Trends in Transportation Sector Technology Energy Use and Greenhouse Gas Emissions

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Contributed Paper

Concerns about air pollution, environmental degradation, and petroleum consumption have prompted policy makers in many countries to seek advanced transportation alternatives. In response to such societal needs, automobile manufacturers have developed vehicles which either replace the internal combustion engine with an electric motor or which provide a hybrid configuration with a combination of an IC engine (ICE) and an electric motor. In some concepts, fuel cells replace the IC engine in a hybrid vehicle configuration. Several of these technologies have been brought to market by auto manufacturers, with initial product offerings. In other cases, advanced concept cars are being developed to further these technologies. In response to these same concerns, research and development projects are underway to make the ICE vehicles more efficient. These projects have involved both improvements in engine/drive train efficiency as well as more efficient heating-cooling systems. This paper provides an overview of the transportation sector usage patterns, energy consumption, and emissions, and discusses the societal issues which impact decisions on transportation issues. The article then provides an overview of the electrotechnological advances which are being developed to address transportation energy use and emissions issues, and discusses the potential for emissions reduction through the successful deployment of these and competing technologies. The article concludes that reduction in transportation sector carbon emissions are achievable.

Keywords**—***Energy consumption, greenhouse gas emissions, transportation.*

I. INTRODUCTION

Transportation is a major energy user worldwide and is overwhelmingly petroleum based. The transportation sector forms a key component of many if not all of the world economies. However, it is a major source of global carbon emissions, and also contributes to air quality concerns, particularly in and around major population centers. Transportation is a key element of lifestyle issues, and affects employment, housing, and recreation decisions.

Technological advances are being pursued which have the capability to impact energy use, energy source, pollution, and lifestyle issues. A significant portion of these advances involve electrotechnologies. Indeed, for the first time in many years, there is significant competition for the internal combustion engine as a road transportation energy source. Even vehicles with conventional propulsion, however, can be expected to have increasing electrical loads as the flexibility of electrical energy is exploited to increase vehicle efficiencies.

Superior technology alone, however, will not necessarily change the face of transportation around the world. Economics, politics, infrastructure, and lifestyle issues all have an impact on which new technologies will be adopted. It has become apparent over recent decades that technical feasibility combined with projections of competitive costs once market share has been achieved is generally not sufficient to introduce new technologies into the marketplace.

This article presents an overview of the current state of transportation in the world, and possible paths transportation may take in the future. Section II provides an overview of transportation energy usage, and a summary of green house gas (GHG) emissions, which result from this use. Section III briefly covers other vehicle emissions. In Section IV, transportation related activities of the United Nations Framework Convention on Climate Change (UNFCCC) are discussed. Section V provides a discussion of the several developing propulsion technologies, including electric, hybrid electric, and fuel cell vehicles. The potential for GHG reduction by these technologies is discussed in Section VI. Section VII covers emerging trends in electrical technologies, including power electronics, machines, and auxiliaries. In summary, there are several competing technologies which have a clear potential to reduce GHG emissions in the transportation sector. There are however, a number of issues which need to be resolved in order to move these technologies to the marketplace and achieve reduced emissions from the transportation sector.

II. OVERVIEW OF TRANSPORTATION ISSUES

In 1999, the estimated worldwide energy usage was 403 exajoules (382 quadrillion BTUs) [1]. The transportation

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Table 1
Regional Energy Use, Transportation Share of Energy Use

Region	UNFCCC Category	1990 Total Energy Usage, Exajoules	1999 Total Energy Usage, Exajoules	1999 Transportation Energy Usage, Exajoules
North America	Annex II	105.4	122.1	33.8
Western Europe	Annex II	63.1	69.5	16.3
Industrialized Asia	Annex II	24.1	29.4	5.8
Former Soviet Union	EIT	64.4	41.5	3.1
Eastern Europe	EIT	16.1	11.9	1.3
Developing Asia	Developing	53.8	74.8	12.5
Middle East	Developing	13.8	19.3	4.0
Central and South America	Developing	14.4	20.9	4.7
Africa	Developing	9.8	20.4	2.7
Total		366.0	402.8	84.6

Table 2
Year 2020 Predicted Sector Shares of Carbon Emissions, for Three Different Scenarios

Region	1999 Carbon Dioxide Emissions (MMTC)	GDP (billions, 1997 US$)	Carbon emission per $ GDP	Population (millions)	Carbon emission per person (MTC)
North America	1761	10,202	0.17	401	4.39
Western Europe	940	8906	0.11	388	2.42
Industrialized Asia	422	4644	0.09	153	2.76
Former Soviet Union	607	579	1.05	292	2.08
Eastern Europe	203	360	0.56	121	1.68
Developing Asia	1361	3123	0.44	3212	0.42
Middle East	330	513	0.64	239	1.38
Africa	218	474	0.46	767	0.28
Central and South America	249	1498	0.17	410	0.61

