrease, transport's CO₂ emissions have risen steadily since 1990. It should be noted that whilst Figure 2 is presented in terms of CO₂

¹ Graph supplied by Peder Jensen, EEA

emissions, very similar trends are evident for GHG emissions (in terms of CO₂ equivalent) since CO₂ emissions represent 98% of transport's GHG emissions.

Figure 2: Carbon dioxide emissions by sector EU-27 (indexed)²



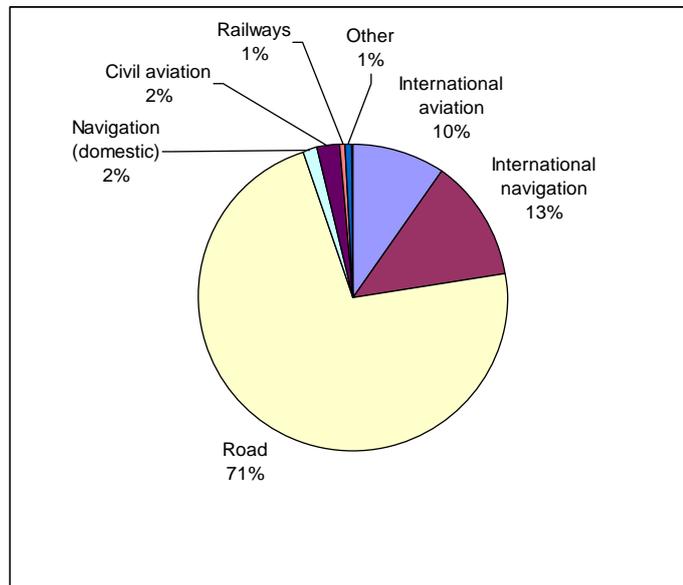
Notes:

- i) The figures include international bunker fuels (where relevant), but exclude land use, land use change and forestry
- ii) The figures for transport include bunker fuels (international traffic departing from the EU), pipeline activities and ground activities in airports and ports
- iii) "Other" emissions include solvent use, fugitive emissions, waste and agriculture

The vast majority of European transport's GHG emissions are produced by road transport, as illustrated in Figure 3, while international shipping and international aviation are other significant contributors.

² Graph based on figures in DG TREN (2008) *EU energy and transport in figures 2007-2008: Statistical Pocketbook* Luxembourg, Office for Official Publications of the European Communities.

Figure 3: Greenhouse gases emissions by transport mode (EU-27; 2005)³



Note: The figures include international bunker fuels for aviation and navigation (domestic and international)

Recent trends in CO₂ emissions from transport are also expected to continue, as can be seen from Table 1 below. Between 2000 and 2050, the JRC (2008) estimates that GHG emissions from domestic transport in the EU-27 will increase by 24%, during which time emissions from road transport are projected to increase by 19% and those from domestic aviation by 45%. It is important to note that these projections do not include emissions from international aviation and maritime transport, which are also expected to increase due to the growth in world trade and tourism.

Table 1: CO₂ emissions projection for 2050 by end-users in the EU-27, in Millions tonnes of Carbon⁴

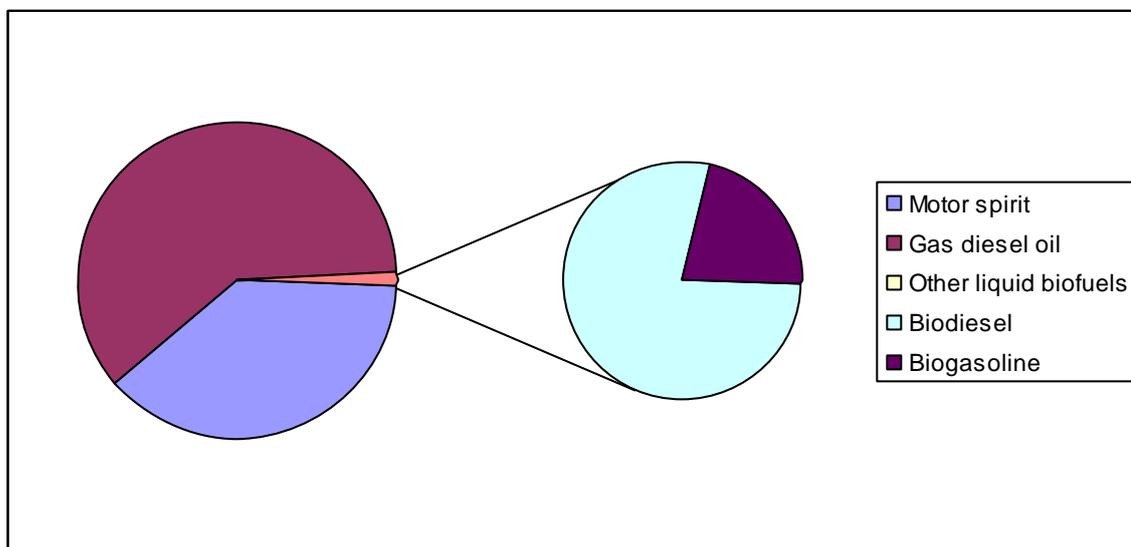
End user Category	1990	2000	2010	2020	2030	2050
Road transport	695	825	905	980	1002	1018
Rail	29	29	27	27	21	20
Domestic Aviation	86	134	179	206	237	244
Inland navigation	21	16	16	17	17	17
Total	810	988	1110	1213	1260	1299

Figures from the EEA (2008), illustrate the recent growth in GHG emissions from international aviation, as they estimate that these increased in the EU by 90% (60 Mt CO₂e) between 1990 and 2005; international aviation emissions will thus become an ever more significant contributor to transport's GHG emissions if current trends continue. Furthermore, the IPCC has estimated that the total impact of aviation on climate change is currently at least twice as high as that from CO₂ emissions alone, notably due to aircrafts' emissions of nitrogen oxides (NO_x) and water vapour in their condensation trails. However, it should be noted that there is significant scientific uncertainty with regard to these estimates, and research is ongoing in this area.

³ Graph based on figures in EEA (2008) *Climate for a transport change – TERM 2007: Indicators tracking transport and environment in the European Union* EEA Report 1/2008, Luxembourg, Office for Official Publications of the European Communities.

⁴ Taken from JRC (2008) *Backcasting approach for sustainable mobility* Luxembourg, EUR 23387/ISSN 1018-5593, Office for Official Publications of the European Communities.

Figure 4: Final transport energy consumption by liquid fuels in EU-27 (2005), ktoe⁵



The principal source of transport's GHG emissions is the combustion of fossil fuels. Currently, petrol (motor spirit), which is mainly used in road transport (e.g. in passenger cars and some light commercial vehicles in some countries), and diesel, which is used by other modes (e.g. heavy duty road vehicles, some railways, inland waterways and maritime vessels) in various forms, are the most common fuels in the transport sector (see Figure 4). Additionally, liquid petroleum gas (LPG) supplies around 2% of the fuels for the European passenger car fuel market (AEGPL, 2009⁶), while the main source of energy for railways in Europe is electricity, neither of which are included in Figure 4. While, alternative fuels are anticipated to play a larger role in providing the transport sector's energy in the future, currently they only contribute 1.1% of the sector's liquid fuel use.

1.3 Background to project and its objectives

The context of the *EU Transport GHG: Routes to 2050* is the Commission's long-term objective for tackling climate change, which entails limiting global warming to 2°C and includes the definition of a strategic target for 2050. The Commission's President Barroso recently underlined the importance of the transport sector in this respect by noting that the next Commission "needs to maintain the momentum towards a low carbon economy, and in particular towards decarbonising our electricity supply and the transport sector"⁷. There are various recent policy measures that are aimed at controlling emissions from the transport sector, but these measures are not part of a broad strategy or overarching goal. Hence, the key objective of this project is to provide guidance and evidence on the broader policy framework for controlling GHG emissions from the transport sector. Hence, the project's objectives are defined as to:

- Begin to consider the long-term transport policy framework in context of need to reduce greenhouse gas (GHG) emissions economy-wide.
- Deal with medium- to longer-term (post 2020; to 2050), i.e. moving beyond recent focus on short-term policy measures.
- Identify what we know about reducing transport's GHG emissions; and what we do not.
- Identify by when we need to take action and what this action should be.

⁵ Graph based on figures in DG TREN (2008), page 206

⁶ European LPG Association (2009) *Autogas in Europe, The Sustainable Alternative: An LPG Industry Roadmap*, AEGPL, Brussels. See <http://www.aegpl.eu/content/default.asp?PageID=78&DocID=994>

⁷ http://ec.europa.eu/commission_barroso/president/pdf/press_20090903_EN.pdf

Given the timescales being considered, the project will take a qualitative and, where possible, a quantitative approach. The project has three Parts, as follows:

- Part I ('Review of the available information') has collated the relevant evidence for options to reduce transport's GHG emissions, which was presented in a series of Papers (1 to 5), and is in the process of developing four policy papers (Papers 6 to 9) that outline the evidence for these instruments to stimulate the application and up take of the options.
- Part II ('In depth assessment and creation of framework for policy making') involves bringing the work of Part I together to develop a long-term policy framework for reducing transport's GHG emissions.
- Part III ('Ongoing tasks') covers the stakeholder engagement and the development of additional papers on subjects not covered elsewhere in the project.

As noted under Part III, stakeholder engagement is an important element of the project. The following meetings were held:

- A large stakeholder meeting was held in March 2009 at which the project was introduced to stakeholders.
- A series of stakeholder meetings (or Technical Focus Groups) on the technical and non-technical options for reducing transport's GHG emissions. These were held in July 2009.
- A series of Technical Focus Groups on the policy instruments that could be used to stimulate the application of the options for reducing transport's GHG emissions. These were held in September/October 2009.
- Two additional large stakeholder meetings at which the findings of the project were discussed.

As part of the project a number of papers have been produced, all of which can be found on the project's website, as can all of the presentations from the project's meetings.

1.4 Background and purpose of the paper

This paper is one of five "options" papers (Papers 1 to 5) that were developed under the *EU Transport GHG: Routes to 2050* project. The aim of these papers was to review the technical and non-technical options that could contribute to reducing transport's GHG emissions, both up to 2020 and in the period from 2020 to 2050. A series of papers (Papers 1 to 6) on "policy instruments" that could be used to stimulate the application and take up of these options was also developed. For the purpose of the project, we used the following definitions:

- **Options** deliver GHG emissions reductions in transport – these can be technical, operational or modal shift.
- **Policy instruments** may be implemented to promote the application of these options.

The options were reviewed in the following papers:

1. Technical options for fossil fuel based road transport.
2. Alternative energy carriers and powertrains.
3. Technical options for non-road transport modes.
4. Operational options for all modes.
5. Modal split and decoupling.

This paper is the third in this series of papers, all of which use evidence from existing studies to assess each of the options. It was presented in draft form to a Technical Focus Group meeting (at which stakeholders were present) in July 2009 after which it has been updated on the basis of the discussion at the meeting and any comments and further evidence received. This revised version of the paper can be found on to the project's website.

Whilst road transport currently contributes the majority of GHG emissions from the transport sector this could change in the future. Many recent studies have described low-carbon 'pathways' for road transport such as widespread use of electric vehicles or hydrogen fuel cell vehicles. If sufficient penetrations are achieved then scenarios of that nature could significantly reduce the portion of transport GHG emissions arising from road modes. If left unchecked modes such as aviation and maritime shipping could then form a much larger proportion of overall GHG emissions, particularly in light of the projected growth in those sub-sectors. Therefore, it is important to consider the technical options for reducing GHG from non-road modes since they could become increasingly important tool in a decade or two.

1.5 Structure of the paper

Following the introduction this paper is split into four further chapters:

2. Technical Options for Rail
3. Technical Options for Inland Shipping
4. Technical Options for Maritime Shipping
5. Technical Options for Aviation

Each of the chapters begins with an introduction to the technical options for the sector in questions, which includes an overview of what each option entails. The options are then analysed in turn to assess a range of factors. Where data was available these factors included:

- GHG reduction at vehicle level (short-term and long-term)
- Long term overall reduction potential
- Indication of cost at vehicle level and total cost
- Timeframe for application
- Co-benefits
- Infrastructural requirements
- Stakeholder vision
- Barriers
- Policy instruments
- Interaction with other GHG reduction options
- Uncertainties and main open issues

Each Chapter concludes with a comprehensive list of references.

