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Sustainable ground transportation – review of technologies, challenges and opportunities

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Abstract
Currently there are nearly 750 million ground vehicles in service worldwide. They are responsible for 50% of petroleum (oil) consumption and 60% of all greenhouse gas (GHG) emissions worldwide. The number of vehicles is forecasted to double by 2050. Therefore the environmental issues such as noise, emissions and fuel burn have become important for energy and environmental sustainability. This paper provides an overview of specific energy and environmental issues related to ground transportation. The technologies related to reduction in energy requirements such as reducing the vehicle mass by using the high strength low weight materials and reducing the viscous drag by active flow control and smoothing the operational profile, and reducing the contact friction by special tire materials are discussed along with the portable energy sources for reducing the GHG emissions such as low carbon fuels (biofuels), Lithium-ion batteries with high energy density and stability, and fuel cells. The technological challenges and opportunities for innovations are discussed.

Keywords: Green ground transportation; Aerodynamic drag reduction; Fuel efficiency by weight reduction; Alternative fuels and power sources.

1. Introduction
Among all major modes of transportation, people travel by airplanes and automobiles continues to experience the fastest growth. As shown in Figure 1, the travel as measured by Passenger - Kilometers (PKM) is forecasted to more than double from the 2010 level of ~ 40 trillion PKM to approximately 103 trillion PKM by 2050 [1]. Among these two modes of transportation, air travel is experiencing the faster growth. The number of Passenger – Kilometers Traveled (PKT)/ capita by various modes of transportation in different countries is shown in Figures 2(a) - 2(d) [1]. Figures 2(a) and 2(c) also show that the use of personal vehicles compared to public transport (in PKT) is highest in U.S. followed by the wealthier nations. Furthermore, as the per capita income of nations increase, the travel demand will increase (Figure 3) resulting in greater demand for personal vehicles as well as for air transportation as shown in Figure 1. These projections are based on 3% growth in world Gross Domestic Product (GDP), 5.2% growth in passenger traffic and 6.2% increase in cargo movement. Only major policy changes and intervention by governments through development of infrastructure for public transportation is likely to slow down these trends shown in Figure 1. Most of the energy for transportation is currently provided by the fossil fuels (primarily petroleum). Figure 4 shows the oil consumption for transportation in U.S. and its forecast for the future [2]. Figure 5 shows the relative percentage of fuel consumption by various

categories of vehicles in U.S. [2].The consequence of using fossil fuels is well established in their long term impact on climate and global warming due to Greenhouse Gas (GHG) emissions, primary being the CO_2 and NOx. Figure 6 gives the relative level of GHG emissions from various modes of transportation in year 2000[3]. Table 1 gives the 2010 data for CO_2 emissions worldwide by ground and air transportation and Figure 7 shows the forecast for the future if the current Business as Usual (BAU) scenario continues [4]. The reduction in GHG emissions due to the burning of fossil fuels is the major goal of "Green Transportation." The "Sustainability" goal is to explore both the technological solutions to increase the efficiency of transportation as well as the alternative carbon neutral fuels (e.g. biofuels among others).