sector consumed 85 exajoules (38 million barrels of oil per day), approximately 20% of the total energy usage. In 1998, petroleum use in transportation became equal to nontransportation petroleum usage for the first time ever [1], and petroleum is the primary source of transportation energy, fueling 97% of transportation energy usage in the United States, for example. Energy usage varies widely around the world. In Table 1, 1990–1998 energy use growth and the 1998 transportation energy use data are given. 1990 is an important benchmark year due to the ongoing negotiations concerning carbon emissions and global warming. In tabulating energy usage and greenhouse gas emissions, the UNFCCC has separated these regions into the industrialized countries (Annex I) and the developing countries. The Annex I countries are further divided into Annex II developed countries and countries whose economies are in transition (EIT). These later countries are central and eastern European countries and former republics of the Soviet Union that are in transition to a market economy [1]. Table 1 shows that energy usage around the world varies widely. This basic fact leads to many of the reasons for differing viewpoints on energy use and carbon emissions among the various countries.

In 1999, carbon dioxide emissions totalled 6091 million metric tons of carbon equivalent (MMTC) [1]. Petroleum contributed 2712 MMTC of this, natural gas 1247 MMTC, and coal 2137 MMTC. Table 2 contains carbon dioxide emissions by world region. Regional differences in carbon dioxide emissions relative to energy use reflect differences in energy source and efficiency of conversion. Table 2 also shows the gross domestic product and population figures, and includes emissions relative to both of these figures. These figures are essential to gaining an understanding of the complexities driving transportation energy issues.

Transportation's heavy reliance on petroleum may make it more difficult to reduce transportation carbon emissions by fuel shifting. The International Energy Agency (IEA) [5] notes that transportation emissions increased more than other sectors in the years 1990–1996, and are projected to increase a further 15% by 2010 and 30% by 2020 in IEA member countries.

The total international carbon emissions are projected to grow to 7835 MMTC by 2010 and 9762 MMTC by 2020, in the reference scenario of the U.S. Department of Energy's International Energy Outlook (2001), which is roughly proportional to the projected growth in energy usage. During this time, petroleum's share of the total energy use is projected to increase, in large part due to the rapid increase in the transportation energy usage, where petroleum has relatively little competition. In fact, petroleum will likely lose market share in other energy sectors, due to increased use of natural gas in electricity generation and industrial applications. By 2020, it is projected that transportation will consume 55% of all petroleum usage.

The largest share of transportation energy consumption is road use. Worldwide, in 1997, transportation energy patterns were:

- 74.2% road use;
- 11.5% air use;
- 14.3% other (largest sector of which is rail).

For the United States, Table 3 shows the breakdown in transportation energy use over a wider range of usage categories. Road energy use dominates the U.S. numbers as well as the world numbers. Furthermore, this breakdown shows that automobile and light trucks dominate the road use category.

Saving energy by shifting use patterns for passenger travel could be an option. Table 4 contains an estimate of energy intensity data for the U.S. in 1997. Note that this data is based on actual usage and consumption estimates for the year, and does not represent the achievable efficiencies of these modes. This data shows that gains could be obtained through the shifting of the mode of transportation. Advocates of public transportation, however, cite additional benefits of an increased emphasis of public transportation, including emissions reductions due to increased efficiencies of

Table 3
United State Transportation Energy Use Patterns for 1997

Mode	Exajoules	Percent of Transportation energy usage
Automobile	9.22	34.8
Light trucks	6.53	24.6
Heavy trucks	4.29	16.2
Buses	0.19	0.7
Air	2.45	9.2
Pipeline	1.04	3.9
Rail	0.61	2.3
Water	1.38	5.2
Off-highway	0.77	2.9
Total	25.7	

Table 4
BTU Per Passenger Mile, 1997, United States [2]

automobile	3639
personal truck	4238
motorcycle	2084
buses (transit)	4318
buses (intercity)	872
airline (carriers)	4047
rail (intercity)	2458
rail (transit)	3253

Table 5
Passenger Car Fuel Statistics, United States [2]

Year	Passenger car fuel economy (miles per gallon)	Vehicle travel (billions of miles)	Passenger car fuel use (billions of gallons)
1972	13.5	1,021	75.9
1977	14.0	1,109	79.1
1982	16.8	1,161	69.1
1987*	18.0	1,316	73.3
1992*	21.0	1,372	65.4
1997*	21.5	1,502	69.9

* Data after 1985 does not include minivans, pickup trucks, or sport utility vehicles.

Table 6
Two Axle, Four Tire Truck Statistics, United States [2]

Year	Passenger car fuel economy (miles per gallon)	Vehicle travel (billions of miles)	Passenger car fuel use (billions of gallons)
1972	10.3	156.6	15.2
1977	11.2	250.6	22.4
1982	13.5	306.1	22.7
1987*	14.9	456.9	30.6
1992*	17.3	706.9	40.9
1997*	17.2	850.3	49.4

* Data after 1985 includes minivans, pickup trucks, and sport utility vehicles.