2 Technical Options for Rail

2.1 Introduction

The rail sector has many unusual facets compared to the other main modes of transport. For example, there are hundreds of 'classes' of rail vehicle (which include passenger and freight locomotives, diesel multiple units, electric multiple units and shunting vehicles) in service across Europe. They have a wide range of specifications and operate across a patchwork of networks (AC electric, DC electric, diesel only, light rail, high speed rail etc), many of which are incompatible and have been upgraded with new infrastructure (e.g. signalling equipment) to varying degrees.

Furthermore, rail vehicles typically have a lifetime of 30-35¹⁰ years, so there are limited opportunities to improve emissions performance, particularly in the case of diesel powered engines. This leads to a conservative approach to procuring rail vehicles given that the effects of new technologies that perform poorly could be felt for several decades. Most countries heavily subsidise their rail sector so Governments often have more influence than would otherwise be the case in road transport or waterborne transport.

As a result of the highly complex nature of the rail sector it is very challenging to make accurate estimates of the carbon savings or costs associated with technical options. To establish accurate costs most options would require a detailed local feasibility study to fully understand the issues associated with the specific infrastructure and rolling stock in question. In light of this constraint any costs or carbon savings throughout the remainder of this chapter should be treated with caution.

Before considering the main technical options in more detail it is worth bearing in mind that there are some generic barriers to introducing new technologies in the rail sector. Unlike road or waterborne transport, the rail sector is very much an interlinked system rather than a number of independent actors. It is difficult to understand where savings can be made in that system without a detailed understanding of the interactions between the different parts (infrastructure, train operating companies, regulators etc). Studies such as the ongoing RailEnergy project will seek to understand those interactions before identifying energy efficiency opportunities.

In addition, any change on the railways, particularly to rolling stock, often involves liaising with a multitude of stakeholders:

- Rolling stock owners;
- Rolling stock operators/franchise owners;
- Infrastructure operators;
- Government (since most European railways are subsidised); and
- Passenger groups and shippers.

Many of these stakeholder groups came about following the so-called 'First Infrastructure Package', which was a suite of three Directives introduced in 2001. These Directives transformed the rail sectors in many European countries. State owned monopolies no longer held sway as the infrastructure was managed separately from the train services, which were also opened up to competition¹⁴. The net result of this large number of stakeholders (sometimes with conflicting perspectives) is that introducing new technologies tends to take longer than other transport sub-sectors. A further disadvantage is that investments made to improve the overall system will not necessarily benefit the investor themselves. For example, the infrastructure might make improvements to signalling systems to reduce delays but this would primarily benefit train operating companies.

2.2 Overview of options

This section defines each of the technical options considered in this chapter. A more detailed overview of the costs, carbon savings, barriers etc associated with each technology can be found in section 2.3.

2.2.1 Mass reduction

There are two main types of mass reduction: component-based lightweight design, which focuses on light weighting of specific components without fundamental changes to train configuration, and system-based lightweight design, which redesigns the whole train system optimising for weight.

Component-based lightweight design looks to make use of light weight materials such as aluminium in place of conventional types of steel⁶. In contrast, system-based lightweight design includes reducing the number of bogies and replacing 2-axle bogies with single-axle running gear⁶.

2.2.2 Regenerative braking

A regenerative braking system captures braking energy and puts it to good use (rather than allowing it to be transferred to heat via the brakes and dissipated into the atmosphere). In the rail context the braking energy is captured in the form of electricity, which is either stored on the train and used to supplement the main traction power supply during acceleration, transferred to other trains or in some cases returned to the electricity distribution network¹. Both pure electric or diesel-electric trains can utilise regenerative braking.

2.2.3 Electrification

Electrification usually entails the addition of overhead power lines to an existing rail route that was previously worked by diesel rolling stock. This allows electric trains to draw power from the overhead wires and use it drive their electric motors. There is nothing to stop diesel trains continuing to use the tracks and this so called 'running under wires' is actually fairly common, particularly where there are gaps in the network that are not electrified. 'Light' rail networks such as the London Underground also tend to be powered by electric traction but tend to be designed as electric networks from the outset.

2.2.4 Aerodynamics and friction

By improving the aerodynamics of a train, the air resistance as it travels can be reduced. This has a direct impact on energy consumption and hence carbon emissions, since reduced air resistance will mean less traction power will be required to travel at a given speed. In a similar vein, excessive friction between the wheels and track wastes traction power by dissipating energy as heat rather than using it power the train forward. Rail lubrication can be used to combat excessive friction.

2.2.5 Improved air conditioning

Modern trains are equipped with air conditioning in order to maintain a good level of passenger comfort. In central and northern Europe the extremes of temperature (-20°C to 40°C) are such that so called 'comfort functions', of which air conditioning comprises by far the greatest proportion^{6,7}, equates to around 20%⁶ of total energy consumption of the train. In these

circumstances there is a strong incentive to improve air conditioning systems and reduce their energy consumption.

A Study commissions by the Rail Safety and Standards Board⁷ (RSSB) in UK describes a suite of measures that could be employed to reduce energy use from air conditioning during stabling:

- Heating to a lower temperature for the majority of the time when the trains is stabled;
- Switch off heating at shutdown and restart at some optimum time before the train re-enters service;
- Provide heat for cleaning, but turn off as soon as cleaning activity complete;
- Provide trace heating on components, systems that require to be kept above a minimum temperature (e.g. on water systems); and
- Provide a more efficient auxiliary power source.

The RSSB study also suggests following measures for reducing energy use from air conditioning whilst the train is in use:

- Reduce uncontrolled air ingress or draughts;
- Improve insulation of rail vehicles;
- Reduce solar gain through use of specialist paints;
- Changes to interior temperature set points; and
- Reduce fresh air intake.

The EVENT Study commissioned by the International Union of Railways⁶ also describes two further options:

- CO₂ based demand control which varies the rate of cooling or heating according to an estimate of the number of people in each carriage (based on the CO₂ they exhale); and
- Making use of waste heat from under floor traction equipment (via heat exchangers) to heat the carriages.

2.2.6 Driver support

It is possible to achieve significant energy savings through training drivers in energy efficient driving techniques. These techniques can be reinforced by specialist in-cab software that provides real-time feedback.

2.2.7 Traffic management

Rail 'traffic management' can include the management of timetables, speed of trains, and 'active' traffic management – i.e. clearing signals to green in good time (using auto route setting), keeping heavy freights and high speed services rolling, and warning drivers in advance that they are approaching a congested area and should reduce speed.

2.3 Assessment of options (from existing studies)

This section provides an overview of the information reviewed whilst compiling the paper as well as any relevant stakeholder inputs. Each technology is considered in turn.

2.3.1 Mass reduction

A 2004 study by IFEU Heidelberg concluded that average weight was on the increase for some 'rail vehicles' due to a perceived need to improve ride comfort¹. A more recent position paper (2008) from the Rail Carbon Trajectory Group³ stated that mass reductions could be achieved and concluded that future Rail Vehicles were likely to be lighter than recently designed trains. The group consisted of a broad range of stakeholders including train operating companies, rolling stock owners, Government and infrastructure operators have stated that mass reduction opportunities exist.

The 2008 European Railway Technical Strategy produced by European Rail Infrastructure Managers (EIM) also concluded that mass reductions could be achieved in areas such as the bogies and body work. However, they also noted that there is strong pressure to increase the weight of rolling stock, particularly on high-speed routes. Improvements to the passenger experience such as powered doors, air conditioning and controlled emission toilets are all cited as examples of where passenger expectations could result in weight increases in certain systems.

Accelerating trains up to speed is less of a consideration than cutting the aerodynamic drag for high-speed trains covering long distances between stops. Therefore, train mass becomes less significant for total energy consumption for non-stop high-speed runs. However, it needs to be controlled for other reasons, such as reducing the extent of wear and tear on the track¹⁸.

A report by UIC demonstrates the impact that increased train mass can have on energy consumes (and therefore in reverse the potential savings to be gained from mass reduction). Analysis was undertaken by Fundacion de los Ferrocarriles Espanoles, which showed that a 10% increase in train mass resulted in energy consumption increases of 0.5-1% for high-speed trains; 2-3% for long distance/conventional trains; 5-7% for suburban trains and 6-8% for urban trains.

In their 2005 Study¹², CE Delft outlined a series of mass reduction opportunities for passenger trains. These included:

- *Double deck trains* – Increasing the height of railcars to allow two levels of passenger seating;
- *Aluminium railcar body* – Utilising lightweight aluminium rather than steel for the railcar bodies;
- *Wide-body trains* – Increasing the width of trains to accommodate additional passengers and hence reduce the train weight per seat;
- *Articulated trains* – This entails reducing the number of bogies (i.e. the chassis on which the wheels, railcar body and various other components are attached), which themselves make up a third of the weight of a train¹²; and
- *Lightweight coach interior equipment.*

CE Delft estimated that Aluminium car bodies, articulated trains and lightweight coach interior equipment could each achieve weight savings of 2% to 5% on a single vehicle and 1% to 2% if applied to the whole fleet. It was estimated that double deck trains and wide body trains could achieve greater than 10% on a single vehicle and 2% to 5% for the whole fleet.

The same study also proposed benchmarks in terms of 'best in class' weight per seat. CE Delft suggested that for high-speed trains (where a higher mass is necessary for stability) the Japanese Shinkansen at 537kg/seat should be the target. In contrast, this fell to 342kg/seat for suburban trains in Copenhagen.

EIM also anticipate that a desire to employ larger carriages with greater capacity will drive up axle loads. Overall, the European Railway Technical Strategy predicts that the axle loads for High Speed Passenger and Interurban Passenger train weights will remain static, Conventional Speed Passenger trains will see a modest reduction of around 10% and smaller carriages (e.g. Suburban Metro, Regional Railways and Community Railways) will see significant reductions in

axle loads of 33% to 50%. The EIM strategy predicts that Heavy Freight and Conventional Freight flows will see an increase in axle loads from 25 tons to 35 tons and 22.5 tons to 25 tons. In contrast they predict a 10% reduction in axle loads for High Speed and Logistical Freight.

In their study for Aluminium Institute¹, IFEU estimated that a 10% reduction in weight would result in energy (and hence CO₂) savings of 5% to 7.5%. Interestingly, CE Delft's 2005 study for NS Reizigers¹² concluded that a 10% reduction in weight could result in energy savings of between 1.2% for high-speed trains and 6.4% for suburban trains. The currently available literature does not quantify the costs or the emissions savings that could be achieved by mass reduction so this will be a key question to put to stakeholders.

That said, it seems likely that the use of lighter materials is likely to increase costs. Aluminium is more expensive than Steel, largely due to the energy intensive processes (electrolysis) needed to produce it. Other lightweight materials favoured by the transport sectors such as fibre-reinforced plastics and reinforced polymers are also more expensive than conventional steel¹¹.

Mass reduction has the secondary benefits of reducing energy use (and hence cost) and wear on rails¹ without requiring any significant changes to the infrastructure.

The key barriers to mass reduction are the lifetime of rolling stock; the relatively conservative nature of the industry; and the desire to improve passenger comfort, which tends to entail increased weight. Rail rolling stock can be in use for 30-35 years so it is important that as many of the technical options for rail obtain industry approval as soon as possible. Otherwise there is a distinct possibility that relatively inefficient systems will be 'locked in' for many years. For this same reason, rolling stock owners are reluctant to invest in unproven technology since reliability is a key criteria for them (if they own and operate the rolling stock) or their clients, if they lease the rolling stock to Train Operating Companies (TOCs).

Engineers looking to reduce the mass of trains must also consider the impact on safety, particularly given the long lifetime of trains, which can be in service for as long as 30-35 years. Across most modes of transport improving safety has usually resulted in an increase in mass so this trend will need to be reversed to achieve viable weight reductions.

In addition, there are not currently any legislative drivers to encourage the rail sector to reduce its GHG emissions per vehicle km or tonnekm. That said, the UK Government is beginning to include environmental criteria in franchise terms, which ought to give renewed focus to the issue.

However, there are some secondary-benefits to weight reduction. For instance, mass reduction tends to reduce energy use (and hence cost) and wear on the tracks¹.

2.3.2 Regenerative braking

Regenerative braking is already in widespread use in many countries⁷. However, it is only in the last few years when environmental issues have moved up the political agenda that regenerative braking has received more attention. As a result policy makers have begun to consider whether it could be rolled out more widely and whether the proportion of recovered energy could be increased.