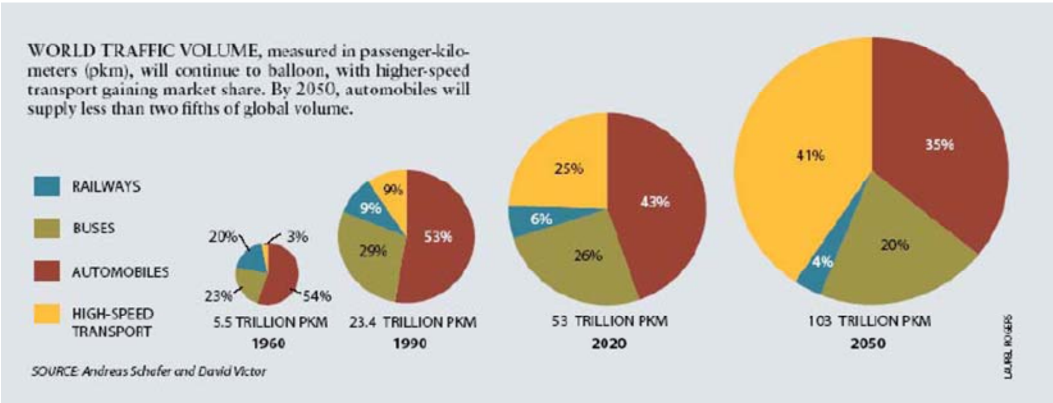
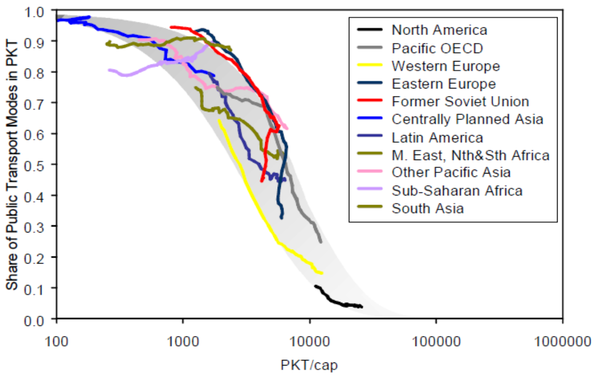
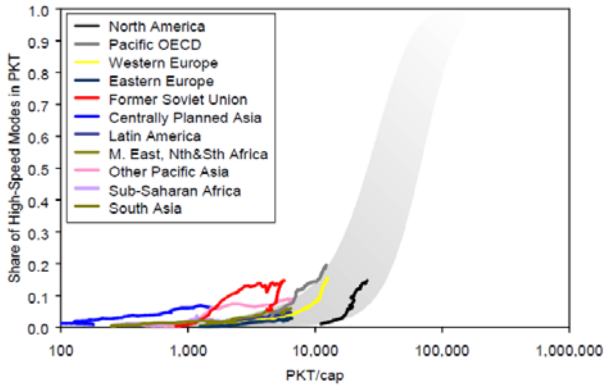


Figure 1. Global mobility trends from various modes of transportation [1]



(a)



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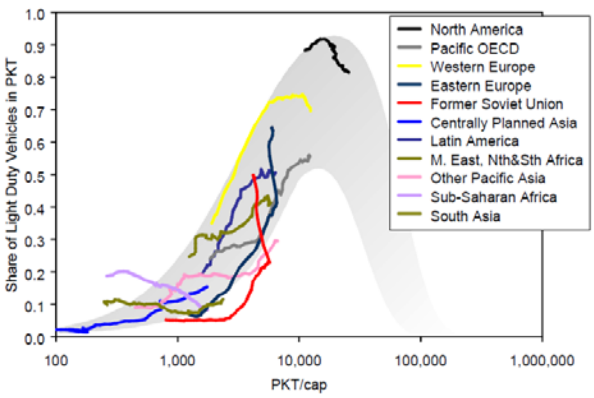

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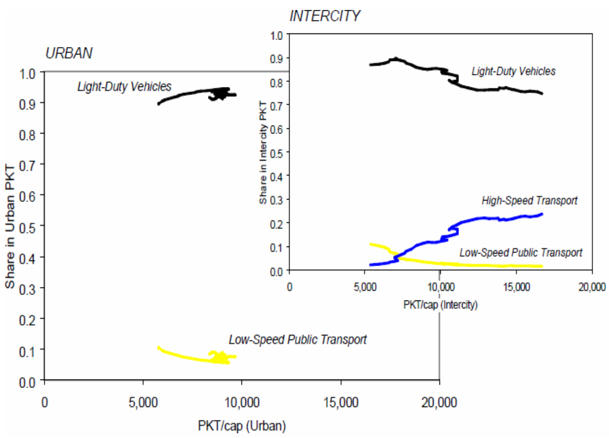

(d)

Figure 2. (a). % share of public transport in various countries [1], (b). % share of high speed transport in various countries [1], (c). % share of light-duty vehicle transport in various countries [1], and (d). % share of various modes of transportation for inter-city travel in U.S. [1]

