TOPIC PAPER #28

TRANSPORTATION EFFICIENCY

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy,* also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

NATIONAL PETROLEUM COUNCIL

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Technologies for Transportation Efficiency

Transportation Efficiency Subgroup

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I. Executive Summary

A. General Overview

This report identifies technologies that have the potential to reduce petroleum fuel demand for the five subsectors of transportation (light-duty vehicles, heavy-duty vehicles, air transport, marine shipping, and rail transport) between now and 2030. The report lists hurdles and possible actions for overcoming the hurdles, but does not attempt to predict which technologies will be adopted.

Over time, new technologies will enter the marketplace if one or more of the following occur: 1) the technologies mature and costs decrease, 2) fuel costs increase and remain high, 3) the technologies are valued by the consumer or 4) policies encourage adoption of improved technologies.

Government and industry play an important role in filling and maintaining the technology pipeline for transportation efficiency, can encourage academic research in high-profile transportation technology areas such as advanced batteries and bio-based fuels, and can encourage students to enter engineering, science, and mathematics professions to work on these challenging issues. In addition, increased funding of R&D increases the number of breakthrough concepts that can be pursued, making the odds more favorable for successful commercialization.

The various modes of freight shipment have much different energy requirements on a ton-mile basis, as do the various modes of passenger travel (automobiles, buses, trains, and aircraft). Policies that encourage efficient use across transportation subsectors were not addressed in this report, and the cost, benefits, and hurdles of these should be studied further.

Finally, alternative fuels have a generic impact across all of the subsectors by displacing some petroleum-based fuel, but have little impact on reducing the energy demand (e.g. BTUs per mile) for a subsector. Hydrogen—when used as an energy carrier in fuel cells—and electricity in plug-in hybrids or battery electric vehicles, result in higher efficiency than existing technologies. Infrastructure requirements and the energy required to produce the fuels need to be considered for these alternatives (e.g. well-to-tank assessment).

U.S. fuel demand for the five transportation subsectors is shown below (Table IA.1). It is based on EIA projections and is defined as the Reference Case in this report.

Sector	**2005**	**2030**	**2005**	**2030**
	Demand (Quad BTU/yr)		Percent of Transportation	
Light-duty vehicles (LDV)	16.28	22.98	61.6	60.5
Heavy-duty vehicles (HDV)	5.65	8.73	21.3	23.0
Air transport	2.81	4.15	10.6	10.9
Marine shipping	1.06	1.12	4.0	3.0
Rail transport	0.67	0.97	2.5	2.6
Total	**26.47**	**37.95**		

Table IA.1. EIA Reference Case - U.S. transportation fuel demand.

B. General Conclusions

Technology can make a significant impact in improving transportation efficiency. The light-duty vehicle sector has the greatest opportunities, but also has a number of challenges. Technology hurdles, costs, and potential infrastructure investments are some of these. In addition, the complication of consumer preferences impacts the deployment of technology. For the other sectors, a sound business case impacts the deployment of technology, including fuel cost savings and operational factors.

It is important that all of the technologies are analyzed from a "wells-to-wheels" efficiency and cost basis. This was not done by the subteam, since the focus was on transportation efficiency at the point of end use (excluding fuel availability, production, and distribution issues). As such, many of the learnings will require further analysis by the Demand and Supply Teams.

It should be noted that, although the technologies discussed below are analyzed from a U.S. perspective, the technologies themselves are generic and can be applied in all parts of the world, when the appropriate attributes and constraints are considered for the specific countries of interest.

C. Light-Duty Vehicles

The EIA reference case projects that in 2030, technology improvements will result in ~13% improvement in new vehicle fuel consumption (BTUs per mile) from 2005 levels. EEA estimated that this included technology improvements of ~30% at constant vehicle performance, and vehicle attribute changes that reduce this improvement by about half. Based on this study's analysis, technologies (drive-train and body improvements, and hybridization) exist, or are expected to be developed, that have the potential to reduce fuel consumption of new light-duty vehicles by 50% relative to 2005 vehicles. This assumes constant vehicle performance and entails higher vehicle cost. The extent to which these technologies translate into reduction in fuel consumption depends on factors not evaluated in this study, including customer preferences, vehicle and fuel costs, and vehicle attributes (acceleration, weight, and size). Improvements beyond 50% will require breakthroughs in batteries or fuel cells, resulting in significantly higher vehicle costs and potentially significant infrastructure investments. Technologies such as hybrids and fuel cells will take longer to deploy in the fleet than more conventional changes (e.g. improved fuel injection or turbo charging). Hydrogen for fuel cells would displace petroleum-based fuels. However, the source of the hydrogen, costs, technical hurdles, and infrastructure requirements are major unknowns and it is difficult to estimate the impact of fuel cells in 2030.

D. Heavy-Duty Vehicles

Technologies exist to reduce new heavy-duty truck fuel consumption by 15 to 20% in the USA by 2030, which is about equal to the EIA reference case. These technologies (e.g. engine efficiency, rolling resistance, and aerodynamic improvements) will involve higher cost and require an associated financial business case. Operational improvements such as reduced idling and improved logistics can provide a benefit of 5 to 10% across the fleet during this period. Advanced technology solutions, such as hybridization and fuel cells, offer fuel consumption reductions of an additional 25%, and applications would likely be initiated in local delivery, short-haul, medium-duty delivery trucks and buses. In the near term, U.S. heavy-duty emission standards will limit the potential to reduce fuel consumption.

E. Air Transport

Fuel consumption improvements on the order of 25% are the basis for the EIA reference case. This is an aggressive projection and all of the known technologies appear to be included in the EIA estimates. New technologies will need to be discovered to achieve additional improvements in efficiency. These new technologies will require a reinvigoration of U.S. research, development, and demonstration initiatives, similar to programs currently being carried out in Europe.

F. Marine Shipping

The EIA reference case is based on a 5% improvement in marine shipping fuel consumption by 2030. This level of improvement is achievable with operational solutions and existing technologies. Improvements greater than 5% will require new hull designs and new propeller designs. Given the long life of ships (greater than 20 years), migration of these solutions into the fleet will not have a large impact until later in the study period. Operational changes, affecting the entire fleet, may be more significant than technological improvements.

G. Rail Transport

The EIA reference case projects that fuel consumption will improve by 2.5% between 2005 and 2030. Incremental improvements in engine design, aerodynamics, and use of hybrids have the potential to reduce new locomotive fuel consumption by up to 30% over 2005 technology. Rollout of new technology into the fleet is slow due to low turnover and will be difficult to achieve in the study timeframe. Emissions standards will tend to increase fuel consumption.

II. Overview of Methodology

The Transportation Efficiency Technology Subgroup consisted of experts in transportation and fuel technology from a cross-section of academia, the federal government, NGOs, vehicle and engine manufacturers, and energy companies. Subgroup members are listed in Appendix 1.

Individual subgroup members provided data, reports, and other publicly-accessible information for review and discussion. These are identified in Appendix 2. Two teleconferences were held to discuss study approach and deliverables. A Transportation Efficiency Workshop was held at the end of October to review all data collected and to discuss the study conclusions. Finally, two teleconferences were held to review final study conclusions.

The subgroup was assisted by Mr. K.G. Duleep of Energy and Environmental Analysis, who acted as a clearinghouse for the collected data and provided analysis summaries. The approach used by the Subgroup consisted of:

- Identification of technologies in the EIA reference case.
- Categorization of technologies that might be considered for improving fuel consumption in the five subsectors (light-duty vehicles, heavy-duty vehicles, air, marine, and rail) by percent fuel consumption improvement and costs, and probability of commercial availability of the technologies, rated as low, medium, or high.
- Identification of potential fuel consumption improvements above the EIA reference case.
- Identification of hurdles to technology advancement and potential policy options to advance the technologies. Potential policies will be analyzed by the Policy Group.

In all of the transportation subsectors, fuel consumption was considered at the end-use point (e.g. tank-to-wheels for the light-duty vehicle sector). Energy is required to produce the fuels associated with the various transportation modes. These well-to-tank energy requirements can be substantial for some alternatives to petroleum (i.e. hydrogen, biofuels, and electricity, depending on the source) and are being analyzed by the Supply and Demand Groups.