The extent to which regenerative braking can be employed will depend on a range of local factors, not least the proportion of locomotives or power units that are fitted with regenerative braking equipment. Compatibility with existing equipment and infrastructure can also be problematic. This is a particularly pertinent issue for electric trains, where a key factor is the type of electric traction (alternating or direct current – AC or DC). AC allows regenerated electricity to be fed back into the national electricity system relatively easily since electricity networks operate on AC⁴. However, on DC networks the electricity will only be put to good use if there is sufficient traffic on the rail network. Otherwise it will be converted to heat by a bank of on-board resistors.

Whilst in theory the DC electricity could be stored or inverted (i.e. converted back into AC electricity) and fed back into the Grid this would require on-train / trackside DC electricity storage or significant investment in inverter substations¹ respectively. Space constraints both on trains and trackside must also be considered at a local level before regenerative braking can be rolled out widely.

Indeed, the rail industry has yet to reach a consensus on what best to do with the electricity – whether to store it on board, store it trackside or feed it back into the Grid. These elements of regenerative braking systems still require some development and refinement.

In view of the above constraints, different solutions may emerge for different circumstances, which could be counterproductive in terms of achieving economies of scale.

Assuming all the necessary conditions are in place the Railway Forum estimated that regenerative braking can reduce energy use (and hence carbon emissions) by at least 10%-15%⁴. In contrast, a report from RSSB/Interfleet illustrated two case-studies with differing outcomes. After equipping a light rail vehicle with regenerative braking Bombardier are anticipating achieving savings of up to 30%⁷. They expect this to be matched by heavier rail vehicles. However, a feasibility study by NS Reizigers found that on-board or line-side energy storage was a major issue and savings would be limited to 6%⁷. The UIC state that where technically feasible in rolling stock, and assisted by appropriate infrastructure management, regenerative braking may lead to positive results, potentially a 10-20% reduction in CO₂. Fleets would have to be fitted with energy recovery function. Its use in regional and commuter traffic could lead to particularly high results, with higher potential in electric lines¹⁹.

As outlined above the steps required to implement regenerative braking are often complex, time consuming and costly, whilst varying substantially from network to network. Therefore, putting a price on regenerative braking is very challenging without carrying out a detailed local assessment. That said, RSSB/Interfleet rated the costs of regenerative braking as 'medium'⁷.

The timescales for implementation would depend on the work that needs to be carried out to strengthen infrastructure and the availability of rail vehicles with regenerative braking. The asset lifetime of rail vehicles will once again pose a problem in this regard, as the rolling stock owners will be reluctant to reduce the utilisation of non-regenerative braking rolling stock for fear of reducing the return on their investment. A further barrier to more widespread use of regenerative braking is the reluctance of power companies to accept and pay for regenerated electricity. Most electricity networks are designed to service a relatively small number of central generating plants so accepting small packages of power is not always desirable from their perspective.

Rail sector stakeholders recognise the benefits of regenerative braking in terms of improving environmental performance and reducing operating costs¹. However, it is the myriad of practical issues described above and the need for coordinated action by a host of stakeholders that threatens to slow progress. As a result, powers under the European Interoperability Directives, may be required to bring a focus for efforts to regenerate a greater proportion of braking energy.

2.3.3 Electrification

Electric traction is already a mature, proven technology in the European rail sector. Indeed it is actually the rail traction technology of choice in many countries whilst is illustrated by the fact that 80% of European rail traffic is undertaken by electric traction⁸ (measured in passenger km and tonne km) whilst just 51% of European tracks are electrified⁸. In many countries it is only the less busy routes that are not electrified. However, there are some countries such as the UK, Czech Republic and Hungary where less than a third of tracks are electrified⁸, based on 2004 figures.

Therefore, whilst there is scope to electrify further routes, or infill gaps in otherwise electrified routes, in a handful of European countries (particularly the UK, Czech Republic and Hungary) the vast majority of the cost effective (high traffic) routes have already been electrified. In other

words, the cost savings (electric vehicles are cheaper and more energy efficient) from electrifying the diesel routes do not outweigh the infrastructure costs, so the investment cannot be justified from a purely commercial perspective. Consequently, with the exception of the countries highlighted above, most future electrification would only take place to reduce GHG or air quality emissions.

Given that the cost of electrification is estimated at around £550k to £650k per single-track km⁵, the rail sector tends to seek Government support to fund the investment in electrical infrastructure. Indeed capital cost is the main barrier to electrification.

Whilst this high capital cost has proved prohibitive in some instances, the switch to electric traction can yield significant carbon savings. For instance, The Railway Forum estimate that there is a 20% to 40% carbon advantage compared to diesel in the UK with the current generating mix⁵. Network Rail estimate the advantage is 20-30% on average⁹. UIC estimates CO₂ savings of up to 50% for the electrification of diesel lines (although this depends on the national energy mix)¹⁹. As Grid electricity is decarbonised this gap should widen significantly and the rail sector has the potential to become very low carbon indeed. However, the extent to which this occurs is reliant upon strong growth on the growth in renewable energy capacity and the replacement of conventional fossil fuel plants with carbon, capture and storage enabled plant.

In view of the high proportion of traffic undertaken by electric traction it is no surprise to learn that the rail industry is very supportive of further electrification⁵. There are various reasons for this strong support: electric traction units are quieter, cheaper to lease, have lower operating costs, have more seats and cause less wear and tear on the tracks than an equivalent diesel train⁹.

Other benefits include a lack of air quality emissions at stations, improved energy security due to the diverse electricity generation mix and increased availability of rolling stock (electric vehicles tend to need less maintenance since they are inherently simpler and more reliable)⁹. Network Rail, who maintain the rail infrastructure in the UK, estimate that electric trains are twice as reliable in terms of miles per breakdown⁹.

2.3.4 Aerodynamics and friction

In their 2003 EVENT Study¹³, The International Union of Railways presented figures from a 1999 study by Anderson and Berg, which described the breakdown of aerodynamic drag for a high speed train as illustrated in Table 5:

Table 5 – Share of overall aerodynamic drag on a component / system basis

Train component / system	Share of overall aerodynamic drag
Bogie and wheels	45.5%
Surface friction from sides and roof	27.0%
Pantographs	8.0%
Underfloor equipment	7.5%
Tail	4.5%
Ventilation	4.0%
Front	3.5%

The same study proposed a number of measures for reducing aerodynamic drag:

- Aerodynamic optimisation of pantographs;
- Aerodynamic ordering of freight cars;
- Bogie fairings;
- Covers for open freight cars;

- Streamlining of head and tail; and
- Streamlining of train sides and underfloor areas.

Bogie covers were estimated to produce a reduction in total drag of around 10%, which translates to an energy saving (and hence CO₂ saving) of 6% to 7% from the train as a whole. The study did not provide any further data on CO₂ or cost savings for the other options to improve aerodynamics.

Bombardier claim¹⁵ their AeroEfficient Optimised Train Shaping can reduce drag by up to 25%, which results in energy savings of around 8% for regional trains, and 15% for high-speed trains.

In the past, there has been a relatively relaxed approach to aerodynamics in the rail sector. This is because fuel consumption didn't make up nearly such a large proportion of the lifecycle costs in the rail sector as other transport sub-sectors such as road transport. The rail sector's focus on addressing a range of operational and infrastructural issues also pushed aerodynamics further down the agenda. In recent years, the environmental impact of the rail sector has become much more of an issue for all rail stakeholders, which has meant closer attention has been paid to issues such as fuel consumption and hence aerodynamics.

In view of the relatively modest fuel savings associated with most of the aerodynamics measures they are most likely to be implemented on new rail vehicles. Given the long lifetime of most rail vehicles this means their introduction will be phased in gradually as rail vehicle stock is renewed.

The UIC EVENT study cites two main causes of friction:

- Linear friction caused by dissipation in the wheel-rail interface; and
- Curve resistance arising from additional frictional forces in curves.

The study identifies rail lubrication as the main means of reducing lateral friction between the rail and wheels. Mass reduction also has a direct impact on friction since linear friction is proportional to the weight of the railcar. The study did not identify any costs or emissions savings.

2.3.5 Improved air conditioning

As described in Section 2.2.4 there are a significant number of measures that could be applied to reduce energy consumption from air conditioning systems. However, many of the measures would require detailed fleet-by-fleet assessments to establish whether they would be feasible from a technical, operational and cost perspective⁷. Consequently, it is very difficult to make an accurate estimate of the cost or carbon savings that could be achieved through improved air conditioning. That said, it will be possible to make some estimates of potential savings.

A study by the Rail Safety and Standards Board (RSSB) in the UK⁷ calculated that the basket of measures to reduce energy use from heating and cooling during stabling could save 115,000 MWh of electricity, 18.5m litres of diesel and 101.1m kg of CO₂ in the UK. The electricity saving equates to 4% of total electricity use on passenger trains. Many of these measures could be implemented relatively quickly assuming feasibility studies and trials did not highlight any major issues. Bombardier estimate that their ThermoEfficient Climatisation System, which actually consists of a combination of two systems (one that senses passenger occupancy and adapts the fresh air rate according and a second that employs heat exchangers to pre-heat or pre-cool the air), can reduce energy use by the air conditioning system by 24% and 26% respectively¹⁵. The UIC identified that air conditioning, along with power for heating and lighting is used in large quantities when the train is standing still. This can typically account for 10% of energy, but if poorly managed, can reach 25% of the total for commuter trains with long layovers between rush hour services¹⁸.

According to the RSSB study, the remaining measures would have a much less significant impact in terms of energy savings and would entail payback periods of around 15 years, which would only be acceptable for new vehicles.

The current European legislative framework does not compel train operators or rolling stock owners to comply with any emissions limits on CO₂. Therefore, other than realising relatively modest cost savings or meeting any self imposed targets there is little incentive for the rail sector to tackle energy use in air conditioning systems.

The biggest barriers to these measures being adopted widely are the need to assess each fleet in turn (which could prove costly and time consuming) and the relatively long pay back period for many of the measures. Furthermore, reducing energy use from air conditioning will not necessarily be a high priority issue for managers with a range of operational issues to address.

2.3.6 Driver support

Training commercial drivers in fuel efficient driving techniques is a routine element of professional development in many transport sub-sectors. In recent years it has become more common in the rail sector as energy efficiency and GHG emissions have risen up the political agenda.

In theory there are some significant savings available from both the driver training and in-cab fuel efficiency displays. The latter provides the driver with information regarding the optimum speed, braking points etc to ensure they drive in the most fuel-efficient manner. Both Bombardier and TTG Transport Technology in Australia claim their 'Drive 50' and 'Freightmiser' driver assistance systems will reduce GHG emissions by up to 15%^{14,15}. In the UK, First Group, who operate several franchises, found that driver training and in-cab fuel efficiency displays produced GHG savings of 5.5% during a recent trial on class 185's¹⁷. Energy efficient driving can become part of all train driver's everyday routine, as has been shown by DB's experience, where 14,000 drivers have been trained in Germany. Many other European railways, including NSB, DSB, SBB and others, have echoed this success. It is estimated that such energy efficient driver training can result in savings of 5-10%¹⁹.

One of the key benefits of driver support tools is the rapid payback, which can be a matter of a few months for driver training.

2.3.7 Traffic Management

Traffic management measures can be applied in order to optimise the performance of the network in terms of energy efficiency, including those aimed at the management of timetables, speed of trains, and 'active' traffic management – i.e. clearing signals to green in good time (using auto route setting), keeping heavy freights and high speed services rolling, and warning drivers in advance that they are approaching a congested area and should reduce speed.

Automatic traffic regulation strategy for the Metro de Madrid was tested and measured and it was revealed that an energy consumption saving of 15% was achieved compared to the previous manual regulation²⁰.

2.4 Summary

Table 6 summarises the CO₂ savings and payback periods for the technical rail measures considered during this chapter. It is important to note that whilst packages of measures could be employed, it would not be possible to apply all of these measures simultaneously. Therefore, the total CO₂ reduction potential will be much less than the sum of the individual reduction potentials listed below.

Whilst this chapter has set out a range of measures capable of reducing CO₂ emissions by significant quantities, electrification is the clear winner with regards CO₂ savings. Unfortunately, it also happens to be one of the most capital-intensive and expensive measures. Indeed, relatively poor payback periods, and hence a reluctance to retrofit, seem to be a common theme for the measures covered in this chapter. This leads to the conclusion that an emphasis should be placed on specifying new vehicles with the best available technology to reduce CO₂ emissions, particularly in view of the long lifetimes of trains. Given their influence in the rail sector, Member State Governments could certainly play a role in ensuring that cost effective low-carbon technologies feature strongly in train specifications.