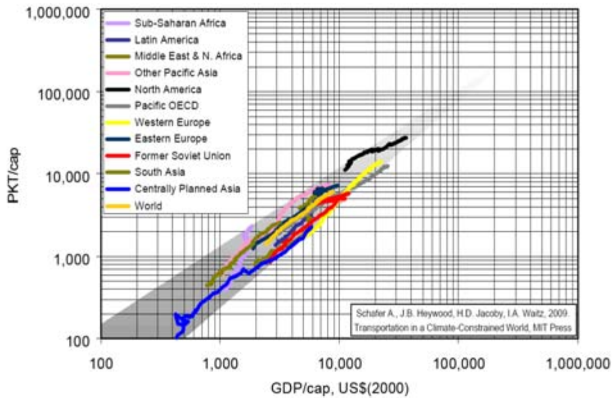

Figure 3. Travel demand/capita with increase in GDP/capita of nations [1]

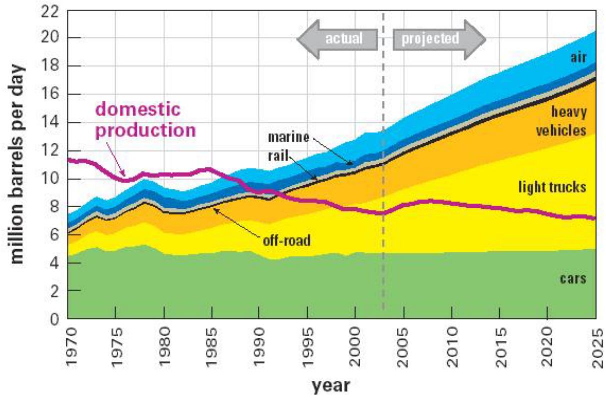

Figure 4. Fuel consumption in U.S by transport vehicles [2]

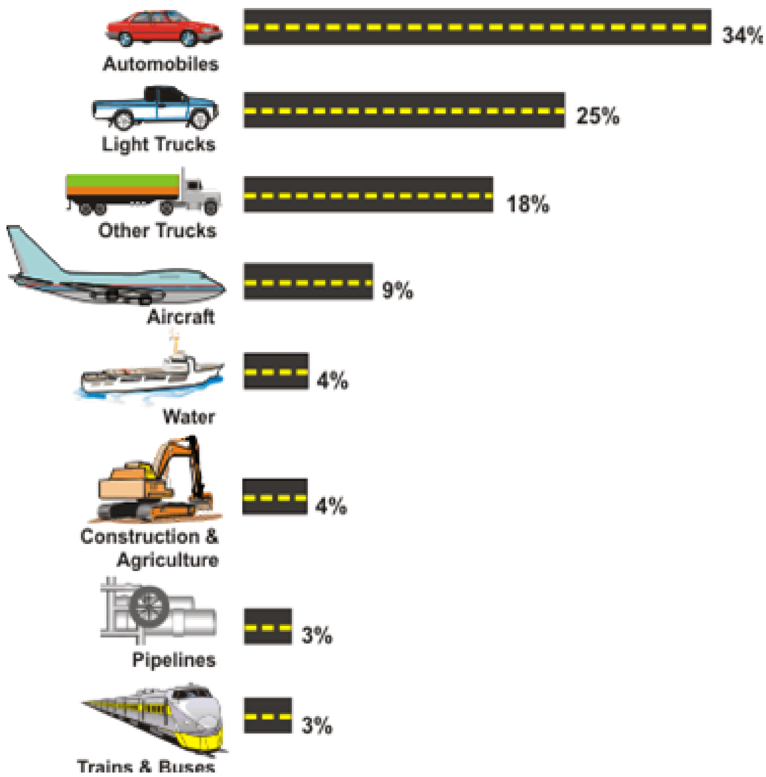

Figure 5. Relative fuel consumption in U.S by various categories of vehicles [2]

