Appendix C-3

TECHNOLOGY ASSUMPTIONS

C-3 TRANSPORTATION

C-3.1 AIRCRAFT TECHNOLOGY

The AEO99 includes six advanced technologies for commercial aircraft, shown in Table C-3.1. Also shown are the assumed introduction dates and fuel economy gain, in terms of a percent increase in seat-miles per gallon. Four other factors complete the inputs to the air model: (1) load factors for domestic and international operations, (2) deliveries of new aircraft by narrow and wide-body categories, (3) average aircraft size in terms of seats per aircraft for narrow and wide-body jets, and (4) efficiency improvement rates for the existing stock due to engine retrofitting and other strategies.

Table C-3.1 AEO99 Aircraft Technology Assumptions

Technology	Introduction Year	Jet Fuel Trigger Price (1987 $ per gallon)	% Gain in SMPG
Ultra-high bypass engine	1995	$0.56	10%
Propfan engine	2000	$1.36	23%
Hybrid Laminar Flow	2020	$1.53	15%
Advanced Aerodynamics	2000	$1.70	18%
Material Substitution	2000	$0.00	15%
Engine Thermodynamics	2010	$1.22	20%

Since jet fuel prices in the AEO99 Reference Case never exceed $6.31 per million Btu ($0.85/gallon) one would expect that only the ultra-high bypass engine and materials substitution technologies would enter the Reference Case, since the trigger price level for all other technologies would not be met.

The Aeronautics and Space Engineering Board of the National Research Council (1992, p. 49) concluded that it was feasible to reduce fuel burn per seat mile for new commercial aircraft by 40 percent by about 2020. Of the 40%, 25% was expected to come from improved engine performance, and 15% from improved aerodynamics and weight. A reasonable preliminary goal for reductions in NO_X emissions was estimated to be 20-30%.

Noting that the energy efficiency of new production aircraft have has improved at an average rate of 1-2% per year since the dawn of the jet era, a recent IPCC (Lewis and Niedzwiecki, 1999) expert panel concluded that similar rates of improvement could be expected through 2050. Only about a 20% improvement in seat-kilometer per kg of fuel was expected for the 18 years from 1997 to 2015, however (Table C-3.2).

To the list of technologies in the AEO99 Reference Case, the IPCC study adds the blended wing body a revolutionary airframe design that transforms an aircraft into essentially a flying wing, resembling the military s stealth aircraft in appearance. The extension of the cabin into the wing allows the drag associated with the traditional aircraft body to be reduced, and permits some weight reduction, as well. Unfortunately the authors do not offer a specific numerical estimate for the reduction in fuel burn the blended wing body might achieve, noting only that fuel burn could be reduced significantly relative to that of conventionally designed transports. (Lewis and Niedzwiecki,1999,p. 7-13). They further estimate that an initial version could enter service in 2020.

Table C-3.2 Historical and Future Improvements In New Production Aircraft Energy Efficiency (Percent)

Time Period	Airframe	Propulsion	Total	%/year
1950-1997	30	40	70	1.13
1997-2015	10	10	20	1.02
1997-2050	25	20	45	0.70

Source: Lewis and Niedzwiecki, 1999, table 7.1.

In operation, aircraft seat-miles per gallon are also influenced by aircraft size, and overall passenger-mile per gallon efficiencies are determined by load factors, as well. The AEO99 assumes that load factors in domestic operations will reach a plateau of 69% around 2010, and that international load factors will flatten out at 72% just after the turn of the millennium. According to Boeing (1998, p. 13) U.S. airlines load factors exceeded 70% for the first time in 1997. Boeing analysts (Henderson, 1999) forecast an increase in global load factors to 73% by 2018. They see only a small potential for increasing aircraft size, however, with most additional capacity expected to be supplied by increased flight frequencies. The AEO99 Reference Case assumes no increase in aircraft size at all through 2020.

Lewis and Niedzwiecki (1999) note that, As always progress and success in meeting these objectives is paced by the scale of the investment by industry and/or government supporting the work, a subject beyond the scope of this report.

C-3.2 MARITIME ENERGY USE

Domestic and foreign shipping[1] and recreational boating consume about 6 percent of U.S. transport energy use, or about 1.5 quadrillion Btu (Quads)[2] out of a total of about 24 Quads used for transportation in 1996. Freight shipping consumes about 1.17 Quad of the 1.5 Quad total. Domestic shipping consumes about .315 Quad or about one quarter of freight shipping energy, and carries about 1.1 billion tons of cargo annually on about 41,000 ships. Recreational boating consumes mostly gasoline; freighters consume residual fuel oil and diesel, with resid taking a three quarters share in domestic shipping and dominating foreign long-haul shipping..

The dominant propulsion source in freight shipping is the diesel engine. Internationally, 98 percent of freighters are powered by diesels, although the 2 percent of ships that are powered by steam-electric propulsion are the largest ships — tankers, bulk carriers, and some containerships —and carry 17 percent of the gross tonnage.[3] Because most steam-powered vessels are expected to be replaced with diesel-powered ships within the next 10 years,[4] any examination of future shipping energy use can focus exclusively on diesels.