Table 7
1998 Gasoline Price and Tax Proportion [2]

Country	Price per gallon (US$)	Proportion of price which is taxes
Canada	1.52	47%
France	3.74	80%
Japan	2.88	60%
Germany	3.26	74%
United Kingdom	3.82	76%
United States	1.24	36%

public transportation usage [31]. Personal vehicles, on the other hand, are a very popular mode of transportation.

The Table 4 data is for composite groups of vehicles. Each of these groups experiences a large range of performance as well. Present internal combustion engine automobiles, for example, have mileage ranges from around 15 mpg to over 50 mpg. Different automobiles exhibit different capabilities in performance, size, safety, etc. This is the primary driver for the wide range of mileage performance.

Vehicle efficiency has been steadily improving over the last 30 years. Government standards and advancing technology have led to this improvement. Table 5 shows the passenger car fuel statistics for the United States over a 25-year period. While the miles per gallon of the fleet has improved by over 50% in this period, overall fuel use has been largely unchanged. Furthermore, as shown in Table 6, usage patterns have changed, and there has been a significant shift in the United States from passenger cars to light trucks.

The gains in fuel efficiency have been offset by the increased number of miles driven and the increasing size of the vehicle. In fact, increases in efficiency and economy in personal vehicles have led to a documented "bounce" in travel patterns that have been estimated to be in the 10%-30% range in the United States. [1] The potential bounce in Europe is less well known, but could potentially be significantly higher due to present travel patterns there. [1] Bounce (or "rebound" [6]) is defined as the tendency to increase miles traveled and travel mode in response to increased economic means, which in turn can be the result of increased efficiency of travel.

Fuel price is another parameter that varies widely around the world. Table 7 contains fuel cost data for several countries. Fuel price clearly impacts decisions on transportation. The International Energy Agency [5] reports fuel intensities in member countries which range from just under 7 liters per 100 km in France and Italy to approximately 9.5 liters/100 km in the United States, for new cars purchased in 1997.

Table 8 shows that there is a wide range in the rate of vehicle ownership around the world. The developing world in general has low vehicle ownership rates, but is projected to experience large percentage increases in ownership. Developing Asia is of particular interest. It has a combination of a large population base and a projected rapid increase in vehicle ownership. Although the ownership rate will still be low

Table 8
Vehicle Ownership Rates by Region[1]

Region	Vehicles per 1,000 population, 1997	average annual percent change, 1997-2020
North America	609	0.5
Industrialized Asia	562	0.6
Western Europe	509	0.6
Eastern Europe/Former Soviet Union	144	1.8
Central/South America	86	3.6
Middle East	54	2.3
Africa	23	2.7
Developing Asia	18	4.2

Table 9
Projected Increase in Transportation Energy Consumption by Region

Region	1997 consumption (million barrels of oil per day)	2020 projected consumption (million barrels of oil per day)
North America	14.0	22.2
Western Europe	7.1	9.0
Developing Asia	5.2	13.3
Industrialized Asia	2.5	3.2
Central/South America	2.1	5.5
Middle East	1.7	3.0
Eastern Europe/Former Soviet Union	1.3	2.7
Africa	1.0	2.6

Table 10
U. S. Transportation Sector Share of the U.S. EPA's Criteria Pollutants

Pollutant	Percentage of total, United States
CO	76.6%
NOx	49.2%
voc- volatile organic compounds	39.9%
PM-10: particulates less than 10 microns	2.2%
PM-2.5: particulates less than 2.5 microns	7.4%
SO2	6.8%
NH3	7.6%

in 2020, as compared to the developed world, the increased consumption will form a significant proportion of the total consumption. Table 9 [1] shows transportation consumption projections for various world regions.

These patterns of energy use and growth rates show wide disparity around the world. They make clear that there will be no single solution to transportation energy consumption and carbon emission issues.

III. VEHICLE EMISSIONS

In addition to GHG emissions, vehicle emissions form a significant component of air pollution. Poor air quality can be a significant local issue, particularly in urban areas, which have high vehicle concentrations. Several major cities around the world have locational issues which compound the problem by being subject to inversions or other weather phenomena.

Transportation's share of the criteria pollutants in the United States in 1997 is shown in Table 10 [2]. In three of these categories, this percentage exceeds the transportation energy share. Also note that these are nationwide values, and these proportions will be exceeded in many cities. Programs such as Europe's Auto Oil Programme [1] were developed largely by urban air standards rather than by carbon emission concerns. It is worth noting that some of the more interesting developing technologies, such as electric vehicles and hybrid electric vehicles, have a very clear advantage over internal combustion engines when comparing direct vehicle emissions.

IV. UNFCCC ACTIVITIES

The United Nations Framework Convention on Climate Change (UNFCCC) is the body where world leaders are meeting to develop a response to the global warming issue. They are the sponsors of the Conference of the Parties (COP), including COP-3 in Kyoto where emission goals were set, and the recent COP-6 in the Hague, which was suspended in November 2000 when negotiators were unable to finalize guidelines for reductions. As part of the UNFCCC effort, many countries are preparing policy and "best practices" statements for the world body.