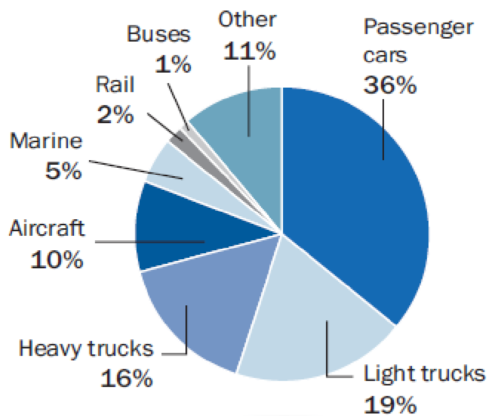

Figure 6. Relative GHG emissions in U.S by various categories of vehicles in 2000 [3]

Table 1. 2006 levels of CO_2 emissions from air and ground transportation [4]

- World Total CO_2 Emissions = 28.4×10^9 tonnes (100%)
- US Total CO_2 Emissions = 5.75×10^9 tonnes (20.2%)
- China Total CO_2 Emissions = 6.10×10^9 tonnes (21.5%)
- World Total from all Transportation = 5.99×10^9 tonnes (21.0%)
- World Total from Road Transportation = 3.69×10^9 tonnes (13.0%)
- World Total from Air Transportation = 5.68×10^8 tonnes (2.0%)
- US Total from Road Transportation ~ 4.46×10^9 tonnes (15.6%)
- US Total from Air Transportation ~ 1.39×10^9 tonnes (0.5%)

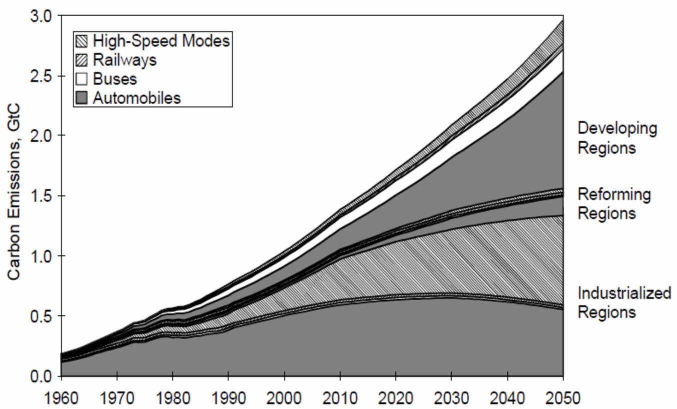

Figure 7. CO_2 emissions due to world passenger travel in Business as Usual (BAU) scenario [4]

2. Sustainable ground transportation

In the area of environmentally responsible ground transportation, the focus of this section is entirely on road transportation comprising of automobiles, and light and heavy duty trucks. As shown in Figure 5, these vehicles in U.S consume 77% of the fuel used by all modes of transportation. The total consumption of fuel by these vehicles will continue to rise in future as shown in Figure 4. Table 1 approximately provides the 2006 level of CO_2 emissions by road transportation worldwide and in the U.S. The consequence of this Business as Usual (BAU) scenario will be a dramatic rise in the Greenhouse Gas (GHG) emissions in the future as shown in Figure 7. The GHG emissions from road transportation can be reduced by improving the energy efficiency of ground vehicles through technological solutions and by the use alternative fuels or power sources. The energy efficiency of the vehicles can be improved by technological solutions such as (a) reducing the vehicle mass using the high strength low weight materials, (b) reducing the aerodynamic drag and the tires/road contact friction, (c) improving the engine efficiency using hybridization, (d) smoothing the operation speed profile, (e) improving the efficiency of vehicle movement on the road by automation, and (f) efficient utilization of road infrastructure etc.

The GHG emissions can be directly reduced by the use of alternate fuels such as biofuels (ethanol and bio-diesel) and by developing vehicles based on the use of alternative power sources such as portable low carbon electricity stored in batteries with high energy density and stability and hydrogen fuel cells (which require affordable low cost hydrogen production and storage). In the following sections, the technological solutions and alternatives fuels and power sources are briefly discussed. It should be noted that the goals in reducing the GHG emissions from ground transportations are not as well defined by various governments and industries worldwide as for the air transportation because of large number of manufacturers and consumers (operators) involved; in case of air transportation, a few manufacturers of aircrafts and engines and a relatively small number of airlines are involved in implementation of the two strategies, namely improving the energy efficiency through technological solutions and using low carbon fuels and power sources.