Diesel marine power plants are extremely efficient. Older diesel engines may have efficiencies of about 35 percent peak/28 percent part load. Modern diesels are more likely to have efficiencies of about 46-47 percent peak/36 percent part load. Assuming that most freighters use their engines at peak load during the greater part of their journeys, the diesel drivetrain aboard a modern freighter may obtain greater than 40 percent efficiency (45 percent engine,[5] 97 percent reduction gear and shafting yields 42 percent efficiency from engine to propeller).[6]

Both the U.S. military and MARAD, the Maritime Administration within DOT, have focused attention on fuel cells as a less polluting and more efficient alternative to current marine power plants. Design studies have identified some of the following potentials for fuel use reduction:

- Coast Guard cutter conversion from diesel electric to Molten Carbonate fuel cell system using a diesel fuel reformer; the estimated fuel cell system efficiency is 54 percent, coupled with weight reduction from removal of exhaust stacks and sound isolation bedplate required for diesel engines, yielding much improved efficiency
- Navy design study converting from gas turbine generator to PEM fuel cell with diesel reformer, yielding 30 percent fuel reduction
- MARAD study replacing medium-speed diesels with molten carbonate fuel cells using natural gas, yielding 17 percent decrease in fuel use; adding a steam turbine bottoming cycle to the fuel cells boosts system efficiency to 64 percent.[7]

The efficiency superiority of fuel cells over diesel systems is not assured. Recent studies of PEM fuels cells for highway use[8] have questioned whether fuel cells coupled with fuel reformers (in this case, methanol and gasoline) will be as efficient as modern diesel systems. To convert these results to a marine context, note that diesel fuel reforming should be no more efficient than gasoline reforming, and marine diesels are spared some of the transmission losses incurred in highway duty cycles. Although molten carbonate/natural gas systems might yield a more definitive efficiency advantage, reliance on natural gas as a fuel might not be attractive to freight carriers without extensive fuel infrastructure development.

Aside from propulsion system improvement, there are a number of measures that can be taken to improve ship efficiency, including:

1. propeller maintenance (<5% improvement in fuel use)
2. antifouling paint (3-4%)
3. weather routing (4%)
4. adaptive autopilot (2.5%)
5. changes in hull form (3%)
6. larger ships (to 30% for doubling size)
7. fuel switching (reduction in greenhouse gases)[9]

Presumably, many ships will adapt some of these measures as a matter of course, on the basis of fuel savings and without need of new government policies. Fuel switching is less likely to be adopted without government support of fuel infrastructure development. The use of larger ships, though offering significant fuel savings, may be less attractive to ship purchasers because of port limitations and, perhaps, the greater capital risk inherent in such ships.

OECD has identified a number of policies that could be used to improve ship efficiency, including charges and fees varying by efficiency; direct regulations; voluntary agreements; best practice programs such as EPA s Energy Star Program; technology prizes (golden carrots); and increased RD&D through government programs or tax incentives. Programs like voluntary agreements, best practice programs, and increased RD&D fit in well with the Moderate Scenario definition; direct regulations and efficiency-based charges and fees could be added for the Advanced Scenario. How might such programs translate into changes in projected levels of shipping energy consumption and greenhouse gas emissions?

EIA s AEO99 projects that domestic shipping efficiency will increase at the rate of 0.5%/yr from 1996-2020, in contrast to the historical domestic plus foreign shipping in the U.S. efficiency growth rate of about 1%/yr.[10] The actual growth rate could be higher if more ship owners used the available efficiency-enhancing maintenance measures and operational changes and shipbuilders used enhanced hull designs and increased use of fuel cell propulsion. Our assumptions for the Moderate and Advanced Scenarios are as follows:

1. For both scenarios, improved maintenance and operations can attain a 10 percent fuel efficiency improvement for each ship that adopts them.

2. The combination of fuel cell propulsion and advanced hull design can achieve a 20 percent efficiency improvement per ship.
3. Assumed baseline: 20 percent of ships adopt improved maintenance and operations by 2020; negligible number of ships with advanced hull design and fuel cell propulsion..
4. Moderate Scenario: 60 percent of ships adopt improved maintenance and operations by 2020; 5 percent of ships have advanced hull design and fuel cell propulsion by 2020; **fleet improvement 5 percent.**
5. Advanced Scenario: 90 percent of ships adopt improved maintenance and operations by 2020; 15 percent of ships have advanced hull design and fuel cell propulsion; **fleet improvement 9 percent.**.

C-3.3 RAIL ENERGY USE

U.S. railroads consumed about .578 Q in 1996, about 2.4 percent of U.S. transportation's approximately 24 quads of energy use.[11] By far the greater share of this energy use, .499Q, was consumed by freight carriers. Passenger carriers consumed the rest, with AMTRAK consuming .043Q in intercity passenger service, rail transit systems consuming .012Q, and commuter rail consuming .023Q.