In February 2000, a forum was held in Japan involving representatives with both governmental and nongovernmental backgrounds [7]. They had been charged by the G8 Environmental Ministers to develop a set of best practices for reducing GHG emissions. The results of this forum were presented to that group the following month. They noted several barriers to GHG reduction in the transportation sector, such as resistance to lifestyle change, and previous policies encouraging dispersed land use patterns. Necessary conditions for a successful program approach were felt to be comprehensive and attractive transportation policy plans, developing appropriate price signals, and appropriate research, development and demonstration programs.

In 1996, the European Community agreed to a carbon reduction strategy for passenger cars [8]. The objective is to achieve an emission level of 120 grams of CO_2 per kilometer for new vehicles, which represents a 25% reduction from then current levels. This would be achieved through a combination of education, improved fuel efficiency and management of transport demand. The efficiency improvements are being sought through a combination of a voluntary fuel efficiency agreements with automobile manufacturers, and fiscal strategies. Similarly, Brazil relies on improved vehicle efficiency, but targets trucks and busses to a greater extent. Brazil is implementing a large ethanol program to reduce emission levels and also to reduce dependence on oil imports [9], with savings in the range of 70–90 MMTC per year. Canada reports a program that combines public education/awareness, fleet improvement incentives, and fuel shifting incentives, which they credit with reducing growth from 22% to 13% over the 1990–1997 period. Denmark has developed a new car energy/emission labeling program, which has the objective of providing consumers with high quality efficiency information, raising public awareness of efficiency issues, providing an incentive to manufacturers to improve efficiency, and enhancing any fiscal initiatives that are in place.

The United States has implemented the Partnership for a New Generation of Vehicles (PNGV) [10], a combined government/industry research and development effort which has a primary goal of developing a practical 80 mpg passenger vehicle. This initiative was begun in late 1993, and has resulted in a number of developments in areas ranging from advanced internal combustion engines to fuel cells to materials.

V. TRANSPORTATION ENERGY ISSUES

There are a variety of near-term and long-term technological developments, which could have a significant impact on transportation energy efficiency and emissions. The near-term options tend to be refinements of existing designs and techniques, while the long-term technologies include major changes in vehicle drive technology [2].

A. Two Stroke Engines

Despite its high emissions, the two-stroke gasoline engine persists in surprising numbers throughout the world. Two-stroke engines have been shown to exhibit seven to 20 times the emissions of similar four-stroke engines in recent tests of lawnmowers and small watercraft [11], [12]. These engines can be found in automobiles, motor scooters, snowmobiles, etc. The emission rates are high enough that two stroke engines have a significant impact on overall emissions although they form a relatively small percentage of the total engine usage.

Two stroke engines have emissions that are clearly higher than is technically necessary. It is clear that programs that reduce hydrocarbon emissions of two stroke engines would be an effective way to reduce overall emissions.

B. Electric Vehicle

The electric vehicle (EV) employs a battery for energy storage and electric motors for vehicle drive. The batteries are recharged at special recharging stations, which are located either in the owner's home or business, or conceivably at a service station. Recharge time would typically range from several hours up to as many as 10 h, with short recharge times carrying a penalty in cost, weight, or life [29]. While electric vehicles have existed for many years, renewed efforts on EV development have provided gains in vehicle performance and economy. The major weakness of the EV remains the batteries, which are heavy, costly, and have relatively short lifetimes. From the users point of view, vehicle range and cost (both first cost and life cycle costs) are the major problems.

The battery technology has been an active topic of research and development for many years. Progress has been made on a variety of fronts, and today there are several near-term competitors to the lead acid battery, with the nickel–metal hydride and lithium ion technologies having the strongest potential at present. [13], [29]

A 1999 study [14] considered economic and technical aspects of EV deployment. The study included both lead acid and nickel-metal hydride battery packs. Battery cost estimates are based on an assessment of material costs and manufacturing requirements. The study considered vehicles which were optimized for electric propulsion. Table 11 contains a summary of the near term and long-term cost projections from this project.

The projected range of these two EVs is shown in Table 12. While the NiMH vehicle has superior range as compared to the EV with lead–acid battery pack, range remains an issue which limits the acceptance of EVs.

Electric vehicles meet certain requirements as "zero emission vehicles." It is true that they have no exhaust, and thus do not degrade the local air quality. Their typical energy source, however, is the electric power grid. Their carbon impact therefore depends on the electricity generation, which would range from coal to lower carbon sources such as hydro, nuclear, wind or photovoltaics [2].