Alternative fuels can influence demand for petroleum-based fuels in two ways: 1) they displace the demand for petroleum in the transportation sector on an energy-equivalent basis (e.g. use of biodiesel in heavy-duty trucks) and 2) they may change fuel consumption (positively or negatively) at the point of use (e.g. hydrogen use in fuel cells is more efficient than gasoline from a tank-to-wheels perspective). Only the second effect is identified in the technology tables in this report. The petroleum displacement effect can be applied generically across all of the sectors and quantitative analysis is being conducted by Demand Group.

It should be noted that shifts in transportation from one sector to another can have a significant influence on energy demand. For example, the table below shows a relative comparison of fuel consumption of freight moved by heavy-duty truck, rail, and ships.

Mode	**Relative Consumption**
Truck	1.0
Rail	0.31
Ship—Container	0.24
Ship—Bulk	0.10

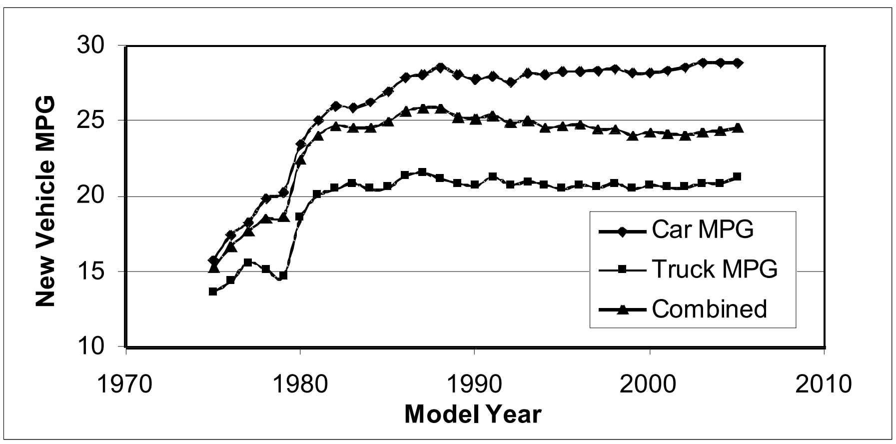
Table II.1. Relative consumption, based on energy used/ton-mile, with trucking set to 1.0.

Where sector shifts are possible, these are identified but no further analysis was conducted.

III. Light-duty Vehicles (LDV)

A. Background

Light-duty vehicles comprise cars and light-duty trucks (minivans, pick-ups and SUVs) and account for 62% of the U.S. demand in the transportation sector and



smaller amounts elsewhere.

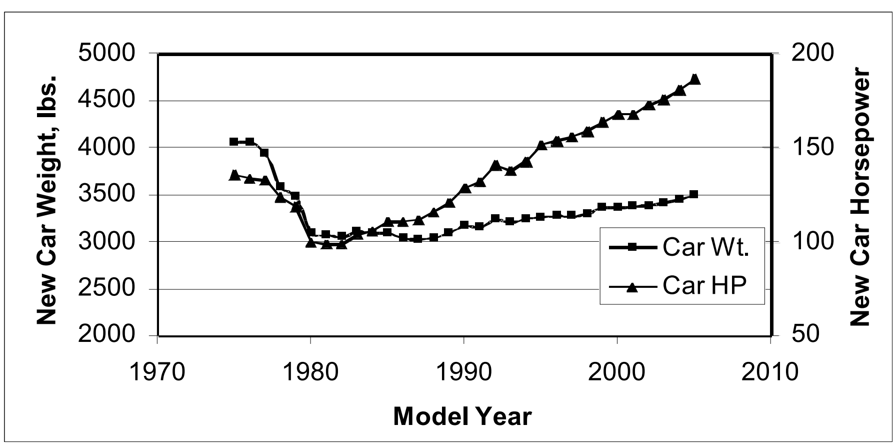


Figure IIIA.1. New vehicle fuel economy from EPA Trends report.

Figure IIIA.2. Horsepower and weight for new cars from EPA Trends report.

The U.S. new-vehicle fuel economy has been constant for about 20 years, in line with Corporate Average Fuel Economy (CAFE) standards. Figure IIIA.1 shows average U.S. new-vehicle fuel economy for cars and light-duty trucks (LDTs) since 1975, and Figure IIIA.2 shows the average horsepower and weights of new cars over the same time period. Engine and drive train efficiency improved significantly over this period and, in response to consumer desires and expectations, many of these gains were used to provide increased engine power and performance features while meeting CAFE standards. The efficiency improvements were made through steps such as advanced fuel metering, feedback emission control, better engine breathing, and more efficient transmissions.

Growth in market share of LDTs, currently about 50% of new vehicle sales, has also affected fleet fuel economy. Due to higher mass and greater aerodynamic drag, these vehicles have lower average fuel economy than passenger cars.

In the U.S., new LDVs are mostly gasoline-fueled and are split evenly between cars and LDTs. Many of the heavier LDTs are diesel-powered. In Europe, diesel vehicles account for about half of new LDV sales. In many developing countries, notably China and India, the fleet consists of a large percentage of relatively small vehicles with small engines and few amenities such as air conditioning. As these economies grow, the path of fuel economy is uncertain. The new fleet might be larger, heavier, more powerful and with more accessories than today’s fleet, and this will tend to lower fuel economy. Infrastructure growth and government policy will impact fuel economy and total demand through the ability of the economy to absorb more LDVs and through potential limitations on growth in miles traveled.

B. Tables of advances

In the USA, the EIA reference case, summarized in Table IIIB.1, projects that new LDV fuel economy will improve by 0.6%/year, from 25.3 mpg in 2005 to 29.2 mpg in 2030.

	2010	2020	2030
Technology improvement[1]	10.0%	19.7%	28.5%
Vehicle attribute changes[1]	-4.8%	-10.1%	-15.1%
EIA reference case net improvement	5.2%	9.6%	13.4%
New vehicle fuel economy in EIA Reference Case	26.7 mpg	28.0 mpg	29.2 mpg
[1] Calculated by EEA			

Table IIIB.1. Projected fuel consumption (BTU/mile) improvements for 2010, 2020, 2030.

The reference case projects that the market share of LDTs increases from 48% to 55% and that performance continues to increase, but at a slower rate than in the past. Incremental improvements in conventional engines will account for about two-thirds of the total (28.5%) technical improvements. In 2030, hybrids are projected to make up 12% of new LDV sales, and diesels will be 8% of new LDV sales. Fuel prices are assumed to stay relatively constant at about $2/gallon in inflation-adjusted dollars. The EIA reference case also projects a yearly growth in horsepower/weight ratio of about 1%, compared to a yearly growth of 4% for the past two decades.

Some subgroup members disagreed with several of these projections. The growth in market share for LDTs was questioned as too large, and some felt that their market share could even decline somewhat. The other area of disagreement was fuel economy. Some members felt that increases in technical efficiency might not be converted into increases in fuel economy in the absence of new policies or increases in fuel cost.

Table IIIB.2 below shows potential improvements in fuel consumption that could be applied to LDVs. All values are relative to a typical mid-size 2005 U.S. gasoline car. For each advance, the study estimated the improvement in fuel consumption relative to the base vehicle, an assessment of the cost of this improvement (low, medium or high) and the likelihood that this technology will be ready for sale in a commercial vehicle. Reductions in vehicle size or power were not considered. Such changes would likely be considered only in response to policy initiatives.

Some of the items listed in the table are not defined explicitly, e.g. engine efficiency improvements. It was concluded that there will be many items available to improve efficiency. Predicting exactly which ones would be developed and available for application is beyond the scope of this study. Appendix 3 lists the individual items that were identified.

It should be noted that the individual values in the table may not be additive, because not all improvements are independent of each other. For instance, hybridization can either be diesel or gasoline, but not both.