In other words, rail passenger service plays a very small role in U.S. transportation. The combination of AMTRAK and transit and commuter rail lines service about 26 billion passenger-miles yearly, only .4 percent of total U.S. passenger travel. This leads to some interesting conclusions about prospects for using rail systems to increase the efficiency of U.S. passenger travel. First, were the U.S. to double its total rail passenger patronage —a difficult goal, certainly —it would reduce travel on other modes by only .4 percent, assuming that all such trips involved modal shifts rather than induced trips. Second, the actual energy savings of such modal shifts are quite varied. Table C-3.3 shows a comparison of the energy intensities of competing modes, adjusted for likely travel conditions and passenger occupancy rates. For increases in intercity rail, energy savings in modal shifts from air travel would be significant. In contrast, modal shifts from autos would yield minimal savings unless the increases in rail passenger loads are obtained by higher occupancy rates (e.g., from lowering fares) —which would allow the additional rail trips to be made with virtually no additional energy use. This is because intercity auto trips tend to be relatively efficient highway trips with higher-than-average vehicle occupancy rates —on average, they are as energy-efficient as rail intercity trips. Additionally, if passenger rail competes for modal share by moving to high speed service, its energy efficiency should be reduced somewhat[12] —making overall energy savings even more problematic. On the other hand, shifts from auto to commuter rail or rail transit services should yield substantial per-trip energy savings because the auto trips replaced are primarily work trips with low average auto occupancy, under congested (thus energy-inefficient) traffic conditions. An important uncertainty in such shifts, however, is introduced by the possibility that the auto commuters most likely to shift to transit may be those most likely to carpool; a three-person carpool is more efficient than any type of transit.

Table C-3.3 Modal Shifts to Rail: Comparison of Energy Intensities

RAIL MODE	BTU/PM	SHIFT FROM	AVG BTU/PM	ADJUSTED BTU/PM*
Intercity	2389	auto	3671	2470
Intercity	2389	air	4000	4000
Transit	3444	auto	3671	6000
Commuter	2855	auto	3671	4670

*Adjustments made to average energy intensities to account for different-from-average driving conditions and vehicle occupancy rates (e.g., auto trips that compete with rail transit tend to be made under congested driving with low occupancy rates)

In 1996, railroads moved nearly 1400 billion ton-miles of freight, over one-third of all U.S. freight transport. Much of the goods moved are bulk cargo; coal makes up about one-quarter of rail ton-miles, and the combination of farm products, chemicals, and nonmetallic minerals makes up another fifth. Rail does not compete with trucks for this cargo —it is the higher value, often time-sensitive cargo for which rail and trucks compete. Current trends in freight movement show significant growth in multi-modal traffic, much of it truck/rail; this allows the long-haul portion of many shipments to be made in containers on rail, often stacked double. Accelerated capture of long-haul cargo by rail would save energy. Although rail s average (nearly) 8 to 1 superiority over trucks in energy efficiency is misleading because of the large share of dense, easy-to-haul bulk cargo on rail, rail and truck simulation studies show that rail retains a substantial efficiency advantage for similar cargo —more than 2:1 for hauling automobiles, for example, to 4:1 or better for mixed freight.[13] The same simulations show that doublestack container shipment via rail is about twice as efficient as competing truck shipment.

During the past two and a half decades, rail freight energy efficiency has improved steadily; energy intensity has declined from 717 Btu/ton-mile in 1971 to 368 Btu/ton-mile in 1996, a rate of decline of 2.4 percent/yr. OTA[14] attributed this decline to:

1. Increase in average trip lengths, with fewer stops and greater sustained speeds,
2. Operations and communications improvements, including improved routing, scheduling, etc., and
3. Technical improvements, including improved wheel-slip detection, flange lubricators, better aerodynamics, etc.

A study by Oak Ridge National Laboratory[15] concluded that 85 percent of the energy savings between 1972 and 1992 was due to increased ton-miles per car-mile, that is, simply higher car loadings. Part of this improvement was associated with large increases in the bulk hauling of coal and other commodities, which may not be repeated, and part due to operational improvements, which may have room to continue.

A 1991 study by Abacus Technology documents both available rail efficiency technology and the extent to which it is being used. Key technologies include:

1. Locomotive design
   - Engine redesign, including larger turbocharger, lower idle
   - More efficient auxiliary equipment (better matching of equipment to needs; electrical rather than mechanical drive for cooling fans, braking auxiliaries; more efficient traction motors; wheel slip detection; better controls)
   - flange lubricators
2. Equipment changes
   - Lighter, more aerodynamic cars
   - Air foils
   - Improved trucks/self-steering, improved alignment and lower wheel slippage
   - Improved bearing seals
3. Improved operations
   - Reduced idling
   - Better dispatching
   - Better pacing to reduce stops

Between 1977 and 1990, the number of Class I locomotives in service dropped from 27,298 to 18,835[16], implying that more than 2/3 of the 1977 fleet was retired during the '77-'90 period. Since 1990, the number of locomotives has stabilized and even increased a bit. Recent data shows that the age distribution of locomotives remains biased towards an older fleet: 27% built since 1/1/90, 23% built between 1/1/80 and 1/1/90 (9-19 years old) and fully 50% built prior to 1/1/80 (18 years old and older).[17] However, this age distribution is unlikely to be reflected in ton-miles hauled, because the oldest locomotives are downgraded to yard and local service and are not used as intensively as newer, more efficient locomotives.

Abacus' research indicates that new generation locomotives are significantly more efficient than those they replace. On the other hand, it appears that railroads are not widely adopting the latest improvements in railcar design. Finally, about one-fifth of locomotives in 1990 were equipped with flange lubricators, with about 3500 systems installed; the current number is higher, apparently about 4,000-5,000, or about 20-25% of all locomotives.[18] Because one flange lubrication system is adequate for a complete train and most trains have multiple locomotives, it is conceivable that a substantially higher percentage (than 20-25) of trains use flange lubrication.