As shown in Figure 8 [5], in a typical automobile or light duty vehicle (class 1 truck) of weight of the order 2500 ~ 6000lbs, 87% of the energy in the fuel is wasted due to various losses indicated in the figure; only 13% of the energy is available for the tractive load. About 60 to 65% of the energy loss in the conventional fuel (petroleum or diesel) based vehicles occurs due to the engine and the drive train. Of

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the 35 to 40% of the mechanical energy available, it gets used in overcoming the aerodynamic drag, rolling resistance and other losses due to idling, braking resistance and other accessories.

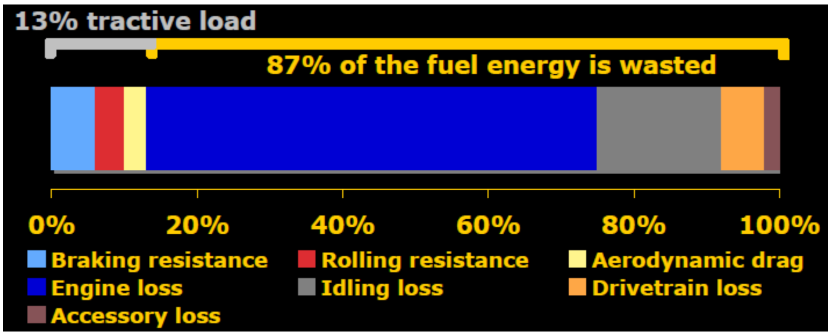


Figure 8. Expenditure of fuel energy in a typical automobile [5]

Similar is the situation for a class 8 truck of weight ~ 35000 lbs as shown in Figure 9 [5] operating on diesel fuel. Engine and drive train are only ~ 38% efficient. Of this 38%, only 30% reaches the wheels. As noted by Lovins [5], engine efficiency is very difficult to improve further; it is easier to improve the end use efficiency by technological solutions that are discussed below:

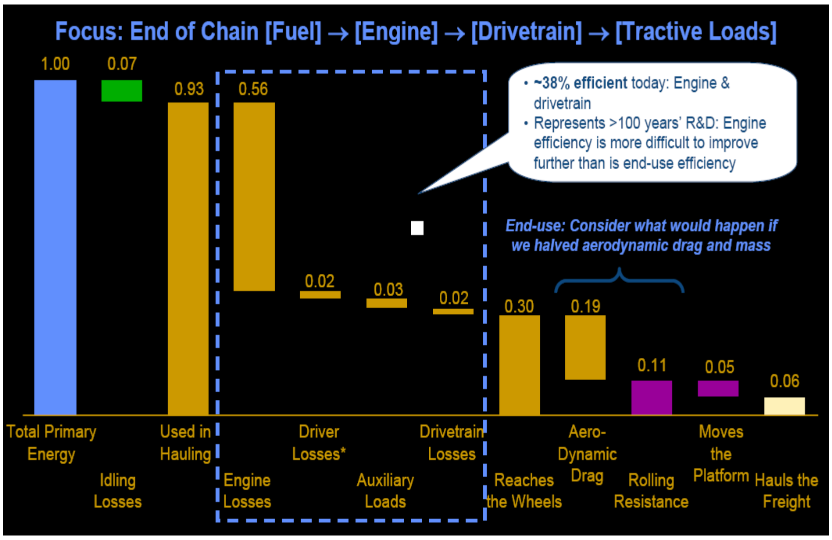


Figure 9. Expenditure of fuel energy in a typical class 8 truck of weight ~ 35,000 lbs. [5]

Most of the mechanically usable energy (nearly 35 to 40% of the energy available in the fuel) in the fuel goes into overcoming the aerodynamic drag of the vehicle. For example, in case of a truck at highway speed of 55mph, 53% of the available mechanical energy goes into overcoming the aerodynamic drag, 32% to overcome the rolling resistance; only 9% is required for auxiliary equipment and 6% is used by the drive-train [2] as shown in Figure 10. Losses in all these categories can be reduced by employing the presently available technology. In the following sections, a few of these technologies are discussed.