Based on all of these data, the study group concluded that technology exists, or is likely to be developed, that can reduce fuel consumption of new light-duty vehicles by 50% by 2030, at higher costs and at 2005 vehicle performance levels. Actual technology deployment and fuel consumption benefit will depend on factors not evaluated in this study, including vehicle and fuel costs, customer preferences, and changing vehicle attributes. See Appendix 4 for examples of technology combinations that might be employed to achieve 50% reduction in fuel consumption.

Light-Duty Fuel Consumption Improvement, Cost, and Probability

	2010			2020			2030		
	Improvement	Cost	Probability	Improvement	Cost	Probability	Improvement	Cost	Probability
Gasoline									
Engine Efficiency									
Level 1	***3.5 %***	Low	High	-	-	-	-	-	-
Level 2	10.0 %	Low	Med	***11.0 %****	Low	High	***12.0 %****	Low	High
Level 3	14.0 %	Med	Low	14.0 %	Med	Low	16.0 %	Med	Med
Body Improvements									
Level 1	***1.5 %***	Low	High	***3.5 %***	Low	High	***5.5 %***	Low	High
Level 2	5.5 %	Low	Low	7.5 %	Low	Med	9.5 %	Low	Med
Level 3	10.5 %	High	Low	10.5 %	Med	Low	12.5 %	Med	Low
Driveline/Acc.									
Level 1	***4.0 %***	Low	High	-	-	-	-	-	-
Level 2	6.0 %	Low	Med	***6.5 %****	Low	High	***7.0 %****	Low	High
Hybrids									
Fueled	9 - 33 %	M/H	High	11 - 35 %	L/H	High	11 - 35 %	L/H	High
Plug-in	54.0 %	High	Low	55.0 %	High	Med	55.0 %	High	Med
Diesel									
Base engine	14.0 %	High	High	16.0 %	High	High	17.0 %	High	High
Driveline/Acc.									
Level 1	4.0 %	Low	High	-	-	-	-	-	-
Level 2	6.0 %	Low	Med	6.5 %*	Low	High	7.0 %*	Low	High
Body Improvements									
Level 1	1.5 %	Low	High	3.5 %	Low	High	5.0 %	Low	High
Level 2	5.5 %	Low	Low	7.5 %	Low	Med	9.5 %	Low	High
Level 3	10.5 %	High	Low	10.5 %	Med	Low	12.5 %	Low	Med
Hybrids									
Fueled	17 - 36 %	M/H	Med/Low	19 - 38 %	M/H	Med/Low	20 - 39 %	M/H	Med/Low
Plug-in	56.0 %	High	Low	58.0 %	High	Low	59.0 %	High	Low
Alternative Fuels									
Battery Electric	75.0 %	High	Low	75.0 %	High	Med	75.0 %	High	Med
CNG	5.0 %	High	Low	5.0 %	High	Low	5.0 %	High	Low
Biofuels	5.0 %	Low	High	5.0 %	Low	High	5.0 %	Low	High
Fuel Cell	50.0 %	VHi	Low	55.0 %	High	Med	55.0 %	High	Med

* Includes Level 1 improvements

Glossary and Notes

Gasoline

Engine	Level 1	VVT, Electronic Throttle Control, Engine Friction Reduction
	Level 2	Level 1 + VVL + GDI + Continuing Friction Reduction
	Level 3	Level 1 + HCCI (assumes cam-less valve actuation) or downsized, turbocharged GDI
Body	Level 1	Aero. Drag and Rolling Resistance reduction, Reduced Brake Drag
	Level 2	Level 1 + Optimized High Strength Steel body, Composite hood/deck lid/fenders
	Level 3	Level 1 + Aluminum Structure, Composite Hood/Deck lid/ Fenders
Driveline/ Accessories	Level 1	6-speed automatic versus 4-speed automatic
	Level 2	Level 1 + Electric Power Steering / Electric Water Pump/ Improved Alternator
Hybrids	Fueled Hybrid	Represents range of hybrid technologies from integrated starter generators (ISG) that allow vehicles to stop at idle to systems that involve more than one electrical motor and use sophisticated control algorithms to share power between the engine and motors.
	Plug in Hybrid	Assumes 50% of annual travel uses power from grid

Diesel

Base Engine		Improvements from reduced friction, improved turbo, and HCCI
Driveline/ Accessories	Level 1	6-speed automatic versus 4-speed automatic
	Level 2	Level 1 + Electric Power Steering / Electric Water Pump/ Improved Alternator
Body	All levels	Same as gasoline
Hybrids	All levels	Same as gasoline, but does not include ISGs, which are not applicable to diesels

Notes:

1. All improvements are relative to a typical 2005 mid-size U.S. passenger car, gasoline equivalent gallons per mile. The energy required to produce the fuels can vary significantly and must be considered when comparing different fuels.
2. Care should be taken when combining technologies. In general improvements are not additive within technologies but can be additive across technologies. For instance, an engine improvement can be added to a driveline improvement. See Appendix 4 for details of calculations.
3. Costs are defined as L: <$1000, M: $1000-$3000, H: >$3000.
4. "Probability" is the likelihood that a technology will be available in a commercially viable form.
5. Further definition of hybrid technologies is provided in the Discussion section.
6. Values underlined and italicized are included in the EIA reference case.

Table IIIB.2. Light-duty fuel consumption improvement, cost, and probability.

C. Discussion

Specific items from Table IIIB.2 are discussed below in order of their overall ability to influence fuel consumption. For each item, the study group considered its impact, steps that might be taken to increase the chance of implementation, and the potential to advance its implementation sooner than might be possible in the base case.

It may take up to 15 years for new technology to achieve full penetration of new vehicle sales. As a rule of thumb, and in the absence of policy drivers, the bigger the change, the longer it takes to penetrate new vehicle sales. Technology available toward the end of the study period will not have a large impact on demand in 2030, but may affect demand trends past that date.

1. Hybrids and Battery Electric Vehicles

Hybrid vehicles use batteries and an electric motor in combination with an internal combustion engine—gasoline or diesel. Relative to today's gasoline vehicles, hybrids may achieve from 9% to 55% improvement in fuel consumption. Two broad categories are considered: fueled and plug-in. In fueled hybrids, the battery is recharged by a combination of regenerative braking and the engine. At the low end of the efficiency and cost range is the start-stop configuration, where the engine shuts off during stops and possibly during coasting or braking. The battery may also contribute power during acceleration or at low speeds. Larger batteries and sophisticated power sharing with the engine can provide more fuel savings at a higher cost.

In a plug-in configuration, the battery is large enough to provide a significant fraction of the total driving force and is recharged in off-hours by external power. A major unknown is the mileage driven on battery power. In the table, a value of 50%

was assumed. A full analysis of plug-in hybrid technology needs to account for the energy used in producing the electricity to recharge the battery.

Hybrid vehicles are being sold today in relatively small numbers. The type of hybrid and market penetration cannot be predicted. Factors that could impact these choices include higher CAFE standards, incentives, and fuel taxes. Fuel costs relative to incremental vehicle costs can also impact the customer's decision process.

In addition to market issues, two limiting technical factors were identified for the application of hybrid technology. The first is battery technology, where significant advances are needed to bring plug-in hybrids to readiness. The second limiting factor is battery manufacturing capacity. The steps required to increase battery manufacturing capacity should be investigated.

Battery electric vehicles are a logical progression of technology beyond plug-in hybrids. They require batteries with higher energy density than plug-in hybrids. Considering only the vehicle, battery vehicles have the potential to reduce energy consumption by about 75% relative to today's vehicles. The energy required to produce the electricity for battery charging needs to be taken into account. As the potential for hybrids to increase fuel consumption efficiency grows, the incremental improvement from battery-electric vehicles is reduced. Technical challenges for battery-electric vehicles include higher energy density, greater driving range, and faster recharge rates.

2. Diesels

Diesel engines for LDVs are available today in large quantities in Europe, and they have a fuel consumption benefit of up to 17% (gasoline equivalent energy) relative to a gasoline powered vehicle. Diesel engines cost more to produce than their gasoline counterparts. Their popularity in Europe is a result of high fuel costs, government tax incentives, and aggressive fuel consumption targets. Diesel vehicles are also able to meet current European emission standards, which are less stringent than U.S. standards.