The qualitative estimates of payback time correspond to the following time periods:

- Very short payback period = less than 1 year
- Short payback period = 1 to 3 years
- Moderate payback period = 3 to 8 years
- Long payback period = > 8 years

Table 6: GHG emissions reduction potential of the technical rail options

	Current CO₂ reduction potential on rail vehicle level where applicable	Estimated payback period
Mass Reduction		
Double deck trains	>10%	Moderate payback period
Aluminum railcar body	2% to 5%	Moderate payback period
Wide-body trains	>10%	Moderate payback period
Articulated trains	2% to 5%	Long payback time
Lightweight coach interior equipment	2% to 5%	Moderate payback period
Regenerative Braking		
AC network	10% to 15%	Long payback period
DC network	0% to 5%	Long payback period
Electrification		
Electrification	20% to 40%	Long payback period
Aerodynamic and friction		
Aerodynamic optimisation of pantographs	<1%	Long payback period
Aerodynamic ordering of freight cars	<1%	Long payback period
Bogie fairings	6% to 7%	Moderate payback period
Covers for open freight cars	<1%	Long payback period
Streamlining of head and tail	<1%	Long payback period
Streamlining of train sides and underfloor areas	<1%	Long payback period
Improved air conditioning		
Improved air conditioning	4%	Moderate payback period
Driver support		
Driver training and in-cab displays	5% to 15%	Short payback period
Traffic Management		
	Not available	Not available

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3 Technical Options for Inland Shipping

3.1 Introduction

Inland shipping is one of the most energy-efficient means of transporting goods over long distances inland [1], [2]. However, there are many additional options for reducing energy demand and GHG emissions that are yet to be exploited, or could be exploited to a greater extent. Although the project team were not able to identify any systematic studies on GHG-reduction options for inland shipping, some relevant information sources were identified. Firstly, a brochure published by Bureau Innovatie Binnenvaart in the Netherlands, sponsored by the Ministry of Transport, Public Works and Water Management [3] presents a good overview of many of the modern techniques that are of interest. One literature study [6] that focussed on emission reduction (not just GHG) also mentions several techniques that can be applied in inland shipping. ECN published a small but useful study on improving the cost effectiveness of inland transport [4]. Wiegman undertook a broader study covering strategies and innovations to improve the performance of barge transport [8] and of course many examples of case studies for new technologies can be found in specialised maritime magazines/websites. However, explicit evaluation in terms of GHG-reduction potential is often lacking or very difficult to extract from such highly specialized studies.

The Netherlands together with Germany have the largest share in inland waterway transport in Europe (more than 80 percent of total tonnekm moved). This is the main reason why much of the information relating to inland shipping has its origin in Germany or the Netherlands.

IPPC has published a comprehensive study of GHG mitigation in transport [5]. However for inland shipping only a few specialised options for GHG mitigation were identified. For maritime transport more comprehensive studies are available such as IMO's study from 2000 [20]. That said, the validity of 'maritime transport' conclusions for inland shipping transport is questionable in many cases.

3.2 Overview of options

3.2.1 Power train efficiency improvements

More efficient diesel engines

More efficient common-rail diesel engines are being developed which feature technologies such as high-pressure fuel injection combined with turbo-loaded engines. Therefore, replacement of less efficient older engines (15 years or more) is an option for reducing GHG.

Optimising conventional propeller propulsion

Several optimized propeller designs such as ducted propellers, contra-rotating propellers and propeller boss cap with fins are being tested or have already been introduced to the market.

Revolutionary new propeller designs

In view of the fact that conventional propellers have restricted axial propulsion efficiency, revolutionary new designs such as whale-tail propellers with much higher efficiencies could emerge in time.

Application of diesel-electric power trains in special situations

Diesel-electric propulsion can be an efficient option when lower engine power makes up a relatively high proportion of the drive cycle.

3.2.2 Reduction of required propulsion

Improved hull designs

Improved hull designs can increase speed or reduce the required propulsion power on inland barges.

Larger barge units

Larger barge units are often more efficient on larger inland waterways because viscous water resistance is reduced. However on small waterways, small ships will experience less resistance than big ships. In addition, elongating ships can improve their performance since this also acts to reduce water resistance.

Computer assisted trip planning

Computer assisted trip planning and speed management could help to optimise ship engine power with the aim of striking a balance between minimising emissions and achieving delivery schedules.

Lightweight ship hulls

The introduction of very lightweight ship hulls for transporting fluids, manufactured from materials such as carbon fibre, are already being tested.

Air lubricated hulls

Viscous water resistance is very important for inland ships travelling at relatively low speeds. Setting aside the resistance caused by imperfect streamlines and waves, viscous resistance can often amount to 80 percent of total water resistance. Air lubrication is a radical option for reducing viscous water resistance.

3.2.3 Advanced/alternative power trains

LNG-optimised diesel engines

As a fuel, methane has a low carbon content which is around 25 percent lower than conventional diesel fuel. Therefore, in principle, it offers the possibility of GHG emission reduction when used as fuel. This has been demonstrated in some niche marine propulsion applications such as LNG-transport [23].

Alternative biofuels

Alternative biofuels such as biodiesel and pure plant oil are available now whilst hydrothermal produced biodiesel and second-generation biofuels will become available in time.

Power from the sun and wind

Instead of being produced by auxiliary diesels, auxiliary power on inland ships could be supplied by solar cells and small wind turbines. On many ships deck there is plenty of space available.

Fuel Cells

In principle fuel cells could be used to provide auxiliary power on inland ships. However, cost, durability and power density concerns (which also preclude them use as the main source of traction power) mean they are unlikely to see significant uptake for the foreseeable future.

3.3 Assessment of options

3.3.1 Power train efficiency improvements

More efficient diesel engines

The fuel efficiency of diesel engines in shipping currently ranges from 160 gram fuel/kWh to 240 gram fuel/kWh. However, 160 gram fuel/kWh is only achieved on large marine diesel engines. Assuming inland shipping averages around 200 gram fuel/kWh, this gives a range for the overall reduction potential of around 15-20 percent. The cost of engine replacement for 1 barge unit is around 100,000-300,000 Euro. Given that approximately 50 percent of the engines in service are more than 20 years old [6] about 5,000 barges from the European fleet could be replaced. This would cost 0.5 to 1.5 billion Euro. The financial and competitive position of many inland shipping companies does not allow investments that are not strictly necessary (PINE-study). Therefore, without financial support such a massive engine replacement would, in all likelihood, not be achievable.

Co-benefits of engine replacement would include the reduced pollutant emissions leading to improvement of air quality. However, engine replacement should become much more attractive when inland shipping engines are obliged to meet stages IIIA and IIIB of the Non-Road Mobile Machinery (NRMM) Directive, which is likely to be introduced in 2012 for inland waterways. The NRMM Directive sets air quality emissions (e.g. PM and NO_x) for non-road sectors such as rail and inland shipping.

Many existing financial investment programs are mainly undertaken to improve air quality. However, GHG-reduction could be proposed as an alternative rationale for investment.

Optimizing of conventional propulsion by propellers

Conventional propellers on inland ships have an estimated average power transfer efficiency of 50 %. The losses are caused by unavoidable pulses of water in the radial direction. These radial flows are not contributing to the propulsion of the ship in forward axial direction. Improving this rather low propeller efficiency has been the objective of hydrodynamic engineers for many years. In seagoing ships with radical propeller designs the propeller efficiency can reach 70 % [10].

At the ship level, improvement of propeller thrust of 20 to 30 % seems to be feasible [9]. With flattened ducted propellers (propeller tubes) fuel efficiency improvements from 10 to 25% can be achieved [3], [4].

The long-term overall GHG reduction potential has yet to be estimated in published literature. Assuming an unused potential of 50% the total reduction potential may be in the order of 5 to 10%.

Cost at a vehicle level will be around 50,000 Euro (example derived from financial support by the Dutch funding organisation SenterNovem). Replacement on around 5,000 ships would cost approximately 250 million Euros.

The attractiveness of propeller replacement is highly dependant on future fuel prices and the financial position of individual boat owners. In addition, not all ships hulls will be suitable for installation of improved propellers without a hull rebuild which would be prohibitively expensive.

No interaction with other GHG options is foreseen.

Revolutionary new propeller designs

The whale-tail wheel is a revolutionary propeller design that has an estimated efficiency of 50% [1], [2]. Kasifa [6] gave an estimate of 25-33% energy efficiency improvement compared to conventional propeller designs. Kasifa [6] also mentioned that similar experimental ships, such as the so-called "penguin-boat", have been tested in the US.

It is hard to say whether the whale-tail wheel has the potential to become a mainstream technology since there is not enough real world experience to judge the technology from either a mechanical durability or cost-efficiency perspective. Pilot-projects are needed before the concept can be accepted as a proven technology [3]. As this technology is not to be considered as proven technology no indication of cost-efficiency in the long run can be given. Grave [3] ranks this technology under the chapter "future technologies". This new concept will probably only be fitted on new-build ships that feature a specially adapted hull design.

Diesel-electric propulsion

Diesel-electric propulsion (sometimes called AES i.e. All Electric Ship) can deliver a fuel efficiency improvement in some cases. A reduction of 5 to 10% seems to be feasible. This reduction can be realised by switching on and off several smaller diesel units. In this way the diesel engines are always used in their optimal power range [3].

Only a few diesel-electric inland freight ships are currently in use. Most famous are the Airbus freight ships MS Breuil en MS Brion (carrying capacity 1,019 ton) [3].

Retrofit of current ships is not currently an attractive option because the propellers also have to be replaced which often necessitates a partial rebuild of the hull. That said, the prospect of a new hull design also offers the possibility of hulls with less water resistance.

Not enough practical experience exists for a statement about the future perspectives of this rather new technology in inland shipping.

Co-benefits include noise reduction and easy use of electric power from the grid when ships are moored at berth [3]. Consequently, this technology may be more attractive for certain market niches (especially inland transport of people such as ferries and river cruise ships).

Barriers are probably more of psychological nature ("hardly any engine sounds"). Financial support is given in the Netherlands for all conceivable measures of reduction of energy consumption.

Diesel-electric propulsion technology can easily be combined with the application of bio-diesel

3.3.2 Reduction of required propulsion

Improved hull designs

The Improvement of the hydrodynamic design of ships hulls has been within the working domain of maritime research institutes for many years. However, in contrast to seagoing ships the progress for inland ships has been relatively slow and modest. In newly built ships improvements of between 5% and 20% are possible. On existing ships improvements of around 5 % are more likely. Some new concepts have been demonstrated recently such as the so-called 'duck-tail', which is the hydrodynamic equivalent of lengthening the ship. It is usually 3-6 meters long. The basic idea is to lengthen the effective waterline and make the wetted transom smaller. This has a positive impact on the ship's water resistance. The effect is 4-10% lower propulsion power demand. A corresponding improvement of 3-7% in total energy consumption is typical for a ferry [12]. In contrast to seagoing shipping the "bulbous bow", which is a special form of elongation on the front site, is rarely seen in inland shipping. That said, an inland ship called "Aspali" features an elongation on the front site and the backside resulting in an estimated fuel efficiency improvement of 19 percent.

For a single wall hull inland ship hull elongation of 10 meters the estimated cost is in the order of 50,000 Euro (Example derived from financial support published by a Dutch public funding organization SenterNovem). Elongating the new 'double wall' hull ships will be much more expensive.

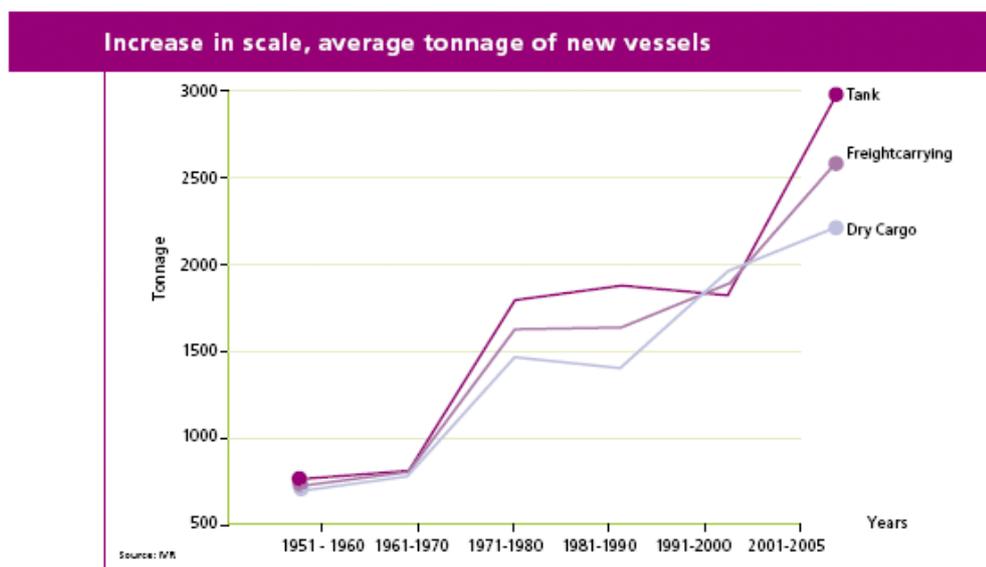
Assuming that 50 percent of the ships can be equipped with improved hulls the total potential GHG reduction will be in the order of 5 %. Replacement of around 5,000 ships would require 250 million euros.