Table 11
Comparison of EV Options With Conventional ICE Vehicle

Item	Near term conventional vehicle	EV-Lead acid Introductory	EV-Lead acid high manufac'g volume	EV-NiMH, introductory	EV-NiMH, high manufact'g volume
Total Life Cycle Cost ($/mi)	0.23	0.29	0.21	0.39	0.24
Initial Battery pack cost ($)		2,850	1,980	14,300	5,710
Initial battery pack lifetime (years)		2.3	4.7	5.8	8.0

Table 12
Range Prediction for Near Term Electric Vehicles

Vehicle	Projected Range
Small market, Lead-acid	52 miles
Large market, Lead-acid	68 miles
Small market, NiMH	106 miles
Large market, NiMH	106 miles

In conclusion, battery capability remains the dominant factor limiting electric vehicle penetration into the market. A breakthrough in battery technology is needed to address this issue. As discussed in the previous section, however, there are a wide variety of usage and economic scenarios that will play out around the world, and electric vehicle technology is sufficiently developed that it is likely that a number of niche markets could emerge in the next ten years. It is apparent that the near term electric vehicle market niche will involve relatively lightweight vehicles that operate with a limited range. Vehicles that operate entirely or largely at low speeds are also attractive. There is evidence that manufacturers are developing vehicles or concepts to address these niche markets, and are recognizing that in many cases, these markets will involve fleet vehicles.

A competitor to the electrochemical battery is the flywheel, also known as the electromechanical battery [27], [28]. This has been evaluated for electric and hybrid electric vehicles, with considerable developments underway. The idea is to use the rotating energy in the inertia of the flywheel as an energy storage system. As energy is released from the flywheel, its speed reduces. Commercial flywheels operate in the 40 000 rpm range. This demands operation of the flywheel in a vacuum to minimize rotational losses. This however imposes cooling difficulties on the rotor, demanding a low-loss rotor. Permanent magnet ac machines have been used up to now, because of the low rotor losses and overall higher efficiencies over electrical machine types. Flywheels can be designed for energy storage or high power sources at the two extremes, depending on the size of the motor-generator set. There are several advantages of flywheels over batteries. They are more efficient in the conversion of energy, with efficiencies in the 90% range, while batteries are around 70%. Batteries pose a serious environmental hazard, particularly in developing countries where recycling is not prevalent. Flywheels can withstand an extremely low depth of discharge, whereas a low depth of discharge in batteries reduces the already low life. Motors and generators have been designed for continuous operation with lifetimes of 20 years or more and there is no reason why flywheels cannot reach this, particularly with magnetic bearings. Current commercial uses range from improving power quality by providing either short-term (several cycles) or long-term (hours) of energy during outages to electric and hybrid vehicles.

C. Hybrid Electric Vehicle

Unlike the conventional electric vehicle, a variety of hybrid vehicle topologies exist. The primary configurations are the series and the parallel. Each employs a conventional internal combustion engine (ICE) to provide motive energy. These engines are fueled by the same products that are or could be used for today's conventional vehicles. The hybrid vehicles are significantly more efficient than conventional vehicles however, and provide energy and emissions savings due to this efficiency.

An HEV with a series configuration converts all engine energy to electricity. The vehicle has a battery for energy storage, and an electric drive for propulsion power. There is no mechanical connection between the engine and the drive wheels. In the series configuration, the engine will never idle, and engine performance can be optimized independently of wheel speed.

An HEV with a parallel configuration has a direct mechanical connection between the conventional engine and the wheels as in a conventional vehicle, but also has an electric machine on the same shaft. The electric machine provides torque during peak needs, and limits the torque requirement of the engine. Also, the direct application of engine torque to the drive shaft limits power conversion loss.

Hybrid vehicles are under development by many automobile manufacturers, and (in early 2001) two are currently on the market and available to consumers. One vehicle is a five-passenger vehicle which carries EPA mileage estimates of 52 mpg city/45 mpg highway. It includes a 33-kW permanent magnet motor and a 274-V nickel–metal hydride battery.

The second vehicle carries an EPA mileage estimate of 61 MPG city/68 MPG highway. It has a 10 KW motor and a 144 V, 6.5 Ah nickel-metal hydride battery.

These near term hybrid vehicles appear to have the potential for good market acceptance, and thus to provide significant benefits in emissions.

The development of flywheels are well suited to hybrid electric vehicles, since they can be designed to provide high power for short periods of time.

D. Fuel Cell Vehicle

The fuel cell (FC) vehicle employs a fuel cell to convert energy to electricity, and includes a battery for load leveling and an electric drive for propulsion. Most fuel cells employ hydrogen as a fuel, and exhaust water vapor. Hydrogen is difficult to store, however. On board storage options include compressed gas or liquid systems. The other option is chemical storage, using materials such as carbon nanostructures,

Table 13
Present Capability and Near Term Targets for the FC Vehicle Program.

Category	Present capability	2004 target
Cost ($/kw)	300-1200*	50
Durability (hours)	1000	5000
Energy efficiency (at 25% of peak power)	34	48
Start-up to full power (minutes)	6	0.5
Power density (W/liter)	120	300
Transient response (sec.)	15	1
Specific power (W/kg)	120	300
Emissions (<Tier II)	Met	Met

*Commercial fuel cells for this market are not currently available. These numbers are representative of the range of predictions that have been made for commercialization of current designs with mid to high market volume.

Table 14
Predicted Reduction in GHG Emissions for New Technology Vehicles.