Further development is required to achieve U.S. Tier 2 emission standards, especially for the lower emission bins. At least initially, it is likely that the fuel consumption benefit of LDV diesel engines may be negatively impacted by the need to meet Tier 2 exhaust emission standards. The data in Table IIIB.2 are based on this debit disappearing over time. Future emission standards may also impact the potential fuel-consumption benefit of diesels. Diesels may also be hybridized, with associated reductions in fuel consumption. The lowest level of hybridization, integrated starter-generators, is not expected to be applied to diesels.

If diesel-engine penetration grows, fuel properties such as cetane may have to be adjusted for these vehicles. Refinery investments may also be required to match the shifting gasoline/diesel demand ratio. Introduction of LDV diesel engines can be encouraged through additional research on exhaust emission control, and through government policies promoting fuel economy.

Improvements to gasoline-engine technology may reduce the fuel consumption differences between gasoline and diesel engines. One improvement being implemented for gasoline engines, direct injection, has already been applied to diesels. Other steps, such as improved transmissions and aerodynamics are common to both. More stringent emission standards would likely have a larger impact on diesels than on gasoline engines.

3. HCCI (Homogeneous Charge Compression Ignition)

HCCI technology is at an early stage of development for gasoline and diesel applications. For diesel, HCCI may reduce emissions but will probably not reduce fuel consumption. Gasoline HCCI has the potential for low engine-out emissions and a reduction in fuel consumption by up to 16%. Since this is a compression ignition engine, some of the advances in drive-train efficiency are not relevant. A major technical hurdle for HCCI is to maintain stable and complete combustion over the entire operating envelope. Significant progress has been made to date, but HCCI is not likely to be available until near the end of the study period.

HCCI engines will probably benefit from a fuel with different properties than today's gasoline. The fuel might have a low octane number, different volatility characteristics, and might require a new specification for combustion properties. It might be possible to advance HCCI technology by additional research, either privately or government funded. Fundamental issues that require study include combustion control and fuel properties matched to the engine.

4. Fuel cells

Fuel cells have the potential to halve LDV fuel consumption relative to the base gasoline LDV, on an energy equivalent basis. This estimate includes only tank-to-wheels effects, and does not consider the energy required to make the fuels (gasoline or hydrogen). Fuel-cell powered vehicles are available today in small numbers only in demonstration programs and are not likely to be ready for large commercial application until well into the study period. Significant scientific and technical advances as well as cost reductions will be required in order to bring fuel cells to readiness. Hydrogen storage on-board the vehicle is a major technical question. High-pressure storage has weight, cost, and safety issues that need to be further addressed. Other storage ideas, such as metal hydrides, are not feasible at this time. On-board production of hydrogen by reforming petroleum fuels is also far from ready.

In addition to vehicle technology, there are major infrastructure issues concerning the supply of hydrogen. Hydrogen can be made at central stations and shipped through specialized pipelines or in trucks. It may also be made in a decentralized fashion at service stations. An economic process for manufacturing hydrogen is also not fully developed. It can be made by electrolysis of water, or by reforming a hydrocarbon such as natural gas or petroleum.

The main areas requiring additional research are:

- On-board hydrogen storage
- Reducing fuel cell cost, improving durability
- Cold start, system optimization
- Hydrogen infrastructure.

5. Alternative Fuels

Biofuels such as ethanol are available today and can be used without vehicle modification, when blended in small quantities into gasoline (≤10%). Use of higher concentrations of biofuels, such as E85 (85% ethanol), requires changes in fuel-system materials and fuel metering. Use of E85 also requires changes to materials in the fuel distribution system. The technology changes are well known and the major barrier to large increases in ethanol use is the availability of suitable land and water. Development of low cost cellulosic ethanol, a significantly more difficult and costly process, could change the supply outlook.

Technology to use compressed natural gas (CNG) is also well known, and CNG is used widely in other countries such as Argentina. On-board fuel storage requires high-pressure tanks that add weight and take up significant volume. Fuel systems must be designed to deal with high pressure and to meter gases instead of liquids. The major barriers to large increases in CNG use are high cost, poor vehicle range, and alternative uses for CNG (e.g. power generation).

LDVs built for the exclusive use of alternative fuels such as E100 or CNG may achieve a modest decrease in energy use of about 5% through higher compression ratios. Both ethanol and CNG use can be increased through government incentives or mandates. If significant volumes of either alternative are used, the impact will be reduced demand for LDV petroleum fuel.

6. Potential Negative Impacts on Fuel Consumption

A number of factors could have a negative impact on fuel consumption, including:

- More stringent emission regulations, especially for diesel engines
- Safety regulations that add vehicle weight
- Heavier, more powerful vehicles
- Shift from cars to LDTs.

In developing countries, as discussed earlier, economic factors may contribute to a shift to larger, more powerful, and less efficient light-duty vehicles.

7. Potential Policy Options to Reduce Fuel Consumption

Potential policy initiatives to reduce LDV fuel consumption include:

- Fuel economy standards
- Fuel taxes
- Incentives to buy fuel efficient vehicles, penalties for inefficient vehicles
- Incentives and mandates that increase use of mass transit and carpooling
- Government funding of additional research on new technologies, including alternative fuels.

IV. Heavy-duty Vehicles (HDV)

A. Background

EIA estimates that energy demand for heavy-duty vehicles constitutes approximately 20% of total transportation energy consumption in the USA. Overall fuel consumption from HDVs is projected to rise by 1.8% per year over the forecast period (2005-2030), along with a total ton-mile growth of about 2.3% per year. EIA projects approximately 0.5% per year improvement in U.S. freight truck fuel economy, from 6 to 6.8 miles per gallon.

In the near term, U.S. regulatory requirements for reduced NOx and particulate matter emissions from the heavy-duty sector will compete with technological improvements in fuel consumption, since after-treatment devices and combustion strategies will consume some energy. Therefore, most believe that fuel consumption will remain flat or even increase slightly in the short term, improving again in the 2015-2030 period.

B. Tables of advances

The fuel consumption improvements included in the EIA projections relative to 2005 are shown in the last line of Table IVB.1 for 2010, 2020, and 2030. Negative numbers indicate an increase in energy consumption per ton-mile traveled, positive numbers indicate a decrease.

	2010	2020	2030
Technology Improvements[1]	+1%	+9.5%	+18%
Operational Factors[1]	-1%	-3.2%	-6.2%
EIA Reference Case	0%	+6.3%	+11.8%
[1] Estimated by EEA			

Table IVB.1. Projected fuel-consumption improvements relative to 2005.

Table IVB.2, below, lists technological and operational improvements with the potential to reduce fuel consumption in the heavy-duty sector. The analysis was conducted by EEA and was based on work by DOE and results of interviews with heavy-duty engine manufacturers. The data in the table are primarily applicable to the Class 8 category of trucks (a.k.a., heavy heavy-duty), but most technologies can also be applied to the medium heavy-duty classification (e.g. delivery trucks). Where differences between the two classifications exist, these are noted in the Discussion Section. Underlined and italicized fuel consumption improvements in the table identify the technologies that could be adopted to achieve the projected improvements in fuel consumption in the EIA reference case. In analyzing the EIA reference case, EEA concluded that the difference between technology improvements and the EIA reference data resulted from operational factors such as increased traffic congestion which negatively affects fuel consumption, as shown in Table IVB.2.