This information is not readily translatable into estimates of future energy efficiency, but some general idea about improvement potential can be postulated. First, as of the end of 1997, about 50 percent of the locomotive fleet was purchased before 1980, though they will all have been rebuilt during their lifetimes, perhaps a few times. Perhaps 75% of locomotives will still not be equipped with flange lubricators, though the percentage of *trains* unequipped with lubricators will be substantially lower than this. Further technical potential clearly exists, with the Association of American Railroads suggesting that wheel slip detection and improvements in motors present important opportunities for increased efficiency in the locomotive fleet.[19]

There has been very substantial consolidation of freight service during the past decade, but there are still opportunities for further consolidation and efficiency gains, e.g. in the East when Norfolk Southern and CSX integrate Conrail s operations into their own. This kind of consolidation would yield an increase in multimodal transport — long haul truckcargoes converted to rail —in addition to the efficiency gains for existing traffic.

A countervailing efficiency effect could be associated with the Environmental Protection Agency s new emission standards for NO_X, hydrocarbons, and particulates, reducing NO_X by 2/3 and the other pollutants by half.

EIA s 1999 Annual Energy Outlook projects an 0.5%/yr growth in rail energy efficiency between 1997 and 2020, a modest rate in comparison to the historic (1970-1996) rate of 2.4%/yr, and the more recent rate of 2.7%/yr (1986-1996). This rate appears low in light of the remaining potential for efficiency gains. We postulate that government policy that encourages those remaining consolidation opportunities that promise real efficiency gains, coupled with an increased R&D budget and tax incentives for energy efficiency measures, should be able to boost efficiency gains to 1.0%/yr in the moderate case and 1.5%/yr in the advanced case (but we believe that continuing the high historic rate of increase is unlikely, based on analysis of the importance of increased loadings in the efficiency gains). Further, we postulate that policies that help freight railroads add to capacity and improve their multimodal operations, in addition to the consolidation mentioned above, will draw added traffic into rail from trucks, with a corresponding net reduction in freight energy use and greenhouse emissions. We postulate that 2 percent of truck freight in the Moderate Scenario and 5 percent in the Advanced Scenario are shifted to rail. For the year 2020, the shifts are approximately 33 billion ton-miles for the Moderate Scenario and 83 billion ton-miles for the Advanced Scenario.[20]

C-3.4 Light Duty Vehicles

The current NEMS model contains a detailed representation of technology improvements to cars and light trucks and these technologies define the forecast of vehicle characteristics. Technology improvements can be discussed in six vehicle areas: weight reduction, aerodynamic drag reduction, engine improvements, transmission improvements, reduction in rolling resistance and accessory loss reduction. All technology improvements are considered holding vehicle attributes of size, ride, and acceleration performance constant, relative to a 1990 baseline.

The following discussion first presents technology characteristics of the NEMS version currently in use by the Energy Information Administration, and then presents changes made to the technology characterizations for the Clean Energy Futures study.

EIA VERSION OF NEMS (EIA-NEMS)

Weight reduction by material substitution is considered for four material types, reflecting advances in materials technology. More extensive use of HSLA steel is already in progress and can deliver a five percent weight reduction at low cost of about $0.50 per pound saved. Greater use of composite materials in body panels, low temperature engine parts and vehicle interiors can save an additional five percent at $0.80 per pound saved. An aluminum intensive design retaining the current unibody structure can reduce 20 percent of the weight of the baseline (1990) vehicle while an intermediate step of plastic/aluminum use can reduce weight by 15 percent. These options are priced at $1.50 and $1.00 per pound saved, respectively.

Drag reduction from the baseline level of an equivalent CD of 0.36 is available in steps of -0.03 CD to a minimum CD of about 0.25. It should be noted that most cars have a CD between 0.30 and 0.33 in 1999.

Engine related improvements include those related to engine breathing that increase engine specific output, and those related to engine friction reduction. At constant performance, improved engine output can be translated to increased fuel economy by reducing engine size. The use of port fuel injection, four-valves or five-valves per cylinder and overhead camshafts instead of pushrod activated valves are the engine breathing related technologies. (These technologies are already widely available in 1999). Friction reduction technologies include roller cam followers, roller rockers, low tension rings, low mass pistons and valves, and improved lubricants. Except for roller followers/rockers, all other technologies are expected to contribute to a 25 percent reduction in friction mean effective pressure over the 1990-2020 period, corresponding to a four percent increase in fuel economy. Roller followers/rockers contribute an additional 1.5 percent increase in fuel economy.

A specialized type of engine is the direct injection engine (gasoline engine). EIA-NEMS estimates that fuel economy improvement (compared to a modern 4-valve OHC engine) from this type of technology, which enables lean combustion, is 17 percent. Variable valve timing (VVT) is another new technology that reduces pumping loss. A simpler form of VVT currently used by Honda is estimated to provide a seven percent benefit in fuel economy, while a more advanced fully controllable system can provide a ten percent benefit in fuel economy. The benefits of these different engine technologies are not additive.