Technology	Class	GHG reduction potential
Diesel engine, w/compression ignition, direct injection	Near term	27%
Electric vehicle, US mix of electricity generation	Near term	25%
Electric vehicle, CA mix of electricity generation	Near term	70%
Hybrid electric vehicle, spark ignition, direct injection, ethanol, grid connected, CA mix	Near term	51%
Electric vehicle, CA mix	Long term	79%
Hybrid electric vehicle, spark ignition, direct injection, 90% ethanol (woody biomass) fuel, grid connected, CA mix	Long term	95%
Fuel cell vehicle, Ethanol fuel (woody biomass)	Long term	110%
H2 fuel cell vehicle, liquid natural gas derived	Long term	68%

fullerenes, metal hydrides, organometallics, or catalyzed hydrides. A discussion of fuel cell operation is contained elsewhere in this issue. There are currently several FC vehicles currently undergoing road tests.

Reformers which run on gasoline, diesel, ethanol, etc., are under development, and reformer performance remains an issue. Targets for PNGV fuel cell programs include fuel processor efficiency of 68% and multi-fuel capability. Research and development issues include a search for high-activity, low cost catalysts, increase power density and specific power, reduced start-up time, and increased purity in order to increase system reliability.

A recent report [15] compared current or near term fuel cell vehicle capability with PNGV vehicle targets for 2004. Table 13 provides this comparison. The target vehicle would provide a 380 mile range. If these goals are met, the FC vehicle would not be subject to the inherent EV problems of range and recharge time, and this vehicle would be a direct competitor with the ICE vehicle for all applications. These goals are aggressive, however, and may be difficult to achieve by 2004.

VI. POTENTIAL CARBON SAVINGS

At present, there are a number of interesting options for providing motive power for transportation. These include improvements in internal combustion engine (ICE) technology [30], changes in fuel source, and new technologies, which include electric vehicles, hybrid electric vehicles, and fuel cell vehicles. Lave, *et al.* [17] have evaluated the potential impact of 18 near term options and 100 long-term options. This evaluation considers the total fuel cycle emissions associated with the technology. The study also includes fuel consumption and criteria pollutant emission results. The effect of these options on greenhouse gas (GHG) emissions ranges from a small increase to an overall reduction of over 100%. Several of these options along with the predicted GHG reductions are shown in Table 14. Note that in these figures, carbon dioxide emissions from ethanol are neglected, based on the logic that the carbon is removed from the atmosphere during plant growth, and is returned to the atmosphere during ethanol use, resulting in no net change in atmospheric carbon. Also, these figures include carbon emissions involved in the production of the energy sources. Reductions of over 100% would indicate a prediction that the cited technology would result in a net decrease in atmospheric carbon.

It is apparent that a number of transportation options exist which have the potential for significant reduction in GHG emissions, both near term and long term. It is also clear that these technologies will compete in the marketplace in the upcoming decades. This marketplace competition will be based largely on economics. But reliability, convenience, range, and performance will also influence the acceptance of the new technologies.

In a series of articles, Lave and Maclean [17], [18] and others have explored a similar set of near term vehicle technologies. In their analysis, they have included economics and infrastructure issues, as well as GHG and criteria pollutants. In their analysis, they use a low value of $14 per metric ton of CO_2, which, although based on several estimates of social costs, ignores the projected expense of carbon reductions to meet the Kyoto targets. They note much higher social costs for volatile organic compounds, nitrous oxide (NOX), and carbon monoxide. Their analysis suggests the ICE will remain dominant in the near term. Several alternative fuel options are of interest, but face obstacles due to the improving performance of gasoline engines, and the infrastructure that is present to support gasoline usage. They cite compressed natural gas and ethanol as attracting greatly increased market shares in some scenarios.

Nevertheless, it is clear that a number of very interesting technologies are or will soon be available which will impact the GHG emissions of the transportation sector. Many of these technologies have other attractions, including reduced emissions of the criteria pollutants and a shifting of transportation energy consumption away from a strict petroleum base. Ideally, incentive programs will be developed which will reflect the new technology's impact.

VII. ELECTRICAL TECHNOLOGIES

The previous sections have focused on the fundamental energy conversion issues. All of these new technologies include significant changes in the electrical systems of the vehicles, and electrotechnology developments are needed for these plans to come to fruition.

A. Motors and Drives

Electric motors and drives allow higher efficiencies and greater flexibility in design when compared to their hydraulic counterparts, not only in ground transportation but in air and shipboard applications as well. These advantages are allowing a greater number of vehicle applications to be actuated by electric motors and drives, with the impact being felt in the ICE, EV and HEV. While the traction drive motor in the HEV and EV is an obvious application of the electric motor, less obvious are auxiliaries in conventional ICEs. These include fans and pumps as well as power steering, brakes and intake and outlet valve actuation.

Fans connected directly to the ICE through a fan belt, operate regardless of whether cooling is needed or not, resulting in inefficiencies. Many ICEs today already have electric fans, which operate only when needed. A similar problem exists with power steering in ICEs where the hydraulic motor for the power steering is driven constantly, regardless of whether the steering is used or not. The move to an electric motor provides a significant one mile/gal increase in the mileage of the ICE for every vehicle. The first commercial product developed uses a brushless dc motor, which drives the hydraulics only when power steering is needed and is being incorporated into a commercial product line at this time. It is likely that this innovation will see significant market penetration in the next few years.