Heavy-Duty Fuel Consumption Improvement, Cost, and Probability (Class 8 Truck)									
	2010			**2020**			**2030**		
Technology	**Improvement**	**Cost**	**Probability**	**Improvement**	**Cost**	**Probability**	**Improvement**	**Cost**	**Probability**
Engine Efficiency									
- Level 1	***-4%***	N/A	High	***+4%***	Low	High	***+6%***	Low	High
- Level 2	+2%	Med	Med	+7%	Med	Med	+9%	Med	Med
- Level 3	+13%	High	Low	+14%	High	Low	+18%	High	Low
Rolling Resistance	***+2%***	Low	High	***+4%***	Low	High	***+6%***	Low	High
Aerodynamics									
- Level 1	***+3%***	Low	High	***+6%***	Low	High	***+6%***	Low	High
- Level 2	+5%	Med	Med	+10%	Med	Med	+10%	Med	Med
Elec. Accessories									
- Level 1	+2%	Low	High	+3%	Low	High	+3%	Low	High
- Level 2	-	-	-	+5%	Med	Med	+5%	Med	Med
Mild Hybrid	+8%	High	Low	+10%	Med	Low	+10%	Med	Low
Full Hybrid	+15%	High	Low	+20%	High	Low	+20%	High	Low
Reduced idling	+5%	Low	High	+5%	Low	High	+5%	Low	High

Engine Efficiency Level 1:	Combustion improvements, advanced injection, turbo charging, emissions control
Engine Efficiency Level 2:	Friction reduction, electric water and oil pumps
Engine Efficiency Level 3:	Turbo compounding, electric turbo
Aerodynamics Level 1:	Air deflectors, wheel covers
Aerodynamics Level 2:	Trailer and tractor integration
Electric Accessories Level 1:	Electric power steering, power accessories
Electric Accessories Level 2:	Electric cooling fans

Cost: Low < $2000; Medium < $6000; High >$6000

Probability: Likelihood that technology will be available in a commercially viable form

Table IVB.2 Heavy-duty fuel consumption improvement, cost, and probability (Class 8 truck).

C. Discussion

Opportunities for technology retrofits or operational changes have the potential to impact the entire fleet and could have a greater immediate impact on fuel demand than even quite large efficiency improvements in new engine platforms affecting only the new vehicles entering the fleet.

1. Emissions Reductions/Engine Efficiency

New U.S. heavy-duty emission standards for NOx and particulate matter are likely to have a negative impact on fuel consumption of diesel engine systems, at least in the near term. Other factors being constant, an increase of fuel consumption of 2 to 5% would not be unexpected. DOE is attempting to address this in the 21st Century Truck Program, a research partnership between the DOE, DOD (Army), EPA, DOT, and truck engine builders. This program addresses diesel engine efficiency, aerodynamic drag reduction, auxiliary loads reduction, and drive train improvements.

Additional R&D directed specifically at the issue of engine efficiency/emission trade-offs could provide benefits in the short-term. Although not part of the current DOE program, efforts to address potential fuel/engine optimization or fuel-enabling strategies could advance cost-effective deployment of the engine technology options sooner.

Alternative fuels, such as biofuels, may also play a role in the relationship between emissions control and engine efficiency. Although biofuel use would not directly result in a fuel consumption improvement, research to understand the fuel-engine interaction of diesel biofuel combustion characteristics could result in identification of new, effective "system" strategies.

The use of biodiesel or any other non-petroleum fuel for the heavy-duty sector displaces demand for petroleum-based diesel. The significance of this displacement depends on the available supply of biodiesel. This issue is being assessed by the Supply Team.

2. Reduced Idling, Other Operational Improvements

Reduced idling and use of external power to operate vehicle systems while the vehicle is not in transit offer the greatest potential to impact a broad portion of the fleet in the short-term. A potential fuel consumption improvement of 5% in the USA could be achieved if applied across the entire fleet. The technology is currently available and deployed in limited application where the economics are favorable or local idling restrictions exist. A possible method to encourage broader deployment across the heavy-duty fleet would be through incentives or mandates.

Another example of an operational improvement is better scheduling, for example reduced empty backhauling. These improvements are presently driven by the business case for such efforts and the potential cost-saving dynamics associated with individual trucking companies.

3. Aerodynamics and Rolling Resistance

Simple aerodynamic improvements (Level 1) and rolling resistance improvements are considered in the EIA reference case. Both items are low-cost and high-probability technologies that will likely be deployed due to their economic payback. Level 2 aerodynamic technologies, involving physical integration of the tractor and trailer, have a potential fuel consumption benefit for Class 8 trucks. Deployment may be application-specific, and the financial incentive of this technology in reducing fuel costs is probably adequate to bring it to commercialization.

4. Hybridization

Unlike the light-duty vehicle sector, the fuel-consumption improvement, cost, and probability basis for deployment of hybrid technology for heavy-duty application is not as clear cut. Although hybridization has a potential fuel-consumption benefit of 10 to 20%, achieving these fuel savings in practice may be a challenge for the U.S. Class 8 trucks. Long-haul trucks require power trains that provide adequate power for long-duration, high-speed, high-load conditions, resulting in limited opportunity for engine downsizing. The most promising applications for hybridization are medium-duty delivery trucks or local transit buses. These vehicles encounter a high frequency of start-stop conditions in which hybrid technologies provide the most fuel consumption benefits, through engine on-off cycling, engine downsizing and regenerative braking. The evolution of hybrid technology for heavy-duty application would leverage off the development in the light-duty sector. Therefore, deployment of hybrid technology does not appear to be limited by technological hurdles unique to this sector.

5. Potential Negative Impacts on Fuel Consumption

The most significant negative impact on fuel consumption in the heavy-duty sector is the near-term U.S. emission regulations for NOx and particulate matter that will affect the 2007–2010 product offerings. The need for higher-power engines or additional truck-safety or convenience devices is expected to have a secondary impact on fuel consumption.

6. Potential Policy Options to Reduce Fuel Consumption

Potential policy options to reduce fuel consumption from the HDV sector include:

- Reduced idling
- Fuel taxes or incentives (e.g. alternative fuels)
- Vehicle system-efficiency requirements (tractor plus trailer together)
- Policies that provide incentives for shifts from heavy-duty freight to marine or rail freight, if more fuel efficient
- Reducing Class 8 operations in stop-and-go traffic
- Long-term government research and demonstration on promising, breakthrough technologies to help address heavy-duty manufacturers' R&D shortfall during low revenue periods brought on by pre-buy/no-buy cycles (condition in which buyers purchase engines immediately prior to new emission standards for lower cost and higher fuel economy and do not buy after emission standards takes effect).

V. Air Transport

A. Background

IEA estimates the 2005 world-wide demand for air transport as 12% of the total transportation sector. Future projections of growth rate from Boeing and Airbus show a world-wide annual demand growth rate of 5 to 6% (seat-miles/year) out to 2030, whereas IEA projects a much lower growth rate of 2% per year. At a recent Commercial Aviation Alternative Fuels Initiative meeting, participants suggested that worldwide travel rates would increase by 3.8% per year. In the USA, the EIA projects a growth rate of 1.9% per year.

Efficiency of air transport (seat-miles/gallon) is projected to improve by about 1.2% per year on average, which is substantially less than the 2% per year improvements achieved from 1970-1990.

B. Tables of advances

The EIA reference case fuel consumption improvements for 2010, 2020, and 2030 are shown in Table VB.1. Table VB.2 lists fuel consumption improvement opportunities.

	2010	2020	2030
EIA Reference Case	4.4%	16.6%	25.8%

Table VB.1. EIA reference case fuel consumption (BTU/seat-mile) improvements for 2010, 2020, 2030.