Transmission related technologies are primarily related to providing more gear ratios. Four-speed automatic transmissions are currently used in almost all vehicles, while the three-speed was more common in 1990. The five-speed automatic has recently become available in some vehicles. Continuously Variable Transmissions (CVT) are an emerging technology whose design may make it limited to lower power applications. The five-speed transmission is expected to provide a two percent benefit over the four-speed, while the CVT is expected to provide a five percent fuel economy benefit. Advanced electronic control of transmissions adds another one percent in fuel economy benefit.

Low rolling resistance tires are possible due to improvements in tread design, sidewall construction, and rubber compounding. The NEMS model has technologies that reduce overall rolling resistance by 25 percent from the 1990 base rolling resistance coefficient (CR) of 0.010 to 0.0075, with no reduction in other desirable properties such as wet traction or braking, over the 1990-2020 period.

Accessory improvements include both minor ones relating to reducing friction in the belt drive system and using higher efficiency alternators, to major ones such as the electric power steering to replace the hydraulic system. The EPS alone provides a 1.5 percent increase in fuel economy while the sum of all other improvements provides a 1.0 percent fuel economy benefit.

A composite profile of the benefits of all possible technologies in EIA-NEMS is illustrated by constructing a hypothetical car that includes all technologies that can be used together. Table C-3.4 shows the car characteristics for 1998 and 2015, using a mid-size car such as the Chevy Malibu as the 1998 example. The model projects a 63 percent increase in fuel economy from 27 MPG to 44 MPG at constant attributes. However, the introduction of Tier II emission standards and new safety requirements for side air bags and roof crush requirements —not modeled in EIA-NEMS -- would reduce the overall fuel economy of the hypothetical vehicle to about 42 MPG. Of course, the NEMS model adopts a distribution of technologies based on the cost-effectiveness of each marginal technology, so that this example can be considered as an asymptote to the possible range of outputs for a mid-sized vehicle s fuel economy, with conventional technology.

NEMS also features a gasoline hybrid drivetrain as an option, but it is treated as an alternative fuel vehicle in a submodel that is separate from the submodel that deals with gasoline-fueled conventional vehicles. EIA-NEMS attributes a 45 percent fuel economy benefit to the hybrid drivetrain relative to a base (1990) drivetrain, or about a 30 percent benefit relative to a modern four-valve OHC engine (and less relative to a GDI engine). EIA-NEMS model sets a very high price for the hybrid vehicle. The computation of price, which varies by vehicle weight, would add $9300 to the price of the hypothetical 2015 mid-size vehicle; the vehicle would yield a fuel economy of about 54 MPG if equipped with the full range of other applicable fuel economy technologies, i.e. low rolling resistance tires, aluminum body, etc.

Table C-3.4 Hypothetical Mid-Size Car Improvements (in EIA-NEMS)
(Constant Attribute Case)

Attribute	1998	2015
Weight (lbs.)	3130	2480
Drag Coefficient	0.33	0.25
Rolling Resistance	0.010	0.0075
Engine Type	OHV V-6	DOHC I-4w/VVT
Displacement	3.1 L	2.0 L
Combustion	Homogenous Charge	Stratified Charge
Fuel System	Sequential FI	Direct Injection
Power	160 HP	150 HP
Transmission	4-speed with lock-up	CVT
Steering	Hydraulic	Electric
Fuel Economy (EPA)	27 MPG	44 MPG
Price	Base	+2400
Effects of Future Standards	Base	-2 MPG

CHANGES TO THE NEMS MODEL

EIA has made relatively conservative assumptions about technology in its Reference Case for AEO99, and there exists substantial potential for more optimistic technology assumptions based on different scenarios of technology development and market conditions. A detailed examination of the potential of all of the technologies in the NEMS model suggested that particularly likely technology areas for more optimistic assumptions are material substitution, hybrid vehicles, and fuel cells. We also found that changes were justified in the assumptions about direct injection gasoline engines.

In addition, changed market conditions would likely affect NEMS s calculations of vehicle weight and size; NEMS has built-in factors that increase the weight and size of cars and light trucks within each class over time. For AEO99, EIA extrapolated the weight increase from the observed increase during the period 1987-1996, assuming it would continue at the same rate over the forecast periods. CEF-NEMS uses more optimistic assumptions: for the Moderate Scenario, total weight increase to 2020 for light trucks was decreased by 10 percentage points; for the Advanced Scenario, weight and size were capped at 1998 levels.

The potential for material substitution appears to be greater now than the effect modeled in EIA-NEMS. Several manufacturers have displayed prototypes, such as the Ford P2000, that maintain the same interior room as a mid-sized car but provides a 30 percent weight reduction, or about 1000 lbs at constant attributes, relative to current vehicles.[21] Such cars use more than aluminum, with materials such as magnesium for castings, and titanium alloys in suspension parts. In addition, the costs of material substitution are also being reduced. Recent studies by IBIS have shown that space frame based aluminum body-in-white structures can be assembled for a total cost penalty of less than $1.00 per pound saved, while new casting techniques and forming techniques for aluminum have reduced total manufacturing costs by 30 percent. As a result, the NEMS cost estimates for various levels of material substitution have been reduced by 20-33 percent.

In addition to the increased weight reduction and reduction in cost, it now appears that the technologies could be available sooner than forecast. Ford has announced a first generation aluminum intensive vehicle to be introduced in 2002, and even the highly weight efficient designs that can achieve 30 percent weight reductions are likely to be available by 2007. These time frames are significantly earlier than those forecast in EIA-NEMS.