The next step is an all electric power steering, or steer by wire. Research in this area has already begun with the concept even of the steering wheel being in question and the steering column, being redundant. This will allow an optimization of the engine layout similar to what has been experienced on shipboards with electric propulsion.

While the brushless dc motor has been used in the first generation of electric power steering, another candidate machine technology is the switched reluctance motor. This boasts no windings on the rotor and lower projected material and manufacturing costs than PM machines. Problems to be solved involve acoustic noise and torque ripple.

The increased electrical load represented by power steering, fan motors, etc., has forced the automotive industry to rethink the voltage level and power distribution architecture. A compromise between safety and power needs has resulted in a proposal for the use of 42 V (three 14 V batteries), which will become the new standard. Variations in designs from different manufacturers will still exist relating to which loads to connect to 14 V and which to 42 V. A bus architecture is also proposed, removing the independent connections of loads to the battery, which currently requires in the region of 2 km of wiring in an average sedan [26].

The combination of the starter and generator into one machine has already been examined at the prototype level, with better designs being developed with the availability of 42 V. This reduces space requirements, manufacturing costs and the utilization of raw materials, which translates to additional energy savings. Induction, permanent magnet ac and switched reluctance technologies have all been examined.

While current EV or HEV designs use a single motor for traction applications, the development of wheel motors is still being pursued, with an important application being in motorbikes. The industry has not settled on a single motor type for traction. The GM EV1 uses an induction motor while the Japanese tend to favor PM machines. The PM machine has a higher power density and efficiency in the constant torque region, but its advantages reduce in the flux weakening region. This however does depend on the method for flux weakening, with some newer ideas promising better performance.

The actuation of ignition valves electromagnetically is considered a breakthrough in ICE design and performance. It allows independent control of the valves from the rotational speed or angular position of the ICE. One of the reasons that starter motors have to produce the high torque needed, is to overcome the compression in the cylinders as a result of the valves being closed during starting. Yet the engine has to reach a speed of several 1000 rpm before the ICE can ignite. Thus no compression of fuel, indeed no fuel at all is needed till the engine reaches this critical speed. Independent valve control will allow no fuel to be added to the ignition chamber before the critical speed and reducing the compression in the chamber by keeping the outlet valve open until the critical speed is reached.

Electromagnetic brakes are also being considered. In the case of EV or HEV, a considerable contribution to its fuel economy comes from electromagnetic braking by turning the traction motor into a generator. Electromagnetic brakes have the potential for reduced emissions from brake wear and reduced maintenance. Concerns on reliability are being addressed by multiple phases, separate magnetic paths etc.

B. Power Electronics

The power electronics area has and continues to experience rapid gains in capability. Both the integrated gate bipolar transistor (IGBT) and field effect transistor (FET) provide power switches which provide low cost performance improvements. While the initial applications of these switches were largely experienced in the industrial sector, transportation applications have been receiving increasing attention.

The Power Electronic Building Block (PEBB) program is a program that has concentrated on developing power electronics capability for transportation applications. This program has been led by the U.S. Navy's Office of Naval Research (ONR), and is characterized by aggressive goals in cost, power density, and reliability. Two orders of magnitude improvements are targeted in each of these areas over the decade from 1995 to 2005. A power density goal of 50 kw per cubic foot (1.77 kw/liter) and $0.06 per watt are goals of the program. [20] As this program has progressed, significant advances have been realized in switch capability and in, packaging and heat transfer. As a result, controller costs have become an issue, particularly for small units. Increasing switching frequencies have served to reduce filter component sizes. The passive components, however, are taking an increasing proportion of the converter space, and size reduction of these components passives has been receiving increasing attention. The increased power and switching frequencies also have led to concern over electromagnetic interference and high dv/dt effects. [21], [22]

It is projected that automotive drive applications may require a further reduction to under $0.01 per watt and a power density of 12 kw/liter [19]. At a price of $0.025 per W, a 100 kW power electronic controller would cost about the same as the entire propulsion system for a conventional vehicle, where costs for ICE power plants run around $25-$35 per kW currently.

C. Auxiliaries

The increasing importance of vehicle auxiliaries is highlighted by Farrington *et al.* [23]: "An auxiliary load increase of only 400 Watts (W) can decrease fuel economy of a 3-L/100 km (80-mpg) vehicle by 2.7 km/L (6.5 mpg). The same 400-W [increase] results in a 0.4 km/L (1 mpg) decrease for a conventional 11.9-L/100 km (28-mpg) vehicle." In other words, as vehicle auxiliaries will form an increasing proportion of the total energy consumption as drive train efficiency improves, these auxiliaries must also be considered in future vehicle designs.