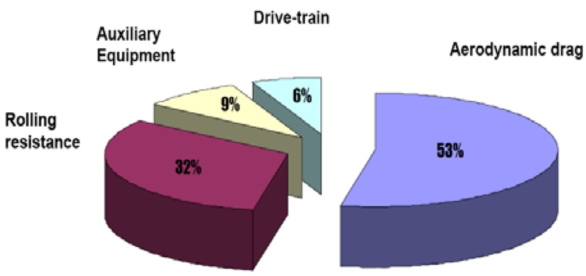


Figure 10. Main sources of energy losses from available mechanical power from the engine [2]

2.1 Aerodynamic drag of the vehicle

The aerodynamic drag represents about 50% expenditure in mechanical energy of the vehicle at highway speed of nearly 55 to 60 mph. The aerodynamic drag is the result of pressure difference between the front and back of the vehicle and the viscous friction due to the entire body surface. As shown in Figure 11, the aerodynamic drag is contributed by the shape of the vehicle and its speed. It increases quadratically with speed in contrast to rolling resistance which varies linearly with speed as shown in Figure 12 [6].

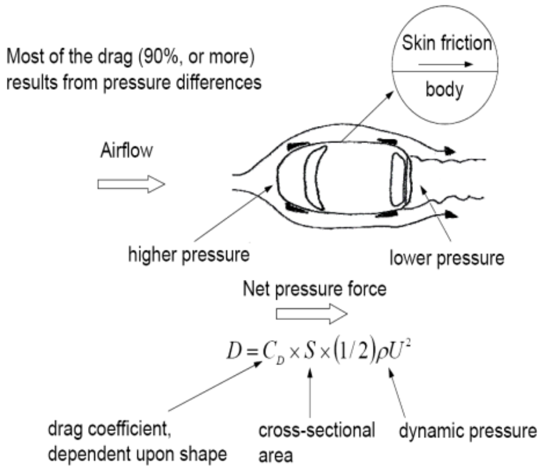


Figure 11. Shape and speed contributing to the aerodynamic drag of a vehicle [6]

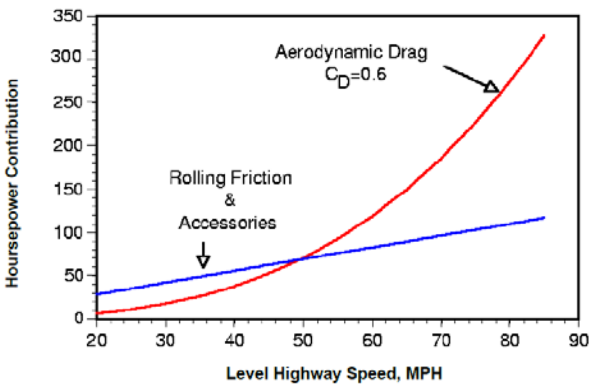


Figure 12. Variation in aerodynamic drag and rolling resistance with speed [6]

The shape of the vehicle and its frontal area of cross-section determine its drag coefficient. Most of the drag (90% or more) results due to the pressure difference between the front of the vehicle and the rear of the vehicle and small part of it is due to viscous skin friction. Therefore, the aerodynamic drag can be reduced by geometry modification and flow modification such that they result in reducing both the pressure drag and the skin friction drag. Both these approaches have been used by the manufacturers within the functionality constraints which are different for light duty versus heavy duty vehicles. For light duty vehicles, the streamlined shapes have been increasingly used by the automobile manufacturers. Some passive flow modifications devices such as spoilers and flaps etc. have also been employed. For heavy duty vehicles, geometry modification is less easy because of the functionality requirements. Figure 13 shows a heavy duty cargo truck with a large frontal area of cross-section and a very complex flow field surrounding it [2].