On the issue of Gasoline Direct-Injection (GDI) engines, EIA-NEMS used a fuel efficiency benefit estimate of 17 percent, which now appears too high. Part of the problem is associated with new regulatory requirements that have added a high speed/load test cycle for meeting emission standards, which impact the GDI engine s ability to maintain lean operation over a wide speed/load range. Newer data suggest that a more reasonable fuel economy benefit estimate is 12 percent, with 15 being the most optimistic estimate. The cost numbers in the NEMS, however, appear significantly higher than the values derived from a recent study sponsored by NRCanada. The study estimates that the price impact of a four-cylinder GDI in $200 (increment) and a six-cylinder GDI in $300. Due to the need for low sulfur fuel, commercialization across the U.S. is not expected till 2004, when such fuel will likely be available.

The fuel economy benefit of hybrids has long been a subject of debate but with the release of the Toyota Prius, an actual comparison can be made. The EPA estimated that the Prius tested on the U.S. FTP cycle was 64 percent better in fuel economy than the average 1998 car in the 3000 lb test weight class, but had significantly lower performance. Adjusting for performance, the EPA estimated that the Prius was 45 percent more efficient than the average car, which is numerically identical to the benefit included in NEMS. The NEMS benefit is with reference to a 1990 baseline, so that the improvement numbers are not directly comparable. Relative to a similarly sized (but lighter) Toyota Corolla, the Prius shows 39 percent better fuel efficiency, which is higher than the NEMS estimate relative to a car with a four-valve engine and four-speed automatic transmission, but approximately constant with the NEMS estimate after performance differences between the Corolla and Prius are accounted for. In addition, the Prius is a first generation hybrid not optimized for U.S. conditions or the FTP cycle, and Toyota has announced that the U.S. model (to be introduced in 2000) will do better. Hence, a more optimistic estimate of 55 to 60 percent appears plausible for fuel economy benefit, even in the short term.

As noted earlier, EIA-NEMS assumed a very high cost for hybrids, about a $9,000 price increment even for a high volume production car. Estimates by OTA and more recent estimates from DOE based on Prius component costs suggest that the price increment will be in the $4000 range for a mid-size car weighing 3000 lbs, and will be lower for lightweight cars (since many of the major cost components scale according to vehicle weight). In the short run, with low volume production, automanufacturers appear willing to subsidize the low volume cost penalty as a short term loss, according to most published reports.

ALTERNATIVE FUEL VEHICLES

The NEMS model also contains data on a wide variety of alternative fuel vehicle technology costs, and considers both the diesel and fuel cell vehicle (powered by hydrogen, methanol or gasoline) in this context. Recent development in diesel engine technology and fuel cell technology have caused a need to re-examine NEMS assumptions.

Turbocharged direct injection four-valve diesel engines have essentially matched the performance of gasoline engines in terms of acceleration, noise, smell, vibration and harshness. Even at current low fuel prices, diesels have proved surprisingly popular in the 8500 to 10,000 lb GVW heavy pickup trucks; over 60 percent of these vehicles sold by Ford and Chrysler are diesel powered in spite of a retail price increase of almost $3000. Major diesel engine manufactures have unveiled V-6 diesel engines for use in the 5000 to 8500 lb GVW range of trucks, and Navistar has a firm contract with Ford to supply such engines starting in the 2001 model year. The EIA-NEMS estimates of fuel efficiency benefit (40 percent) and high volume price increment ($1600) seem reasonable but the availability dates need to reflect current plans. In addition, the issue of any low volume price penalty now seems less significant.

Fuel cell commercialization now seems close at hand. Several manufacturers have announced plans to sell a fuel cell vehicle in model year 2004 or 2005, although these are unlikely to be high volume products.

Current fuel cell costs are far too high – hundreds of dollars per kilowatt of peak capacity – to be competitive in vehicle markets, and successful commercialization will obviously depend on manufacturers' capability of improving stack design, increasing the efficiency and reducing the costs of fuel reformers, and a host of other tasks to bring system costs into the competitive range. DOE's Office of Advanced Automotive Technologies has developed a number of mid-term (primarily for the year 2004) cost goals for the several key areas of fuel cell systems (OAAT, 1998):

• Fuel cell stack (using reformate)	$35/kW
• flexible fuel processor	$10/kW
• hydrogen storage	$10/kWh
• integrated fuel cell system	$50/kW
• electric motor/controller	$11/kW ($10/kW for 2006)

The OAAT goals represent some combination of "what appears to be achievable?" and "what is the progress required to allow commercialization?" with emphasis on the former. Although the goals are set for 2004, a relatively early date in the likely lifetime of fuel cell development, OAAT interprets them as relatively mature cost values – that is, incorporating enough learning so that further large reductions in cost would not be likely (Patil, 1999).

The OAAT goals appear relatively comparable to fuel cell cost projections developed by Directed Technologies Incorporated (DTI, 1998) in a detailed study for the National Renewable Energy Laboratory. DTI proposed a fuel cell vehicle with power storage (for peak power and cold start) provided by hydrogen storage in a buffer, rather than the more common concept of a fuel cell hybrid with battery storage. In the DTI design, the fuel cell is sized to provide approximately 50 kW/metric ton of vehicle weight. Given the weight of hydrogen storage, the fuel cell itself, and the electric motor and controller, DTI estimated that the hydrogen fuel cell would be about 6.7 percent heavier than a conventional vehicle of equal size and performance. A methanol fuel cell vehicle would be 16.2 percent heavier and a gasoline fuel cell vehicle 20.8 percent heavier than the conventional vehicle, with the added fuel reformer and increased fuel cell stack size outweighing the lower fuel storage weight.