Air Transportation Fuel Consumption Improvements, Cost, and Probability									
	2010*			**2020**			**2030**		
	Improvement	**Cost**	**Probability**	**Improvement**	**Cost**	**Probability**	**Improvement**	**Cost**	**Probability**
Wide-body									
- Engine Imprv.	***4%***	Low	High	***10%***	Med	High	***10%***	Med	High
- Composites	4%	Med	High	5%	High	High	***5%***	High	High
- Aerodynamics	***3%***	Low	High	***3%***	Low	High	***4%***	Low	High
Existing Aircraft									
- Engine Retrofit	3%	Low	Med	6%	Low	Med	***9%***	Low	Med
Operations									
- Optimal Routes	1%	Low	Med	***3%***	Low	Med	***5%***	Low	Med
Narrow Body									
- Engine Imprv.	***4%***	Low	High	***10%***	Low	High	***10%***	Low	High
- Composites	0%	-	-	4%	Med	High	***6%***	Med	High
- Aerodynamics	0%	-	-	***3%***	Low	High	***4%***	Low	High
Existing Aircraft									
- Engine Retrofit	***3%***	Low	High	5%	Low	Med	***8%***	Low	High
- Winglets	3%	Low	Med	***3%***	Low	Med	***3%***	Low	Med
Operations									
- one-engine taxi; faster climb	1%	NA	Med	***3%***	NA	Med	***5%***	NA	Med

Cost: Low =$0.5-$1.0B; Med= $1.0-$2.0B; High= greater than $2.0B
*2010 information and data based on 2006 to 2010 time period
Underlined and italicized improvements indicate activities required to meet EIA reference case
NA: not available
Probability: Likelihood that technology will be available in a commercially viable form

Table VB.2. Air transportation fuel-consumption improvements, cost, and probability.

C. Discussion

The air sector differs from the others since virtually all of the fuel consumption improvements in Table VB.2 are required to achieve the EIA reference case. Additional breakthrough technologies or cross-sector shifts of passenger travel to more efficient modes will be required if fuel consumption improvements beyond the reference case are to be achieved.

1. Existing Efficiency Programs

Many of the technologies or operational improvements in Table VB.2 are already being planned or deployed. For example, Boeing and others are developing next-generation wide-body, fuel-efficient aircraft for deployment in 2010. Routing is continually being optimized, and single-engine taxiing is in use at some locations. Research in weight reductions through advanced materials and composites needs to continue, since this technology has broad application to other transport sectors.

2. New and Breakthrough Research

In order to provide opportunity for new discoveries and to fill the early stage of the technology pipeline with new ideas, the airline industry could benefit from new or expanded cooperative programs with government support. NASA had conducted research and development demonstration programs in the 1970s through 1990s, but these research and development demonstration programs no longer exist. In contrast, Europe currently has such an air transportation efficiency program, Euro-Vision 2020. In the fuels area, the DOD is pursuing coal-based synthetic fuels. The U.S. Air Force has a goal to meet 50% of their fuel needs with synthetic fuel by 2015, about 5% of the U.S. air sector demand. Research in understanding the combustion characteristics of new fuels also has the potential to balance the emissions (NOx and particulate) versus efficiency trade-off.

3. Potential Negative Impacts on Fuel Consumption

Several factors may negatively impact the ability to achieve all of the fuel consumption improvements identified in the above technology table.

Air Congestion—The projected increase in air traffic will undoubtedly result in increased air-space congestion, with operational disruptions resulting in lower efficiencies.

Aircraft Noise Reduction—Efforts to decrease noise generation from aircraft negatively impact fuel consumption as modifications are made to aircraft engines, or air-routing logistics are optimized for noise reductions versus fuel efficiency.

Emissions Reduction—NOx and particulate-matter control is managed on aircraft engines in a similar manner as for heavy-duty diesels, via combustion modifications or mechanical changes that have a negative impact on fuel consumption.

Regional vs. Long-Distance Routing—Increasing numbers of regional carriers and "air taxis" have a negative impact on fuel consumption.

4. Potential Policy Options to Reduce Fuel Consumption

The following are potential policies for consideration in the air sector:

- Increased government-funded research for breakthrough technologies
- Incentives and infrastructure improvements to encourage greater passenger use of the rail sector, e.g. Northeast rail corridor
- Incentives or mandates for operational fuel-consumption improvements
- Promotion of increased alternative-fuels research and demonstration activities.

VI. Marine Transport

A. Background

In 2005, world-wide marine transport was estimated by IEA to consume ~9% of the total transportation energy demand. EIA indicates that, in the USA, marine fuel represents about 4% of the 2005 transportation fuel use. EIA projects U.S. marine transport demand increasing 0.2% per year.

Others have estimated that marine energy fuel demand is significantly higher (e.g. 15%, estimated by Eyring). Different approaches of building marine energy demand and different bunker-fuel accounting methods used by individual countries are the likely cause for this variation in energy demand estimates.

B. Tables of advances

EIA projects that the U.S. inland waterway marine freight-fuel consumption is expected to improve by 0.2% per year. The technologies by which these improvements are achieved are not clearly identified in the EIA reference case. A 0.2% per year improvement would result in the fuel consumption improvements shown in Table VIB.1. Table VIB.2 lists the potential technologies and operational improvements that could reduce fuel consumption. In the near-term, focus on NOx and particulate-matter control may degrade fuel-consumption improvements.

	2010	**2020**	**2030**
EIA Reference Case	0.8%	2.8%	4.9%

Table VIB.1. EIA reference case fuel consumption improvements relative to 2005.

Marine Transportation Fuel-Consumption Improvements, Cost, and Probability									
	2010			**2020**			**2030**		
Technology	**Improvement**	**Cost**	**Probability**	**Improvement**	**Cost**	**Probability**	**Improvement**	**Cost**	**Probability**
Engine Efficiency									
- Combustion impr.	***2-5%***	Med	Med	***2-5%***	Med	High	***2-5%***	Med	High
- Fuel Cell Systems	0-10%	High	Low	0-10%	High	Low	0-10%	High	Low
Hull Design	5% (20%)	Low	Med	5% (20%)	Low	Med	5% (20%)	Low	Med
Propeller Design	5% (10%)	Low	Med	5% (10%)	Low	Med	5% (10%)	Low	Med
Hull Maintenance	5%	Low	High	5%	Low	High	5%	Low	High
Propeller Maintenance/retrofit	3% (8%)	Low	Med	3% (8%)	Low	Med	3% (8%)	Low	High
Operational Improvements	*5%* (40%)	Low-Med	Med	*5%* (40%)	Low-Med	Med	*5%* (40%)	Low-Med	Med

Improvement: Numbers in parenthesis are high end of MARINTEK report and likely approach theoretical maximum
Cost: Low = 1% of New vessel; Medium = 1-5% of new vessel; High= 5% of New vessel
Probability: Likelihood that technology will be available in a commercially viable form
Italicized and Underlined improvement percentages represent technologies that could be applied to meet the EIA reference case projections.
Table developed from data in MARINTEK, Carnegie Mellon, and Corbett.

Table VIB.2 Marine transportation fuel-consumption improvements, cost, and probability.

C. Discussion

In general, future marine energy demand will more than offset the fuel-consumption improvements contained in the EIA reference case. Given the relatively low vessel-replacement rate (greater than 20-year lifetime), the most effective options for efficiency improvements in the short term are through actions affecting the existing fleet, with vessel replacement having a potential significant impact in the long-term.

1. Operational Improvements

MARINTEK identified several operational measures which have significant efficiency improvement potential, and many of these are in practice today. Since fuel consumption increases proportionately with the square of speed, "slow steaming" or "just in time" delivery strategies can be effective. Another operational strategy for reduced fuel consumption would be leveraging economies of scale through the use of larger ships. Although not specifically identified in MARINTEK, this is currently being practiced (e.g. shipments of LNG and other bulk shipping applications). These operational changes may have a 5 to 10% benefit.

2. New Hull and Propeller Designs

Due to dimensional limitations of canals and harbors, the ability to dramatically redesign hulls is limited, but fuel-consumption improvements of 5 to 20% are possible; with the lower number being the most likely achievable over a broad set of designs. Hull improvements will be adopted most quickly by larger ships since hull design is a fixed cost ranging from $50K to $200K.

Improvement in propeller design for new ships is also a potential source of fuel-consumption improvement. Examples of propeller designs to improve efficiency include low RPM and increased diameter blades, coaxial contrarotating propellers, and ducted propellers.

3. Engine Efficiency Improvements

Two major categories exist for reducing fuel consumption of the marine power-generation system. The first is an improvement in the fuel combustion efficiency on the vessel. Improvements of an additional 3 to 5% (relative) may be possible with newer engines and emissions control systems. A move from bunker fuel to a cleaner fuel (e.g. distillate) could also enable a systems approach to designing incrementally more efficient propulsion systems.