The attractiveness of a replacement programme is strongly dependant on (future) fuel prices and the financial position of many individual boat owners. For new ships these options are on the market.

No interaction with other GHG options is foreseen.

Larger barge units (efficiency of scale)

In unrestricted water larger barge units are more fuel-efficient. See [2] table 69. A container ship loaded with 150 containers is almost 25% more energy efficient than the conventional Rhine Herne Canal ship. In Wärtsila's brochure it is stated that regression analysis of realised ships has shown that 10 percent increase in ships size will result in about 4-5% energy efficiency improvement [12]. The relationship between a ship's size and energy efficiency is not a linear relationship but roughly follows the ratio between surface and volume being a power law of 2/3. From the figure below it can be derived that ships built in the last 50 years have increased in size between 6 and 8 % per year. Without doubt this has had a tremendous impact the fuel efficiencies of ships.



Increase in scale has the principal trend in the inland shipping sector over the past fifty years. Increases in scale first occur in the tanker sector, as its loading and unloading facilities are simpler to adapt

Source: [13]

It is very hard to say when the limits of maximum ship sizes will be reached. Much will depend on the infrastructure that has to be built and maintained. Climate change itself may have a profound impact on the development of the shipping sector [14]. For instance in the dry summer of 2003 most ships could only travel on rivers with small loads. If such circumstances increased in frequency and duration the steady increase of ships sizes could be curtailed or even reversed. This is outside the scope of this literature study.

Regulators should be well aware of the profound impact of ships size growth on the fuel efficiency of ships. However, smaller ships are more fuel-efficient on small inland waters. For this reason even small ships can still play an important role in GHG-reduction [24] by taking over road freight (see about the paper on modal-shift).

Computer assisted trip planning and speed management

By providing advice on optimal sailing routes and sailing speed a computer program can assist the shipper in optimal trip planning. Currently, there is only one known example of this type of software for inland shipping (advisory Tempomaat). It is likely that more elaborate applications of this principle for inland navigation will appear on the market next years. The producer of the Tempomaat claims a 4 % fuel reduction for most economic sailing shippers and about 15 % reduction for less economic sailing shippers [3]. Long term overall reduction potential is roughly estimated to be between 5 and 10 % with a payback period of less than 1 year

On the downside, technology of this nature means shippers are being provided with more and more electronics to watch (another example is the introduction of AIS). This may become a psychological obstacle for investment or proper usage. This should be kept in mind during the design phase for new electronic equipment.

Lightweight ship hulls

In an experimental ships hull (study on the "CompocaNord") extensive use of composite materials offer the potential for 30 % freight increase at the same ships dimensions [15]. Figures relating to improvements in energy efficiency are not given but estimates are in the order of 15%. A more

conservative approach is found in a brochure from Wärtsila. By using aluminium and other lightweight steel, the weight of conventional ships could be reduced between 5 and 20% resulting in a fuel efficiency improvement of 5% [12].

Long term overall reduction potential is lower than 15 percent as only a limited number of inland ships are suitable for light-weight construction. The realistic GHG reduction potential in the long-term is around 5% according to Wärtsila.

A very preliminary indication of composite material cost at a ship level is in the order of 30 percent increase of hull costs [15].

Some extra emission saving could be attributed to this new concept when a complete life-cycle-analysis is undertaken because composites require less energy during production than steel.

Safety concerns are an important issue for the extensive use of composites where steel has been the standard for long time.

More practical experience will also be needed in building and exploiting this new type of inland ships.

Air lubrication

Viscous water resistance is very important for inland ships travelling at relative low speeds. This resistance can often amount to 80% of total resistance apart from resistance caused by imperfect streamlines and additional resistance caused by waves. Air lubrication could be a radical new way of reducing viscous water resistance. It has to be mentioned that this technique also requires energy investment for the production of compressed air. The energy required for production of compressed air has to be balanced against the fuel saved by lowering of resistance. Experiments have show fuel efficiency improvement of 17% [3]. According to Wärtsila in conventional seagoing ships saving of fuel consumption could be in the range of 3.5 to 15% [12]. In Japan tests were conducted with a ferry called "Misaki" with 34 devices called WAIP (winged air induction pipe). These tests have shown a fuel saving of 10% [16].

It is not known what the potential of this kind of new technology for inland shipping can be in the future. One important aspect is that inland ships are travelling with relative low speeds while the application tested on this technique seems to be much more effective at higher speeds [18].

Because this technology is still in development not much can be said about cost-effectiveness. It was mentioned by the Japanese that barnacle growth on the ship was impaired by this technology. This could lead to less paint maintenance [16].

As this technology is not to be considered as proven technology no indication of cost-efficiency in the long run can be given.

De Grave [3] ranks this technology under the chapter "future technologies"

Summary

Table 7 provides an overview of the above mentioned technical CO₂ abatement measures. Current reduction potential (on ship level) and an indication of current payback times are given respectively. It is important to note that the measures listed in Table 7 cannot be applied to all vessel types. Furthermore, if different measures can be applied to one vessel type, the GHG savings cannot necessarily be summed.

Table 7: GHG emissions reduction potential of the technical inland shipping options

Technical option	Current reduction potential on ship level where applicable	Current payback time
Powertrain		
More efficient engines	15 – 20%	> 10 years
Diesel-electric propulsion	10%	> 10 years
Reduction of required propulsion		
Larger units (economy of scale)	Up to 75% depending on difference in scale	No general conclusion possible
Improved propeller systems	20 – 30%	Short payback time
Improved hull design	10 – 20%	Short payback time
Computer assisted trip planning and speed management	5 –10%	< 1 year
Lightweight hulls	5-15%	> 10 years (experimental)
Air lubrication	10%	Unknown (experimental)
Whale tail/experimental propulsion systems	25%	Unknown (experimental)

There is no comprehensive European emission inventory for inland shipping since energy statistics don't provide relevant numbers for fuel consumption of inland navigation [21]. A representative average of the current emission factor of CO₂ for inland shipping in Europe could be around 40 tonnes of CO₂ per million tonne.km of goods transported (figure derived by author from [22]). In the EU-27 the total distance traveled on inland waterway transport was 141,000 million tonne kilometer in 2007 [21]. Consequently the total estimated CO₂-emission of inland transport will have been about 5.6 million tonnes of CO₂ in 2007.

Whilst average ships sizes are likely to have doubled in 2050, the energy consumption per unit of transport probably will be around 50% of the value in 2000. This enlargement is in line with historic development as been shown above. However transport demand could also have been doubled by 2050. Therefore, approximately 5-6 million tonnes of CO₂ could be abated by exploiting larger units in 2050. The progressive enlargement of ships sizes however is strongly dependant on investments in inland waterways infrastructure [14].

Depending on oil prices and many other factors about 30 – 50% extra abatement by a spectrum of technical measures could potentially result in an additional reduction of about 2 - 3 million tonne of CO₂.

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4 Technical Options for Maritime Shipping

4.1 Introduction

On a seafaring ship fossil fuelled engines generate both motive power and electric power for onboard equipment/facilities to, for example, run the control and navigation systems, to provide crew and/or passengers with lighting, ventilation, fresh water, air conditioning etc. Energy is lost in various areas. For example, engines release hot exhaust gases and propulsion is associated with transmission and propeller losses.

CO₂ emission abatement options aim to reduce these losses by reducing the energy lost in the first instance, through recovering these losses or by preventing losses from increasing over time. Technical abatement options are mainly related to the hull, the propeller, the superstructure of the vessel and the vessels' power and propulsion systems.

The options can either be retrofit or non-retrofit measures with the latter only being applicable to newly built ships. Since the lifetime of vessels is relatively high (about 30 years), retrofit measures are important to realise CO₂ reductions in the short-term and medium-term. Thus it is only in the long run that design optimisation will be effective. Therefore it is important to bear in mind that to realise a high reduction level in 2050, measures have to be implemented far earlier.

For the majority of measures there is still uncertainty as to the costs and the reduction potentials. Costs of the measures vary with the ship types and whether they are retrofitted or applied to a new ship. Cost data is often not available at all or only available for a certain ship type. The abatement potential varies with the ship types but also with the routes these take, as well as with the respective weather conditions. Thus long-term field tests on a large scale are needed to take account of these 'real world' conditions.

Note that this chapter is mainly based on the IMO study "Prevention of air pollution from ships" from 2009 [1] and on Wärtsilä (2008) [2]. The usage of alternative fuels to reduce CO₂ emissions will be covered in paper 2.

4.2 Overview of options

A list of the categories of the technical CO₂ abatement measures for maritime transport that are covered here are provided below. The individual options are specified further in the remainder of the chapter.

1. Hull
 - a. Design optimization
 - b. Hull retrofit measures
 - c. Reducing frictional resistance of (wetted) hull surface
2. Propeller
 - a. Optimization of propeller
 - b. Propeller upgrade
 - c. Recovery of propeller energy
3. Propulsion/engine
 - a. Engine upgrade
 - b. Recovery of engine energy
 - c. Alternative systems

4. Superstructure
 - a. Optimization of superstructure
5. Other abatement measures

4.2.1 Measures with respect to the hull

Optimisation of the design of a vessel's hull form aims to reduce resistance and to improve propulsive efficiency. Reducing the weight of the hull reduces the wetted surface area and thus the drag.

There are different forms of hull retrofit measures. Some measures, such as the insertion of a hull section, can only be applied to a small number of ships and are thus not considered further. What is being considered is adding grids to or optimizing the flow of transverse thruster openings. Another opportunity relates to the frictional resistance of a hull's surface, which can be reduced by various means, including air lubrication and hull coatings.

4.2.2 Measures with respect to the propeller

Optimisation of the propeller is achieved by increasing the diameter of the propeller and reducing the number of revolutions per minute. Ideally, the number of blades should be minimized to reduce blade area and frictional resistance [1]. The fuel consumption could be reduced by a propeller upgrade. This can either be the installation of a new propeller (IMO 2009, Appendix 2), an upgrade of the propeller-rudder combination or various smaller propeller upgrades such as the application of propeller tip winglets [2].

There are many different devices that aim to recover propeller energy losses, either by recovering part of the rotational energy in the flow from the propeller or by providing some pre-rotation of the inflow into the propeller. For example, with a Grim vane wheel, a freely rotating propeller installed behind the main propeller, part of the rotational energy is transformed into propulsive energy. [1].

4.2.3 Measures with respect to the propulsion/engine

The main engine of a vessel can be upgraded by tuning the engine or by making use of the common rail technology.

Energy can be recovered from exhaust or from the waste heat of the engine.

Alternative propulsion/engine systems could be used such as fuel cells. Also wind power can be used either by sails, towing kites or Flettner rotors (spinning vertical rotors that make use of the Magnus effect).

4.2.4 Measures with respect to the superstructure

The superstructure of a ship can be optimised to reduce air resistance. To this end retrofit and non-retrofit measures can be used. For example weld beats could be grinded or deck-houses could be designed in a more streamlined manner [1].

4.2.5 Other abatement measures

Other optimizations/upgrades can be carried out, most of them being related to the auxiliary systems. Solar power can be used to generate electric power. Using more electricity and heat-efficient lighting reduces the need for electricity and the demand for air conditioning [2]. Operating cooling water pumps at a variable speed according to the actual need reduces energy consumption [2]. Equally the speed control of fans can contribute to energy saving.

4.3 Assessment of measures

4.3.1 Measures with respect to the hull

Optimization of the design of the hull form

A 5%-20% fuel/CO₂ reduction is feasible for the optimisation of the behavior of the hull in still water. However performance in waves will differ significantly between ships. (IMO 2009, Chapter 5). For an “optimal main dimension” Wärtsilä gives a reduction potential on ship basis of 9% at most and the payback time is said to be very long, i.e. above 15 years [2].