Although we recognize that any cost estimates for fuel cell systems must have wide uncertainty bands around them, we accept the DTI cost estimates as one feasible outcome of current research directions, though not the only one.[22] Table C-3.5 uses the projections in the DTI report to NREL to estimate retail price equivalent (RPE) increase targets for different fuel cell types starting from a base mid-size car weighing 3130 lbs, with different target years for the two scenarios (we assume different rates of cost reduction in the Moderate and Advanced Scenario). Fixed cost amortization is based on a production volume of 25,000 units per year with an initial investment of $25 million increase over a high volume engine plant, or about $50 to $60 million for a low volume plant to build the fuel cell stack and reformer. An important difference between the final retail price equivalent values in the Table and the DTI values, however, is the higher overhead (75%) charged to the technology production costs. Although there is considerable controversy about appropriate overhead charges to be applied to high-cost advanced technologies, we believe that *in the absence of a compelling argument that the new technology will yield significant reductions in overhead costs*, it is prudent to assume that full overhead rates should be applied to cost increases associated with these technologies. We assume that the target year prices do not represent the final (lowest) prices, since fuel cells will still be a relatively young technology at that point. Given that the Moderate and Advanced Scenarios are putting different levels of resources into fuel cell R&D, we assume that RPEs will continue to drop after the target prices are reached, but far more slowly than in the previous years. Specifically, we assume that the target prices are reached in approximately 2011 in the Advanced Scenario and 2016 in the Moderate Scenario; by 2020, prices have dropped to about 69 percent of the target prices in the Advanced Scenario, and 92 percent in the Moderate Scenario.

Table C-3.5 IRPE Target Computation for Fuel Cell Vehicle @ 25,000/yr.
(For a Current Mid-Size Car)

	Hydrogen	MeOH	GASOLINE
Stack Cost	2750	2900	2970
Motor cost	880	935	960
H2 Tank Cost	935		
Buffer Cost		100	100
Reformer Cost		1640	3400
Total Cost	4565	5575	7430
Less Engine/Trans	(2700)	(2700)	(2700)
Fixed Cost Amortization	280	330	350
IRPE	3660	5510	8820

DTI's estimates of vehicle efficiency improvements are quite similar to those in NEMS for a hydrogen-powered vehicle, but are substantially lower for a methanol or gasoline powered fuel cell. Relative to a current technology vehicle, the hydrogen fuel cell was expected to provide a 162 percent improvement in fuel efficiency (based on hydrogen energy), while a methanol powered fuel cell was expected to be 75 to 95 percent more efficient. Benefits for the gasoline powered fuel cell were estimated to be quite low at 23 to 71 percent with the range reflecting uncertainty in the performance of the reformer that converts methanol or gasoline to hydrogen. Other researchers at A.D. Little have suggested that the upper end of the range of efficiency benefit estimates are more reasonable, since (they claimed) the lower end combined pessimistic estimates for the efficiency of several components simultaneously. We assumed for both scenarios that the hydrogen fuel cell *would* achieve the estimated 162 percent improvement, with the methanol fuel cell vehicle achieving a 95 percent efficiency increase and gasoline fuel cell vehicles achieving a 70 percent increase.

Table C-3.6 presents the original (EIA-NEMS) and revised (CEF-NEMS) versions of the advanced conventional vehicle, and the revised versions of the hybrid vehicle and methanol fuel cell vehicle. Note that these vehicles represent essentially the best cars available in each category; they incorporate *all* of the available fuel efficiency technology in aerodynamics, materials, tires, and powertrain. New car fleet fuel economy averages would be considerably below the fuel economy levels of these vehicles. Note also that the percentage improvements shown for both the hybrid and fuel cell vehicles are substantially less than discussed earlier; this is because the 2015 conventional vehicle contains a much more efficient drivetrain than the current technology drivetrain for which the percentage improvements apply.

Table C-3.6 Hypothetical Mid-Size Car Revised Technology Benefits (CEF-NEMS Versions)

	2015 (NEMS)	**2015 Revised**	**2015 Hybrid**	**2015 Fuel Cell (Methanol)**
Weight (lbs)	2480	2195	2300	2550
Drag Coefficient	0.25	0.22	0.22	0.22
Rolling Resistance	0.0075	0.0075	0.0075	0.0075
Engine Size	2.0L	1.8L	1.2 L	Fuel Cell
Engine Power	150 HP	135 HP	50 HP + 20 kW	58 kW
Transmission	CVT	CVT	Electro-Mech	Electric
Fuel Economy (EPA Combined)	44 MPG	46.5 MPG	60.5 MPG	71.2 MPG (gasoline equivalent)
Incremental Price (1990$)	$2,400	$2,120	$3,350 (Advanced Case)	2010/2015 $3,500/$2,050

C-3.5 REFERENCES

1. Boeing Commercial Airplane Group Marketing, 1998. *1998 Current Market Outlook*, Seattle.
2. Henderson, S., 1999. Load Factors , personal communication, April 19, Project Director - Airline Industry Analysis, Boeing Commercial Airplanes, Seattle.