The second engine efficiency improvement category is the replacement of the diesel-based power systems with a more efficient power source. Fuel cells are being considered for naval applications, and the technology could migrate to commercial shipping applications. Fuel consumption for fuel cells could be 10% less than that for diesel engines, but high costs and issues around sources of hydrogen for fuel cells remain as significant barriers.

4. Hull and Propeller Maintenance and Retrofit

For existing ships, improvements in hull maintenance and coatings can save power demand by reducing roughness (viscous resistance). The potential for saving is ~5%. Also, pre- and post-swirl and flow-smoothing devices can reduce fuel use by ~3%.

5. Potential Negative Impacts on Fuel Consumption

The current focus on NOx and particulate-matter emissions from marine engines will likely consume potential benefits of technologies for combustion efficiency in the near term.

Secondly, the number of new ships entering the fleet is small. Therefore, new technologies, such as reduced-friction hulls or significantly improved engine designs, will not have a major impact during the early portion of the time period. Operational changes and retrofits of existing ships offer the greatest efficiency options in the near term, and each of these is in the modest range of 5% improvement.

6. Potential Policy Options to Reduce Fuel Consumption

Potential policies or incentives that may impact marine fuel consumption:

- Proactive support by local and federal authorities for deepening of harbor channels to accommodate larger ships
- Encouragement of research collaboration between the government and industry on marine efficiency technologies and designs
- Transfer of learnings from the naval community to commercial carriers and power-train builders via government-sponsored forums.

VII. Rail Transport

A. Background

Railroads account for approximately 3% of total worldwide transportation energy demand. IEA projects that worldwide rail-fuel demand will grow at roughly 3%/year and for the USA, EIA projects growth of 1.6% per year. The relative portion of freight versus passenger use varies by region. Freight use dominates in the USA, Latin America, Africa, China and Australia. In Europe, passenger demand is about equal to freight demand, and in India it is larger by a factor of two.

Most rail transport consists of diesel engines powering generators that in turn power electric motors connected to the wheels. A relatively small fraction of rail service is run by direct electric power. In Europe, approximately 30% of the total rail network is electrified. In the USA, the only area of significant electrification is the high density Boston-New York-Washington corridor. Electric service is twice as efficient on average versus diesel power on a tank-to-rails basis, although the advantage is less when the energy used to produce and distribute the electricity is taken into account. It is generally employed only in high density areas since it requires large capital investments for electrical generation and distribution.

The market for new railroad locomotives is relatively small—approximately 1,000 new engines per year in the USA—and the average useful life for engines can be 30 years or more. These two factors make it very challenging for OEMs to support an extensive, privately funded research program and imply that that new technology can have only a small impact on total fuel demand in the short term.

B. Tables of advances

EIA projects an efficiency improvement of 0.1%/year in the USA, providing an improvement of approximately 3% by 2030.

The estimated potential for improvements in fuel consumption in railroad diesel engines relative to today's engines is shown in Table VIIB.1. Considering the small improvement projected for this sector, we did not identify technologies that would be adopted to meet the reference case.

Rail Transportation Fuel Consumption Improvements, Cost, and Probability									
	2010			**2020**			**2030**		
Technology	Improvement	Cost	Probability	Improvement	Cost	Probability	Improvement	Cost	Probability
Operational Optimization Software	10%	Med	Low	15%	Med	Med	20%	Med	Med
Hybrid / Energy Recovery Technologies[1]	10%	VHi	Low	15%	Hi	Low	15%	Hi	Medium
Incremental Engine Improvements[1]	5%	Low	Med	10%	Low	Med	10%	Low	Med
Fuel Cells	10-15%	VHi	Low	15%	Hi	Low	15%	Med	Med

[1] Applies to diesel only
Cost: percent of a new locomotive. L: <5%, M: 5-10%, H: >10%
Probability: Likelihood that technology will be available in a commercially attractive price

Table VIIB.1. Rail transportation fuel consumption improvements, cost, and probability.

C. Discussion

Individual items from Table VIIB.1 are discussed below in order of their overall ability to influence fleet fuel consumption. For each item, the study group considered its impact, the steps that might be taken to make sure that it is implemented, and the potential to advance its implementation sooner than might be possible in the base case.

1. Operational Changes

Changes in railroad fleet operation and control have the potential to reduce energy use by up to 20%. Steps include implementation of new software and control algorithms to optimize the energy management of the train by applying decision-making algorithms to train make-up, scheduling, routing, and track use.

This approach can be adopted relatively rapidly if the implementation is limited to software and minor hardware changes. The potential reduction in total demand is greater than with new locomotive technologies, which, although they may have a large fuel consumption improvement, may take many years to be incorporated into the fleet. Implementation of this technology requires coordination among the railroads. A good model for coordination is U.S. air traffic control, which operates as a single national system. Converting to this type of operation would require the government to play a significant role. Significant engineering development would also be required to identify potential safety issues, bottlenecks, and pinch points that could negatively impact system fuel consumption.

2. Hybridization and Energy Recovery

Trains use considerable amounts of braking energy, which may be captured and redeployed by hybrid systems to decrease fuel consumption by up to 10% on long-haul freight locomotives and up to 15% on passenger locomotives. The major technical hurdle is a suitable storage device and associated control systems. Since the cycle time between braking and acceleration is much longer in trains than in LDVs, the energy storage would have to be much larger for locomotive hybrids. Options include batteries, capacitors, and flywheels, with batteries having the shortest implementation time horizon. Due to the size, operating requirements, and environmental conditions under which locomotives operate, batteries will need to be dramatically different than those that are being used or are being considered for use in LDV or HDV applications.

Hybrid locomotive technology is not likely to be commercially viable for at least ten years. The small size of the market makes it difficult to justify significant research in locomotive hybrid applications. Substantial government funding would be necessary to accelerate the availability of this technology.

Another potential source of energy recovery is the low-grade heat that is lost in the diesel cycle. Up to 60% of the fuel's available energy is released as heat in the exhaust or through the radiator. The opportunity for reducing fuel consumption an additional 5 to10% exists by recovering energy from this low-grade heat.

3. Fuel Cells

Fuel cells may improve fuel consumption by 15% relative to diesels when considered on a tank-to-rails basis. Development and deployment of fuel cells for locomotives will probably lag behind LDV and HDV applications, primarily because of the slow pace of introduction of new locomotive models. There are no fundamental barriers and fuels cells for LDVs should scale up to locomotive use as long as the technology selected for LDVs is consistent with the locomotive application.

4. Engine Improvements

Improvements in engine technology (combustion chambers and fuel delivery systems) have the potential to reduce fuel consumption by 5 to 10%. Most of these are evolutionary improvements and will be adopted when new models are introduced. Additional government research funding would advance the pace of development and introduction of these improvements.

Future emission regulations have the potential to counteract advances in engine efficiency, or even reduce efficiency relative to today's engines. Significant investment in research will be required to reverse this negative efficiency trend.

5. Potential Policy Options to Reduce Fuel Consumption

Potential policy initiatives to reduce rail fuel consumption include:

- Incentives or mandates to operators to switch from diesels to electric trains

- Incentives or mandates to switch freight traffic to rail transport from other less efficient transport modes
- Incentives or mandates to switch transportation of people to rail transport from other less efficient transport modes
- Incentives or mandates for fuel consumption improvements.

VIII. Appendix 1: Transportation Efficiency Subgroup

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IX. Appendix 2: References

A. General

1) Energy Information Administration, *Annual Energy Outlook*, 2006

2) Energy Information Administration. 2003. *Model Documentation Report: System for the Analysis of Global Energy Markets (SAGE*). Volume 2: Data Implementation Guide. DOE/EIA-M072(2003)/2

3) Fulton, L. and Eads, G. 2004. *IEA/SMP Model Documentation and Reference Case Projection*.