It is almost impossible to quantify the abatement potential, on a world fleet basis, of applying hull and propeller optimizing procedures systematically [1]. The optimization of the hull form may be restricted by the dimensions of ports and terminals [1].

Reducing the weight of the hull

For a lightweight construction Wärtsilä gives a maximum reduction potential of 7% of the total energy consumption of the ship. The payback time is considered to be very short, i.e. less than a year. That said, the potential for reducing weight is restricted by the strength and safety requirements and how they are specified in design codes [1].

One barrier to the widespread usage of improvements in design is that designs may be patented. Furthermore, since performance of vessels in waves is not part of the standard test conditions one will tend to pay less attention to this performance. And finally, since the assessment of the performance of a ship at sea is challenging, it might not be easy to see the improvement stemming from optimisation [1].

Transverse thruster opening (optimizing flow, adding grids)

When the flow is optimised with respect to transverse thruster openings or grids are added, a reduction of 1-5% could be realized on ship level. Since this measure is broadly applicable, the total maximum abatement potential is also in that range. According to Wärtsilä the payback time is very short, i.e. less than year [2].

Reducing frictional resistance of (wetted) hull surface

According to Wärtsilä the reduction potential of “modern” hull coatings is up to 5%. More specifically, they give a saving (after 48 months compared to conventional savings) of about 9% for tankers and containers, of about 5% for pure car and truck carriers and of about 3% for ferries. They estimate the pay back time to be very short, i.e. less than a year [2].

Note that there are copper-based and silicon-based coatings available on the market. The latter are significantly more expensive than copper-based hull coatings [1] and only become fully effective at a minimum speed.

Coatings that are based on nanotechnology are being developed. The claimed reduction potential is largely unsubstantiated at present. In the future a reduction of 15% can be expected [1].

Since the number of dry docks is limited, coatings might not be applicable at the optimal point in time. Further, data from fleet management is not accurate enough to decide when maintenance is needed [1].

Air lubrication

It is claimed that the air cavity system provides reductions in resistance that are in excess of 5%, which is significant in this context [1]. According to the system manufacturer the reduction potential is 10-15% for tankers and bulkers and 5-9% for container vessels.

The system is only applicable to newly built vessels. It can be used by tankers, bulk carriers and container vessels with a minimum length of 225 metres. The total maximum abatement potential is estimated to be 1-2% in 2020.

Incremental non-recurring costs are about 2-3% of the price of the conventional newly built vessel. As to the operational costs, it takes 0.5 – 1% of the propulsion power to keep the air compression going. That translates into 0.3 to 0.5 tons of fuel per day.

Researchers from the Stichting FOM and the University of Twente in the Netherlands pointed out that the potential fuel savings of a system like the air cavity system highly depend on the smoothness of the hull. Good maintenance is thus required to actually realize the projected fuel savings.

As for the interactions with other measures, design and according retrofit measures will naturally not be applied to the same vessel. Reducing the frictional resistance of the hull surface by making use of better coatings however can be combined with all the other measures. Since for an air cavity system, which can only be applied to newbuilds the hull has to be, at least partly, flat, the hull form design is restricted in this sense.

Design optimization can be stimulated politically by a wide range of CO₂ regulations (e.g. tax, emissions trading etc.). More specifically, a design standard could be set, R&D could be subsidised, innovation prizes could be awarded. It is also worth noting that the IMO is working on an energy efficiency design index to relate CO₂ emissions to the design of vessels.

4.3.2 Measures with respect to the propeller

Optimization of propeller

High propulsive efficiency is obtained with a large propeller rotating at a low number of revolutions per minute. Ideally, the number of blades should be minimized to reduce blade area and frictional resistance [1].

The extent to which the diameter of the propeller can be increased is restricted by adequate clearance between the propeller and the hull and by the need for the propeller to submerge under any circumstances. Due to the latter restriction, propellers with large diameter are best suited for deep-draught ships like tankers, bulk carriers and general cargo vessels and less suited for container vessels, RoPax and cruise vessels.

For the reduction of the number of revolutions the installation of a reduction gear can be required in some cases.

The cost and the reduction potential for optimizing the propeller in the first instance (non-retrofit) are not known.

Propeller upgrade

If a propeller of larger diameter can be installed improvements may be in the range of 5-10% in fuel consumption. Such upgrades are appropriate for a limited subset of ships [1].

Upgrading a propeller/rudder by changing the rudder profile and the propeller can, according to Wärtsilä, lead to a maximum fuel saving of 4% at a ship level. The payback time is estimated to be medium (on a scale from below one year to more than 15 years). According to Wärtsilä the measure is not applicable to ferries [2].

Wärtsilä also states that the application of special tip shapes to the propeller (winglets) can lead to a maximum fuel saving of 4% at a ship level with a medium payback time. Winglets cannot be applied to RoRo vessels and ferries.

Advanced blade sections make propellers more efficient, leading to a maximum saving of 2% on ship level. The payback time is estimated to be less than a year [2].

Recovery of propeller energy

There are many different devices that aim to recover propeller energy, either by recovering part of the rotational energy in the flow from the propeller or by providing some pre-rotation of the inflow into the propeller.

This sub-section gives a brief overview of the reduction potential and the applicability as described by IMO [1]. Unfortunately, the literature only contained cost data for boss cap fins.

- Contra rotating propeller:
 - Reduction on ship level typically around 3-6%
 - Best results for fast cargo vessels, RoRo-vessels and container vessels
- Grim vane wheel
 - Improvements in power consumption are reported to be around 10%.
- Ducted propeller:
 - Power consumption reduced by 10% for tankers, bulk carriers, tugs and offshore supply and service vessels.
- Post-swirl devices:
 - Reduction potential of additional thruster and fins at the rudder on ship level: 8-9%
 - Reduction potential of boss cap fins on ship level: 4%
 - Can be applied to all new ships.

According to Frey and Kuo (2007) the cost of propeller boss cap fins are about \$20,000 for a 735 kW engine and \$146,000 for a 22,050 kW engine [3].

With regards the interaction of the measures, design and retrofit measures will not be applied to the same vessel. The different propeller upgrades and the different methods to recover the propeller energy will most probably not be combined. That said, a measure to recover the propeller energy could be combined with a propeller upgrade.

It is worth noting that the hull form is crucial for the working conditions of the propeller. Therefore hull and propeller optimization must be undertaken in a single process.

4.3.3 Measures with respect to propulsion/engine

Engine upgrade

Applying common rail diesel technology will lead, according to Wärtsilä, to a fuel saving of a maximum of 1% at a ship level. The payback time is estimated to be relatively short (on a scale from below one year and more than 15 years). For engine tuning Wärtsilä gives the same potential saving. Here no indication of the payback time is given. It cannot be applied to ferries [2].

Barriers to engine upgrades are the significant engineering work that has to be undertaken for the design of the upgrade (and thus the cost) and the fact that they are best applied to older engines that have a shorter residual life time [1].

Recovery of engine energy

Energy can be recovered from the exhaust gases or from the waste heat produced by the engine. Different technologies are used to recover energy from diesel and gas-fuelled engines. Gas engines offer a higher potential for energy recovery. Heat recovery systems are better suited for low-speed than for medium-speed diesel [1].

According to Wärtsilä, at a ship level the energy saving potential of waste heat recovery is up to 10% and the payback time is medium (on a scale of less than 1 year and more than 15 years).

Barriers to installing a thermo efficiency system include the size, the weight and the complexity of such systems. An installation is optimized for a single operating point, with the power production rapidly decreasing at other loads [1]. Steam cycles as a means of energy recovery, have some properties that are quite challenging on board a ship (IMO 2009, Annex 2).

In the IMO report Organic Rankine Cycle systems are judged to be an interesting forthcoming development, leading to a significant impact on the gain in the engine efficiency. The reduction potential and the costs are not specified [1].

Fuel-cell propulsion

With the help of fuel cells electricity can be produced, which can be used directly or to power electric engines. Fuel cell vehicles are either directly fueled with gaseous or liquid hydrogen or fueled with hydrogen reformed from gasoline, methanol or other sources. (EPA, 2002) Fuel cells can also be used for hybrid propulsion by combining them with diesel engines. Fuel cells themselves have high potential thermal efficiency and low emissions. Fuel cells use non-conventional fuels, like for example hydrogen or hydrocarbons such as methanol, and/or require significant treatment of the fuel. Production of hydrogen from hydrocarbons is an energy intensive process. That said, fuel cells have been identified as particularly promising power generators for ship hotel power and for (hybrid) propulsion systems [1]. However, costs are high at the moment:

As a result of the Zemships project a 100-passenger capacity fuel cell ship has been developed. The project attracted 2.4 million Euro by the way of European funding, with the partners involved contributing a further 3.1 million Euro. (The Naval Architect, 2008c) A fuel cell passenger ferry is being developed and built in the Netherlands. Here development and building costs are reported to be about 2.9 million Euro [4].

Apart from the costs there are other investment barriers: reliability, excessive weight and volume, safety of onboard storage and handling the fuel [1] and a high administrative effort to get approval. Further R&D priorities include:

- Development of fuel processing systems for fuel-cell units capable of running liquid fuels;
- Standardization of fuel-cell systems; and
- Development of intrinsically safe systems for onboard storage of fuel and fuel handling [1].

Sails

There are various rigid and soft sail designs that can lead to energy and emissions savings in maritime shipping. In 2007 the Technische Universität Berlin carried out a simulation for a product tanker and a bulk carrier. The simulation considered different rigid and soft sail designs for standard routes and made use of the ERA-40 database on wind speed, wind direction and significant wave heights. The savings vary with the speed of a vessel and the route taken. The average savings of the different sail types at 10 knots turned out to be 16-26% for the product tanker and 11-20% for the bulk carrier. At 15 knots this reduces to 5-7% for the product tanker and 5-8% for the bulk carrier. Route optimisation leads to higher savings. Cost data is not given for the sails [5].

Towing kites

According to the producer the reduction potential of a towing kite on average 10-35%. A towing kite can be used on vessels with a minimum length of 30m and works best on ships with an average speed no higher than 16 knots. In view of this speed restriction, tankers and bulk carriers lend themselves to the technology when considering the merchant fleet. The total maximum abatement potential is estimated to be 3-8% in 2020.

The purchase price of a kite is 480,000-3,400,000 \$U.S. and varies with the kite area (160 – 5,000 m²). Installation and operational costs can be assumed to be a certain share of the purchase price. Installation costs are 5-10% of the purchase price depending on whether the kite is retrofitted or applied to a new vessel. The operational costs, including replacements during the life time of vessel, are 5-15% depending on the kite area.

The disadvantages of a kite system are the complexity of the launch, recovery and control systems that are needed. The durability of the lightweight material is also a challenge.

Flettner rotors

According to Greenwave [6], 3 rotors on Handymax bulk carrier would achieve 12-14% fuel saving. According to Wärtsilä the maximum saving at a ship level is 30% [2]. The rotors can, according to Greenwave, be applied to any vessel type, as long as there is no interference with the operations that take place onboard [6]. Container vessels are thus not suitable. There is no cost data available. Stowage of the rotors is not solved yet but the idea is to develop a telescope mechanism.

As for the interaction with other measures, different engine upgrade measures could be combined. Recovery of the engine energy can be applied to both, conventional and alternative propulsion systems (e.g. fuel cells). Some alternative propulsion system could be combined, such as propulsion systems making use of solar and wind power. Others however will in all likelihood not be applied together. For example, different measures that use wind power might interact in an undesirable way, constituting a security hazard for a ship.

4.3.4 Measures with respect to the superstructure

Optimization of the superstructure

For ships with large superstructures and for ships operating at relatively high speeds the reduction potential is estimated to be 2-5%. For other ships there is a potential in the order of 1-2%. The main barriers are the requirements for and the usage of covered spaces [1]. Different measures that optimize the superstructure can be combined and these will not constrain the applicability of other measures.

4.3.5 Other abatement measures

Solar power

Current photovoltaic cells have an efficiency of about 13%. Therefore on average current solar-cell technology is only sufficient to cover a fraction of the auxiliary power [1]. The reduction potential differs per ship type, since the area to place solar panels varies. Wärtsilä estimates 3.5% for tankers at the ship level, 2.5% for a pure car and truck carrier and 1% for a ferry [2]. Current best-available technology has an efficiency of about 30%, which is expected to increase to 45-60% is expected in the long-run. Photovoltaic cells as a partial source of power, especially if combined with (or even integrated into) sails could thus be of interest in the long-run [1].