The FY 2000 Progress Report for Vehicle Systems Programs [24] includes a goal to reduce fuel use for vehicle air conditioning by 50%. The National Renewable Energy Lab (NREL) has the lead responsibility to research, assess, and develop auxiliary load reduction technologies. Air conditioning causes a 22% fuel economy reduction in midsize vehicles. One approach to achieving air conditioning load reduction is to reduce the heat inflow to the cabin, through the use of reflective glazing and heat pipes. These techniques can lead to reduced size requirements for the air conditioning system. The resulting weight reduction will lead to reduced fuel usage and can be a factor in the sizing of the vehicle engine, which is a particularly important factor in hybrid electric vehicle design. Advanced glazings also can reduce the thermal asymmetry in a vehicle.

Another factor in cabin climate is the need to provide outside air in order to maintain cabin air quality. One approach to reduce energy use [23] would be to decrease the dependence on outside air by increasing the percentage of air recirculated through the cabin. Air quality could be improved through air cleaning systems. An emerging factor with high efficiency vehicles is cabin heating. EVs and HEVs have less waste heat available, and alternate forms of cabin heating are required. Farrington, *et al.* [23] project that only 25%–35% of the heating requirements might be available from an HEV with a high efficiency ICE.

There are several technologies which have the potential to provide energy efficient/lightweight cooling for automobiles. These include metal hydrides, absorption, and desiccant systems. Each of these technologies holds the potential for automotive application in the future. With metal hydrides, the hydrogen absorption process produces heat, while heat is absorbed when hydrogen is released. This process can be used in a heat pump, avoiding the need for compressor and evaporator. Absorption systems [25] use a chemical compressor in place of a mechanical compressor. These systems achieve significant weight and size reductions. Furthermore, the chemical compressor uses thermal energy, which is readily available in conventional internal combustion engine vehicles. The long-term goal is a reduction of cooling fuel requirements of 75% over present day technology.

Vehicle electrical loads have been climbing steadily for several years [26]. Today, power demands run double that of a few years ago, with demands in the range 1–2 kW being common. The demand is increasing as the flexibility of electric power is being applied in a variety of novel applications, including fans, braking systems, water pumps, and power steering. In many cases, these electrical applications are replacing hydraulic, pneumatic, or direct mechanical systems, and are providing an overall energy savings.

At these power levels, the 14-V vehicle system is reaching its limits. Vehicles will soon go to a 42-V system. This new system will provide immediate benefits by providing better generator efficiency and reduced wiring weight and losses. It is projected that this higher voltage will make additional technologies attractive, such as those that have been described in Section VII-A.

VIII. CONCLUSION

It is clear from the discussions above that there are a number of exciting new technologies on the horizon. For the first time in many years, the internal combustion engine (ICE) has competition in automotive applications. Both hybrid electric vehicle (HEV) and fuel cell (FC) technologies seem poised to become commercially viable products, and electric vehicles (EV) have the potential to carve out significant niche markets. Still, there remain significant technical and cost challenges to overcome. The primary challenge appears to be in energy storage, where petroleum based fuels hold a significant advantage in energy density, convenience and cost. Furthermore, the existing petroleum infrastructure is a significant factor favoring petroleum based transportation. Breakthroughs in electricity or hydrogen storage technologies could provide a rapid shift toward electric drives in vehicle drive technology. Significant material improvements are needed to develop a practical FC vehicle fueled by liquid hydrocarbons with an on-board reformer. Each of these technologies also must achieve significant cost reductions to compete with standard ICE vehicles with current gasoline prices.

As is true in any competitive situation, improvements are being made in ICE technology. Compressed ignition, direct injection (CIDI) engine technology has the potential to provide a significant boost in engine efficiency. At the moment, it appears that CIDI and HEV technologies will compete to reach the efficiency goal 80 mpg for a six-passenger vehicle.

These issues provide both opportunities and challenges for the global goal of reducing carbon emissions from the transportation sector. Transportation energy use and carbon emissions are undergoing rapid growth, both in the developed and developing worlds. Previous vehicle efficiency improvements have not led to reductions in energy use or carbon emissions, as they have been more than offset by increasing population and higher rates of travel. Governments do not anticipate making harsh policy decisions which would restrict modes of transportation. They are willing, in general, to provide financial incentives to modify transportation energy consumption. These initiatives include, for example, gasoline taxes which promote the purchase of fuel efficient vehicles, R&D programs to develop more efficient vehicles, subsidies for public transportation, and subsidies for ethanol use. Carbon emission reduction is not the only goal (or perhaps even the primary goal) for many of these programs. Other goals include reducing petroleum imports, improving urban air quality, and improving global competitiveness; all impact regional transportation policymaking. In many cases, however, the personal choice of the consumer may have the largest impact on transportation issues.

Finally, it is important to note that transportation sector is a major component of modern life. It accounts for approximately 25% of worldwide energy usage, and employs a significant proportion of the workforce in many countries. Transportation sector carbon emission reductions must be achieved without major disruptions in transportation patterns.

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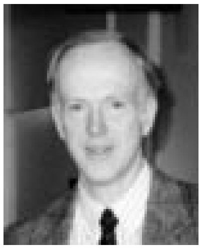

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