B. Light-Duty Vehicles

1) National Academy of Science Press, Effectiveness and Impact of CAFE Standards, July 2001

2) MIT Energy Laboratory, On the Road In 2020, Prepared by J. Weiss, et. al., October 2000

3) ACEEE, Technical Options for Improving Fuel Economy of U.S. Cars and Light Trucks, ACEEE Publication, April 2001

4) EEA, Technology and Cost of Future Fuel Economy Improvements for Light-Duty Vehicles, Report to the National Academy of Sciences, June 2001

5) "Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2005", Robert M. Heavenrich, ATD-OTAQ U.S. Environmental Protection Agency, Report EPA420-R-05-001, July, 2005.

C. Heavy-Duty Vehicles

1) "Technology Roadmap for the 21st Century Truck Program, a Government-Industry Research Partnership", the U.S. Department of Energy (DOE), December 2000.

2) "Truck Essential Power Systems Efficiency Improvements for Medium Duty Trucks", Presentation by Caterpillar at HVSO Review Meeting, April 20, 2006.

3) McCallen, R., et al "DOE's Effort to Reduce Truck Aerodynamic Drag through Joint Experiments and Computations", Presentation, April 2006.

4) Milovanovic, N., Kenchington, S., "Lotus AVT™ System for Advanced Diesel Combustion", Presentation by Lotus Engineering, October 2006.

5) Easley, W. L., Kapic, A., Milam, D.M., "The Path to a 50% Thermal Efficient Engine", Presentation by Caterpillar, DEER Conference, August 23, 2005.

6) Puetz, W, "Future Diesel Engine Thermal Efficiency Improvement and Emissions Control Technology", Presentation by Detroit Diesel, August 2005.

7) "UPS Expands "Green Fleet" with 50 Hybrid Electric Vehicles", UPS Press Release, February 17, 2006.

8) Gaines, L., "Analyzing Technologies to Reduce the Fuel Use of Heavy Vehicles", Presentation by Argonne National Laboratory, April 2006.

9) "Goodyear Launches Fuel-Efficient Truck Tire Lines", Goodyear Press Release, August 24, 2006.

10) "DOE Program on Parasitic Energy Loss Reduction for Class 7/8 Trucks", Presentation by Caterpillar, April 19, 2006.

11) "EPA to Build World's First Full Hydraulic Hybrid Urban Delivery Vehicle", the U.S. Environmental Protection Agency, Press Release, February 10, 2006

D. Air

1) Airbus. 2004. Global Market Forecast 2004-2023.

2) Boeing. 2006. Current Market Outlook, 2006.

3) Energy Information Administration. 2003. Model Documentation Report: System for the Analysis of Global Energy Markets (SAGE). Volume 2: Data Implementation Guide. DOE/EIA-M072(2003)/2

4) IPCC. 1999. IPCC Special Report: Aviation and the Global Atmosphere – Summary for Policymakers.

5) Greene, David L. 1992. Energy-Efficiency Improvement Potential of Commercial Aircraft. Annu. Rev. Energy Environ 17, 537-573.

6) Lee, Joosung J., et al. 2001. Historical and Future Trends in Aircraft Performance, Cost, and Emissions. Annual. Rev. Energy Environ. 26, 167-200.

7) Peeters, P.M. and Hoolhorst, Middel J. 2005. Fuel efficiency of commercial aircraft: An overview of historical trends. National Aerospace Laboratory NLR (Nationaal Lucht- en Ruimtevaartlaboratorium)

E. Marine

1) Eyring, V., et al. 2005. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. Journal of Geophysical Research 110, D17306

2) Eyring, V., et al. 2006. Multi-model simulations of the impact of international shipping on atmospheric chemistry and climate in 2000 and 2030. Atmospheric Chemistry and Physics Discussions 6, 8553-8604.

3) Fulton, L. and Eads, G. 2004. IEA/SMP Model Documentation and Reference Case Projection.

4) MARINTEK et al. 2000. Study of Greenhouse Gas Emissions from Ships – Final Report to the International Maritime Organization. http://unfccc.int/files/methods_and_science/emissions_from_intl_transport/application/pdf/imoghgmain.pdf.

F. Rail

1) King, Robert D. 2002. *DOE Heavy Vehicle Systems Optimization: 21st Century Locomotive Technology (locomotive system tasks).* Presentation by GE to DOE, available at http://www1.eere.energy.gov/vehiclesandfuels/pdfs/hvso_2006/22_salasoo.pdf.

2) Liu, Rongfang and Golovitcher, Iakov. 2003. *Energy-efficient Operation of Rail Vehicles. Transportation Research Part A* 37, 917-932.

3) Miller, Arnold et al. 2006. *Analysis of Fuel Cell Hybrid Locomotives.* Journal of Power Sources 157, 855-861.

4) Stodolsky, Frank. 2002. *Railroad and Locomotive Technology Roadmap.* Argonne National Laboratory. Center for Transportation Research, Energy Systems Division.

5) Thelen, Gerhard and Lovette, Michael. 1996. *A Parametric Study of the Lubrication Transport Mechanism at the Rail-wheel Interface.* Wear 151, 113-120.

6) UIC – International Union of Railways. 2003. *Energy efficiency strategies for rolling stock and train operation.* http://www.railway-energy.org/ templates/EnergyEfficiencyTech.pdf.

7) UIC – International Union of Railways. 2002. *Industry as a partner for sustainable development - Railways.* Prepared in a process facilitated by UNEP. Available at http://www.uneptie.org/outreach/wssd/docs/sectors/final/railways.pdf.

X. Appendix 3: Details of Steps to Reduce Fuel Consumption in LDVs

Technology	% Reduction in Fuel Consumption
Body	
Ultra light Steel	6.0
Aluminum Structure + Composite Closure	9.1
Drag Reduction	2.0
Reduced Rolling Resistance	1.5
Engine	
Four Valves per cylinder	4.0
Variable valve timing	1.5
Discrete VVL/VVT	6.0
Continuous VVL/VVT	9.1
Camless valves	12.3
Cylinder cutout + VVT	10.1
Direct Injection (Stoichiometric)	3.9
Friction Reduction	2.0 (2010) 3.5 (2020)
Turbocharging	6.5
DI+Turbo	11.0
Transmissions	
CVT	7.0
5 Speed Automatic	2.4
6 Speed Automatic	4.3
Aggressive Shift	1.5
Accessories	
Electric power steering	1.5
Improved Alternator	1.0
Low Friction Oil	0.5

(Provided by K. G. Duleep, EEA Inc.)

XI. Appendix 4: Calculation of LDV Fuel Consumption

Fuel consumption, as used in this report, has units of gasoline equivalent gallons/mile, or energy/mile. To determine the total change in fuel consumption from a series of steps, use the formula:

$$R_T = 100 \times \{1 - \prod_{i=1}^{n} (1 - r_i/100)\}$$

where:

R_T = total reduction in fuel consumption, %

r_i = reduction in fuel consumption for step i, %

Two examples illustrate the calculation and show steps that might be taken to achieve 50% reduction in fuel consumption. All values are taken from Table IIIB.2.

Example 1 (2030)

r_1: Engine efficiency Level 3, 16%

r_2: Body improvements Level 3, 12.5%

r_3: Driveline improvements Level 2, 7%

r_4: Fueled Hybrid, 27%

Total improvement (%) = 100 x {1 - (1 - 0.16) x (1 - 0.125) x (1 - 0.07) x (1 - 0.27)}

= 100 x {1 - 0.84 x 0.875 x 0.93 x 0.73}

= 100 x {1 - 0.50}

= 50%

Example 2 (2030)

r_1: Diesel Engine, 17%

r_2: Driveline improvements, 7%

r_3: Body improvements Level 3, 12.5%

r_4: Fueled Hybrid, 26%

Total improvement (%) = 100 x {1 - (1 - 0.17) x (1 - 0.07) x (1 - 0.125) x (1 - 0.26)}

= 100 x {1 - 0.83 x 0.93 x 0.875 x 0.74}

= 100 x {1 - 0.50}

= 50%

In each example, the fuel consumption benefit for hybrids is chosen within the range of possible outcomes to achieve a 50% total reduction. As such, it is illustrative of the possibility and is not meant to represent an actual outcome.