It is important to note that back-up power is needed when making use of solar power, unless an energy storage system is available on board [1].

Solar panels can be used on vessels where enough space is available on deck. Solar power is therefore not an option for container vessels.

The technology is very expensive at the moment. There is, for example, a solar-power-assisted cargo vessel (Auriga Leader) equipped with a 40 kilowatt solar generation system (328 panels) that is connected to the onboard electrical network [7]. Costs for development and installation are said to be about 1.4 million U.S. \$ [8].

Research is currently being undertaken to enhance the life time of solar panels, given the conditions they face on ships: shaking/vibration, wind pressure, contact with sea water [9].

Electricity and heat efficient lighting

Electricity and heat efficient lighting is best suited for ferries, RoPax and cruise vessels where auxiliary power demand is very high. The reduction potential is relatively low, between 0.1 and 0.8% on ship level. Total reduction potential is about 0.6% in 2020 when looking at the IMO fleet forecast. Wärtsilä reports a medium payback time (with short pay back time being <1 year and a long payback time being > 15 years) [2].

Controlling the speed of pumps and fans

Controlling the speed of pumps and fans leads to a rather small reduction on ship level, i.e. about 0.2-1%. Since the option can widely be applied, the total reduction potential is of the same magnitude. According to Wärtsilä, there is a medium payback time (with a short payback time being less than a year and a long payback time of more than 15 years) [2].

The different "Other abatement measures" could be combined. The use of solar power could, as mentioned above, even be combined with the use of wind power (integrated into sails).

4.4 Policy instruments

There is a wide range of political instruments that can give an incentive to enhance the efficiency of a vessel. A tax could be levied on the CO₂ emissions or on the bunker fuel consumption, an emissions trading scheme could be established, technical standards could be prescribed, harbour- or fairway-dues can be differentiated according to the CO₂ emissions, research and development could be subsidised or R&D prizes awarded.

It is worth noting that the IMO works on the definition of an energy efficiency operational index and an energy efficiency design index (for new ships only), to be able to classify the ships according to their CO₂ emissions. These indices could be the basis for most of the above-mentioned instruments.

4.5 Summary

Table 8 gives an overview of the aforementioned technical CO₂ abatement measures. Current reduction potential (on ship level) and current payback time are given respectively.

Table 8: GHG emissions reduction potential of the technical maritime shipping options

	Current reduction potential on ship level where applicable	Current payback time
Hull		
Design optimization		
Hull form	5 – 20% in still water	Long payback time.
Weight reduction	< 7%	Very short payback time.
Retrofit		
Transverse thruster opening (grids, optimization of flow)	1 – 5 %	Very short payback time.
Surface (reduction resistance)		
Hull coatings	< 5%	Very short payback time.
Air cavity system	10 – 15 %	Very long payback period.
Propeller		
Design optimization	?	Long payback time
Upgrade		
Installation of new propeller	5 – 10%	Unknown
Propeller/rudder upgrade	< 4%	Medium payback time.
Upgrade w.r.t. old propeller	2 – 4%	Short/medium payback time
Recovering energy	5 – 10%	Short/medium payback times
Propulsion/Engine		
Engine upgrade	1 – 2%	Short payback time
Recovery energy	< 10%	Medium payback time.
Alternative systems		
Sails	10 – 25 % at 10 knots	Unknown
Towing kite	10 – 35% at 10 knots	Medium/long payback time.
Flettner rotors	?	Unknown
Fuel cells	0 - ? %	Very long payback time.
Superstructure	1 – 5%	Unknown
Other abatement measures		
Solar power	?	Very long payback time.
Others	< 2%	Medium payback time

As mentioned above, the different measures cannot be applied to all vessel types. It is therefore difficult to get an overall picture of the reduction potential for the maritime shipping sub-sector from this table.

An indication of the total maximum abatement potential of these technical measures can be derived from IMO [1]. For 2020 the maximum CO₂ abatement potential is estimated here to be in the range of 210 – 440 Mt. This corresponds to about 15 – 30% of the predicted CO₂ emissions of the global fleet in 2020 [10]. Since mainly retrofit measures are being considered, the maximum abatement potential of the above listed measures can be expected to be higher. However, the estimation also takes operational measures into account, leading to an overestimation of the abatement potential of the technical measures above.

The cost efficiency of the measures is highly dependent on the underlying bunker oil price and interest rate. For a bunker fuel price of 500\$/metric ton and an interest rate of 4% a large part of the total emission reduction comes at negative costs in the study regarding the retrofit measures. That means that the fuel expenditure savings exceed the costs for reducing the emissions. Since operational measures turn out to be very cost effective, compliance costs will increase when focusing on technical abatement options only.

Giving an estimation of the reduction potential and the costs of the abatement measures for the year 2050 is very difficult and no information can be found in the literature. Of course, the costs of the technologies that are not yet fully mature (solar power, engine energy recovery with organic rankine cycle, fuel cells, coatings based on nanotechnology) can be expected to reduce due to learning effects, but there is still much uncertainty regarding the likely costs and abatement potentials of the measures in the long term.

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5 Technical Options for Aviation

In a similar vein to the rail sector, there are a number of generic challenges associated with making GHG emission reductions in the aviation sector. Many of these challenges cut across a number of technical options. For instance, aircraft often remain in service for 30 years or more. Therefore, many new technologies can only ever be phased in over a lengthy period. In addition, the aviation sector is rightly very risk averse in terms of implementing any new technology. Whilst aviation actually has a better safety record than most other modes of transport, technical failures can prove more catastrophic. The stringent tests than any new technology is subjected to can act as a barrier.

Weight considerations and power density can also be a factor in the aviation sector, in view of the payload limitations. Whilst not directly relevant to this paper, poor power density is one of the reasons why hydrogen fuel cells are not currently suitable for powering aircraft.

Despite these issues there is a broad range of research being undertaken to reduce the emissions of GHGs from the aviation sector. This research is being undertaken against a background of ambitious GHG reduction targets. For example, The Advisory Council for Aeronautical Research in Europe's (ACARE) targets for aerospace manufacturers include a 50% reduction in CO₂ emissions by 2020 relative to their year 2000 counterparts. Manufacturers have committed to delivering 20-25% of the target through airframe improvements.

For 2050, it is suggested (Greener By Design, 2007) that use of technical, operational and design measures could reduce world fleet emissions per passenger kilometre by factors of 3 for CO₂, 10 for NO_x and 5-15 for contrails and cirrus cloud.

However, other researchers point out (Bows and Anderson, 2006) that while these measures may make an important contribution, forecast passenger growth will mean that aviation's contribution to climate change is still a concern.

Research and development relevant to these targets is outlined below.

5.1 Overview of options

5.1.1 Use of propeller engines (open rotor / turboprops)

Propeller engines have a higher bypass ratio than turbofans or turbojets for an equivalent-sized device. In addition, unlike traditional engines they do not have a casing (which increases weight and drag) around the propeller. Fuel burn and hence CO₂ emissions can therefore be significantly less in propeller engines than in a conventional turbofan engine.

While these propeller engines are, to some extent, existing technologies, advancements are also being made. Open rotors proposed for new single aisle aircraft (Boeing 737/Airbus A320 replacement) will not be conventional turboprops/propfans but will instead incorporate new technologies.

5.1.2 Advanced aircraft materials

Advanced material can play a crucial role in reducing the environmental impact of aviation. Advanced materials currently being investigated and developed include composites, ceramics, advanced metal alloys, nanomaterials and smart materials. Materials that are high strength whilst being light weight, have improved temperature capability or are more adaptive, can all help reduce fuel burn and emissions.

5.1.3 Improved aircraft design

The main opportunities for reducing fuel burn and emission through aircraft design are discussed in more detail below.

Winglets

Winglets are devices which increase the lift generated at the wingtip (by smoothing the airflow across the upper wing near the tip) and reduce the drag which causes vortices to occur at the wing tip. The lift to drag ratio is therefore improved, increasing fuel efficiency and reducing emissions.

Reduced aircraft weight

Reduced aircraft weight can be achieved through the use of advanced lightweight materials, structural optimisation, advanced and adaptive load distribution systems, new manufacturing techniques and weight reduction of internal furnishings and aircraft systems.

Reduced profile drag

Reduced profile drag can be achieved through improved shaping and integration, laminar flow technology, riblets, and electric aircraft systems.

Improved shaping and integration

Improved shaping of aircraft components; better integration of lifting and control surfaces (flaps and ailerons) and completely new aircraft configurations, can help to improve the aerodynamics of the aircraft in order to maintain, thinner, smoother boundary layers along the aircraft surfaces.

Laminar flow technology

Laminar flow technology (reduced airframe drag through control of the boundary layer) can provide additional aerodynamic efficiency potential for the airframe, especially for long-range aircraft. This technology extends the smooth boundary layer of undisturbed airflow over more of the aerodynamic structure, in some cases requiring artificial means to promote laminar flow beyond its natural extent by suction of the disturbed flow through the aerodynamic surface. The two types of laminar flow control are passive and active. The surface is designed to ensure that pressure decreases in the flow direction in passive control, whereas active control involves the use of suction or surface cooling to maintain laminar flow. IATA (2009) anticipates that the most significant aircraft efficiency gains are expected from, amongst others, natural and hybrid laminar flow, which are candidates for use in new aircraft types by 2020.

Riblets

Riblets are sections of finely corrugated plastic skin that can be bonded to the aircraft surface. They work by weakening the eddies that cause turbulence thereby reducing the profile drag (although the use of riblets may result in increased maintenance issues). In some cases the use of riblets can potentially reduce drag by around 2%.

Electric aircraft systems

A mixture of hydraulic, electric and pneumatic power typically powers aircraft systems. With carbon emissions in mind, electric systems are a better alternative than hydraulic or pneumatic systems since they offer reduced weight, reduced fuel consumption, and increased efficiency.

5.1.4 New aircraft design

Novel and innovative aircraft designs are also being investigated. These include:

Blended wing-body (BWB) aircraft (flying wing)

A Flying Wing (FW) aircraft concept is designed to maximise the efficiency of passenger transport thereby minimising fuel consumption. In blended wing-body aircrafts the fuselage and wings of the plane are blended to form a continuous surface. The shape means that the entire upper surface produces lift, whilst the reduced surface area leads to a reduction in drag.

The Flying Wing aircraft concept⁸



Source NACRE (2008)

Pro Green aircraft

The Pro Green concepts use forward swept wings that are designed such that a smooth layer of air is created on the aircraft wings (passive laminar flow). This should reduce the profile drag, resulting in reduced fuel burn (Frota,2006).

The Pro Green (PG) aircraft concept



Source NACRE (2008)

Wing-in-ground effect vehicles (WIGS)

Wing-in-ground (WIG) effect vehicles are aircraft that can attain level flight near the surface of the Earth, usually travelling just above the surface of the sea. The WIG effect is able to keep aircrafts in flight due to a cushion of high-pressure air created by the aerodynamic interaction between the wings and the surface known as ground effect.

5.1.5 Alternative approaches - Airships

An alternative approach to the problem of reducing the climate impact of aviation is to look at entirely different methods of air transportation. One such suggested form is the airship, with modern designs using helium rather than hydrogen.

5.2 Assessment of measures

5.2.1 Use of propeller engines (open rotor / turboprops)

Open rotors are predicted to provide a 25% - 30% reduction in specific fuel consumption and CO₂ emissions relative to current, equivalent turbofan engines (SBAC, 2008a). Easyjet predicts that the ecojet, which is to be powered by open rotor engines, has the potential to deliver CO₂ and NO_x emission reductions of 50% and 75% respectively, and a 25% reduction in noise, compared to current Boeing 737 and Airbus A320 variants.

Concept designs such as the Easyjet ecojet have been produced. Engine manufacturers such as Rolls-Royce have begun work on open rotor engine designs for the next generation single aisle aircraft. It predicts that by 2013 the open-rotor concept will be sufficiently mature for the anticipated performance benefits to be confirmed and that engines will be available between 2015 and 2020 (Barrie et al, 2007)⁹. Academic studies such as the OMEGA 'Integrated study of advanced open rotor' powered aircraft are also underway. Further detailed research and development into open rotor engines will be undertaken by engine manufacturers, through research and technology validation programmes such as DREAM and the CLEAN SKY Joint Technology Initiative, both of which commenced in 2008.