3. Lewis, J.S. and R. W. Niedzwiecki, 1999. Aircraft Technology and its Relation to Emissions , chapter 7 in, *Aviation and the Global Atmosphere*, Intergovernmental Panel on Climate Change, Oxford University Press, Oxford.
4. National Research Council, Aeronautics and Space Engineering Board, 1992. *Aeronautical Technologies for the Twenty-First Century*, National Academy Press, Washington, D.C.
5. Office of Advanced Automotive Technologies, 1998. *Office of Advanced Automotive Technologies R&D Plan; Energy-Efficient Vehicles for a Cleaner Environment*, U.S. Department of Energy, DOE/ORO/2065, March.
6. Patil, P., 1999. Personal communication, Office of Advanced Automotive Technologies, U.S. Department of Energy, September 1, 1999.
7. Thomas, C.E., B.D. James, F.D. Lomax, Jr. and I.F. Kuhn, Jr., 1998. Integrated Analysis of Hydrogen Passenger Vehicle Transportation Pathways, prepared for the National Renewable Energy Laboratory under Subcontract No. AXE-6-16685-01, March.

---

[1] Domestic shipping involves shipping between U.S. ports or within U.S. waterways, including Puerto Rico and the Virgin Islands; foreign shipping involves shipping between U.S. and foreign ports.

[2] 1.46 Quads according to the 1998 Transportation Energy Data Book, 1.43 Quads according to the 1999 Annual Energy Outlook.

[3] Michaelis, L., 1997. Policies and Measures for Common Actions Working Paper 11. Special Issues in Carbon/Energy Taxation: Marine Bunker Fuel Charges, Annex I Expert Group on the UN FCCC, OECD and IEA, March (OECD/IEA Working Paper 11).

[4] Ibid.

[5] OECD/IEA Working Paper 11 confirms a 45 percent operating efficiency for large, slow-speed diesels.

[6] Ahrens, D.O., Caterpillar, personal communication of 1/25/99.

[7] Allen, S. et al,

[8] Thomas, C.E., et al, *Integrated Analysis of Hydrogen Passenger Vehicle Transportation Pathways*, Directed Technologies, Inc. for The National Renewable Energy Laboratory, U.S. Department of Energy, March 1998.

[9] From OECD/IEA Working Paper 11

[10] Oak Ridge Transportation Energy Data Book 18, Table 11.4. 1996 efficiency of domestic plus foreign shipping in the U.S. is 2.4 ton-miles/thousand Btu according to Table 11.4, which matches EIA s 1996 value for domestic shipping efficiency. Presumably, the two categories may be the same.

[11] Transportation Energy Data Book, 18th Edition.

[12] An Argonne National Laboratory study for the Federal Railroad Administration concluded that high speed trains were moderately less energy-efficient than conventional diesel intercity trains — about 650 Btu/seat-mile for the lower speed diesel trains, 890 Btu/s-m for 125 mph electric service, and 970 Btu/s-m for 200 mph electric service resembling the French TGV. Personal communication, Don Rote, ANL, February 2, 1999.

[13] Abacus Technology Corporation, *Rail vs. Truck Fuel Efficiency: The Relative Fuel Efficiency of Truck Competitive Rail Freight and Truck Operations Compared in a Range of Corridors*, prepared for Federal Railroad Administration, Report DOT/FRA/RRP-91/2, April 1991.

[14] U.S. Congress, Office of Technology Assessment, *Saving Energy in U.S. Transportation*, OTA-ETI-589 (Washington, DC: U.S. Government Printing Office, July, 1994).

---

[15] Greene, D.L. and Y.Fan, 1994. *Transportation Energy Efficiency Trends, 1972-1992*, ORNL-6828, Oak Ridge National Laboratory, Oak Ridge, TN.

[16] Oak Ridge Energy Data Book 18, Table 11.7.

[17] Association of American Railroads, Policy, Legislative, & Communications Department, *Railroad Ten-Year Trends, 1988-1997*, p. 110.

[18] Association of American Railroads, Policy, Legislative, & Communications Department, *Railroad Ten-Year Trends, 1988-1997*, p. 110.

[19] Association of American Railroads, Policy, Legislative, & Communications Department, *Railroad Ten-Year Trends, 1988-1997*, p. 110.

[20] EIA projects truck vmt, not ton-miles. We estimated 2020 freight truck ton-miles by assuming that average cargo weight/truck is unchanged, with 1996 truck ton-miles being 986 billion (Table 2.13, Oak Ridge Energy Data Book 18). EIA projects that freight truck vmt will increase by 1.8%/yr between 1996 and 2020.

[21] EIA projects truck vmt, not ton-miles. We estimated 2020 freight truck ton-miles by assuming that average cargo weight/truck is unchanged, with 1996 truck ton-miles being 986 billion (Table 2.13, Oak Ridge Energy Data Book 18). EIA projects that freight truck vmt will increase by 1.8%/yr between 1996 and 2020.

[22] It must be recognized that there are remaining roadblocks that, if not successfully overcome, will cause long-term costs to be substantially higher. On the other hand, there may be potential design paths, especially for fuel reformers, that could allow liquid fuel systems to be less expensive and possibly more efficient than the DTI projections.