The greatest challenge facing the use of open rotor engines is their noise impacts. Whilst some researchers claim that open rotor powered planes will be quieter than the aircraft they replace¹⁰, they will produce more noise than advanced turbofan aircraft. Therefore, there is likely to be a trade-off in the future between noise and GHG emissions. Other challenges associated with open rotors include aircraft integration, certification requirements (blade off), accessibility and maintenance. That said, these issues can be overcome. For example, while the large propeller diameters (~4m) prohibit the use of open rotor engines on most existing aircraft because they will not fit within the dimensional limits of the wing and landing gear. However, close coordination between aircraft and engine manufacturers from design conception to product delivery, which has already started, will help to ensure designs effectively address such issues.

In addition, with open rotors aircraft speed is reduced below typical jet aircraft speeds as a consequence of propeller tip speed limits. Therefore this technology may be more appropriate for short to medium haul operations where speed may be less important. For example, the increase is less than 10 min for a 2-hour flight.

¹⁰ <http://www.flightglobal.com/articles/2009/03/23/324074/open-to-persuasion-how-researchers-aim-to-quieten-tomorrows-aircraft.html>

5.2.2 Advanced aircraft materials

Developing materials with enhanced temperature capability will allow the engine to run at a hotter temperature, improving the engine's thermal efficiency, reducing fuel burn and emissions.

Composites

Composites benefits include high specific strength, ability to resist fatigue, withstand temperature extremes and manufacturability. The use of composites, for example in the Boeing 787 aircraft (that has yet to enter service), could reduce fuel consumption by 20% below that of the aircraft the B787 will replace. For the near term, lightweight composite materials for the majority of the aircraft structure are beginning to appear and promise significant weight reductions and fuel burn benefits. Aircraft manufacturers are progressively increasing the amount of composite material used in the airframe and in aircraft systems.

The biggest drawback associated with composites is their high cost. However, with the use of certain processes and technologies composites can be cost competitive or even lower costs than their metallic equivalents. Furthermore, as manufacturers improve production efficiency, this technology matures and the industry acquires more experience with it, there will inevitably be further opportunities for cost reduction.

In addition, finding a way to safely and efficiently recycle composites is an environmental challenge facing the industry.

Metal Alloys

Titanium, nickel and steel alloys are commonly used for engine components and aluminium and titanium alloys are used for airframe components.

One of the main advantages of metal alloys compared to composites is the lower investment cost; they do not require the high capital investment in fabrication facilities needed for composite manufacture. Metal alloys have a higher damage tolerance than composites which is particularly important for certain airframe structures like the lower wing surfaces (Joshi). Although some further temperature and strength capability may be achieved with metal alloys, the challenge of improving the already highly refined heat treatments, processing and alloying techniques together with the high cost of raw materials means that the aerospace industry is also dedicating significant effort to investigating other options such as ceramics.

Ceramics

Ceramic components can have a brittleness that results in significant issues over their manufacture and use.

Ceramic matrix composites (CMCs) show more promise, since this brittleness is reduced. Benefits (SBAC, 2008b) of CMCs over metals include increased temperature capability, and reduced weight. However there are a number of technical challenges still to overcome. These include: high manufacturing cost and the fact that joining methods like welding cannot be used. Demonstration of CMC's is currently underway on some military aircraft, and Rolls Royce has designed and tested some static CMC components and anticipates that incorporation of rotating components is ten years away.

Nanomaterials

There are many possible aerospace applications for nanotechnology including enhanced structures, modified surfaces and coatings, new sensor and manufacturing technologies.

Nanocomposites, composites in which there is nanoscale separation between the reinforcement and matrix, are one type of nanomaterial being developed by the aerospace industry.

Barriers include the stability and cost of the material and issues associated with scaling up processes for production capability (including cleanliness, quality and consistency). However, the level of effort being expended in this area by the US, Japan and in Europe means that significant advances into nanomaterials can be expected in the next decade (Hicks and Thomas).

Smart Materials

Smart materials are materials that have properties such as viscosity, volume, conductivity or colour that can be dramatically altered by changing the conditions they are subject to. Examples of external stimuli that cause smart materials to alter include changes in loading, temperature, moisture, electric or magnetic fields. Potential aerospace applications for adaptive smart materials include changing the form of the aircraft wing to minimise drag and fuel burn, and altering the shape of the engine exhaust nozzle for optimal performance in all operating conditions.

ADVACT is a €6.6 million, five-year programme. The collaborative effort, which is led by Rolls-Royce and involves sixteen organisations from six EU countries, is developing adaptive technologies in order to optimise the performance of components over all flight conditions. Engine exhaust nozzles made from shape memory alloys are an example of one mechanism that has been developed through ADVACT. With this technology, the area of the nozzle can be varied for optimum exhaust flow characteristics in different flight conditions, with reduced weight and mechanical complexity compared to current variable area nozzles.

5.2.3 Improved aircraft design

Winglets

Winglets can offer GHG and fuel savings of 4% to 6% (Flightglobal, 2008) (for example when used on the a 737). These fuel savings also enable greater range, which can bring more destinations into reach. However, it should be noted that winglets are only a retrofit solution. Many new aircraft incorporate 'raked' wingtips that are more structurally efficient than winglets.

Winglets are currently being introduced. Southwest have order for 170 blended winglet sets to retrofit on its 737-700s and have also specified them for future new build aircraft. Ryanair has arranged for refits and new aircraft deliveries will have factory-installed winglets. American Airlines is using blended winglets, having ordered them for 77 737-800s and 104 757-200s as well as for the 767.

In terms of barriers there are concerns over the long-term performance and that repeated flexing could break down the bonding between the winglet and the rest of the wing (Marks, 2009).

In terms of research programmes the Advanced Wing with Advanced Technology OpeRation has studied and tested new, enlarged winglets (13.5 ft long and 6.5 feet wide).

Improved shaping

Limited information on the GHG savings associated with improved shaping on aircraft savings and better integration of lifting and control surfaces could be found.

For new aircraft configurations readers are directed to Section 5.3.4..

Laminar flow

Studies on laminar flow suggest that fuel burn could be reduced by between 10% and 20% for suitable missions (Braslow, 1999). Further sources corroborate these figures – the application of hybrid laminar flow control to the fin, tail, plane wing and nacelles of a medium range aircraft is predicted to deliver a fuel burn reduction of ~16.5%. A range of studies have identified a 20 to 35% emissions reduction for new aircraft in 2020 compared to predecessors, achieved mainly from the engine type and the use of laminar flow (hybrid laminar flow – 10-15%; natural laminar flow – 5-10%) (IATA, 2009).

Long-term technical and economic viability has yet to be proved, but have been the subject of research work in recent times.

Riblets

Applying riblets to 75% of the surface of an A320 showed a reduction of in draft of ~ 2%. However, the use of riblets may result in increased maintenance issues (e.g. possible lifting of edges and reduced ability to carry out structural inspections for cracks).

Electric aircraft systems

The power take-off takes at the engine from all the aircraft systems are typically responsible for 3-5% of the total power produced by the engine. Through the development of aircraft with increased use of electric systems the power requirement can be significantly reduced, enabling lower GHG emission and fuel burn.

These systems are at the research and development stage. Programmes taking this forward include Power Optimised Aircraft (POA). The POA aimed to validate, at aircraft level, the ability of next generation aircraft systems to: reduce total fuel consumption by 5% and reduce peak non-propulsive power by 25%. Results from this programme are being developed further by the More Open Electrical Technologies (MOET) programme. MOET is a three year programme with a budget of around 70 million euro and aims to establish a new industrial standard for the design of commercial aircraft electrical systems. Outcomes include a 2% reduction in fuel burn, a \$15 per flight reduction in maintenance costs and a reduction in unexpected delays due to system faults.

5.2.4 New aircraft design

Blended wing

The blended wing body (flying wing) is not a new concept and potentially could offer significant fuel burn reductions: estimates suggest 20-30% compared with an equivalent sized conventional aircraft (IPCC, 2007, Greener by Design, 2001; Leifsson and Mason, 2005). The benefits of this tailless design result from the minimised skin friction drag, as the tail surfaces and some engine/fuselage integration can be eliminated. Its development for the future will depend on a viable market case and will incur significant design, development and production costs. IATA (2009) reports that the new generation of Boeing 737 uses this technology. Blended wing technology also has the benefit of reduced noise on takeoff and approach, and reduces emissions through lower cruise thrust.

The European Commission regards the BWB concept as a development to be pursued in place of supersonic or near-sonic aircraft, and the concept has been positively explored in the UK by the aviation industry's Greener by Design Steering Group.

Blended wing design will benefit from the Integrated Wing Aerospace Technology Validation Programme (Integrated Wing, 2009). The first phase runs from 2006 to 2009 and brings together

leading UK organizations with the objective of integrating and validating the most promising combination of technologies related to the development of wings, wing systems, landing gear and fuel systems. After completing Phase 1, the intention is to go on to develop a large-scale physical demonstrator in a second phase.

Some of the challenges associated with the BWB concept include maximizing aerodynamic efficiency and cabin space/ comfort simultaneously and evacuating the passengers from such an aircraft within the required timeframe for certification. It is also likely that the BWB concept will be applicable only to relatively large aircraft.

Nevertheless, given the long service lives of aircraft, it would be many decades before BWB aircraft were able to approach their maximum contribution to air travel (RCEP, 2002).

Pro Green Aircraft

The PG concepts aim to achieve a fuel burn reduction of 25% per seat per km and a noise reduction of 10 dB per operation relative to year 2000 aircraft. Detailed definition of the engines for the two Pro-green aircraft concepts has been undertaken. The baseline wing configurations have also been defined and assessed. The PG concepts use forward swept wings that are designed such that a smooth layer of air is created on the aircraft wings (passive laminar flow). This should reduce the profile drag, resulting in reduced fuel burn. It should be noted that Greener By Design (2001) suggest that laminar flow wings with a turbofan and laminar flow wings with unducted fan engine could offer fuel burn reductions of 53% and 60% respectively.

Challenges associated with the PG concepts include the integration and noise issues associated with tail-mounted engines.

Some multi-disciplinary studies to assess how much shielding of engine noise propagating towards the ground during take-off and landing can be achieved have now been completed. These have involved the design, manufacture and test of a model representative of the engine sources in a major wind tunnel facility.

The Pro Green concept is being developed as part of NACRE – a four year 30.3 million euro programme that involves 36 EU partners.

Wing in ground

WIG technology has been developed over the last 40 years but has yet to reach mainstream maturity. Examples of WIG technology include the SC-32T and the Pelican aircraft.

Due to the marine nature of WIG boats their operating costs are low compared to aircraft. WIG boats can fulfill the need for increased speed of marine transport and may thus fill the gap between shipping and aviation. WIG boats achieve high speeds while maintaining high efficiency, and ride smoothness especially when compared to other high speed marine craft.

The infrastructural requirements for WIG boats are very low, any existing port is sufficient. However, they cannot operate without ground effect meaning that a vehicles operating height is restricted by its wingspan.

Potential barriers include that WIG boats are sensitive to weather conditions such as wave height and wind speed. In addition, small WIG boats are less efficient than big ones and are even more sensitive to weather conditions (Wig Page, 2009).

Flying close to the surface of water will not require sever ditching in the case of an emergency, however there are dangers associated with low flying, particularly if a craft banks too low on one side.

5.2.5 Alternative approaches - Airships

Airships have been identified (Windischbauer and Richardson, 2005) as being better suited to certain trips such as surveillance, airborne early warning and long tourist than aeroplanes and helicopters. The main issues with airships are their manoeuvrability difficulties in wind, particularly during the loading and unloading stages.

However, while a cargo lifter has been designed – the Skycat by Airship Technologies Group (UK) (Windischbauer and Richardson, 2005), to date no successful cargo lifter has been built. With the latter the company has become insolvent as of July 2005, illustrating the economic difficulties of making the technology a reality (Bows et al, 2006).

5.3 Summary

A summary of the reduction potential for the different technology options is provided in Table 9. It should be noted that most of these technologies would only apply to either retrofits of existing aircraft or new aircraft, not both. Therefore, the reduction potential's should not be summed to arrive at a total reduction potential.

Table 9: GHG emissions reduction potential of the technical aviation options

Technical options	Current GHG reduction potential
Open rotors	25-30%
Advanced aircraft materials	
Composites	20%
Winglets	4-6%
Laminar Flow	10-20%
Riblets	2%
Electric Aircraft systems	2-5%
New aircraft design	
Blended wing	20-30%
Pro-green aircraft	25%
Wing in Ground	Information not available
Alternative approaches	
Airships	Information not available

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