For a heavy duty truck shown in Figure 13, very limited reduction in drag can be achieved by modification of the frontal shape and area. However a number of passive and active flow control devices can be used for flow modification that can reduce both the pressure drag and the skin friction drag. Salari [2] have suggested and described a number of add-on passive control devices such as boat-tail plates, base flaps, skirts, underbody fairings, and gap seals/splitter plates for flow modification. These can be specifically designed for a particular heavy duty truck. It is estimated that these devices can result in 10 to 18% reduction in drag of a class 8 truck. The fuel consumption of a vehicle is given by the equation:

$$Fuel\ Consumption \equiv FC = (bsfc) \times Power \tag{1}$$

where *bsfc* is the brake specific fuel consumption. The Power required by the vehicle is given by:

$$Power = D \times U + RR \times U + AuxP \tag{2}$$

where *D* is the aerodynamic drag, *U* is the vehicle speed, *RR* is the rolling resistance due to tires, and *AuxP* is the auxiliary power required for various systems such as for entertainment and climate control etc. The change in fuel consumption ΔFC is a function of three factors given in the equation below [6]:

$$\frac{\Delta FC}{FC} = \frac{\Delta P}{P} = \eta \times \left(\frac{\Delta C_D}{C_D} + \frac{\Delta S}{S} + \frac{3\Delta U}{U} \right) \tag{3}$$

where $\Delta\ C_D$ is the change in the drag coefficient due to passive or active flow control devices and the shape, ΔS is the change in the frontal area, and ΔU is the change in the vehicle velocity. η is a property of the driving cycle which is ≈ 0.5-0.7 for a car or truck at highway speeds. Therefore, 15% reduction in aerodynamic drag at highway speed of 65mph (i.e. $\Delta C_D \approx 0.13 - 0.15$) can result in $\Delta FC/\ FC \approx 7\%$ (about 7% in fuel savings). It has been estimated that 1% increase in fuel economy can save 245 million gallons of fuel/year [2]. Therefore 5% increase in fuel economy can translate into a reduction in 1.3 billion gallons/year in fuel requirement in U.S. alone. The worldwide impact will be four to five times larger.

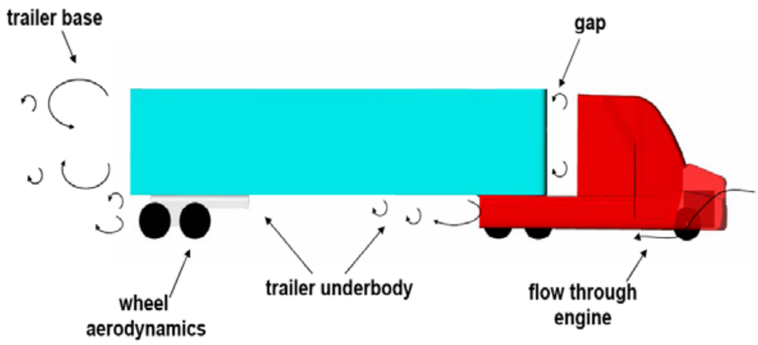


Figure 13. Critical flow separation regions surrounding a heavy duty truck which contribute to drag [2]

2.1.1 Reduction in aerodynamic drag of the vehicle by active flow control

During the past decade, it has been demonstrated in laboratory experiments that the aerodynamic drag can be significantly reduced by employing active flow control (AFC) for flow modification. Several AFC techniques have been developed for altering the wall bounded as well as free shear flows. A variety of impressive flow control results have been achieved by many researchers including the vectoring of conventional propulsive jets, modification of aerodynamic characteristics of bluff bodies, control of lift and drag of airfoils, reduction of skin-friction in boundary layer flows, enhanced jet mixing, and control of external as well as internal flow separation and of cavity oscillations [7]. Many of these techniques use suction and blowing or both, using the pulsed jets, oscillatory jets or micro-jets. Seifert et al. have shown experimentally, by employing the SaOB (Suction and Oscillatory Blowing) actuators [8], the effectiveness of both the steady suction and pulsed blowing that the aerodynamic drag of a heavy duty truck can indeed be reduced by 10-15% by suitably positioning an array of actuators at the rear face of the vehicle. Similar results have been obtained by the author of this paper by using Computational Fluid Dynamics [9, 10]. These actuators can be incorporated and operated into the existing vehicles with great ease at modest cost. The cost may be reduced significantly for a large volume of vehicles.

To show the effectiveness of the AFC in achieving the desired flow modification, here we present a sample CFD simulation performed by the author and his students [9] for a generic 2D truck configuration at various Reynolds numbers and compare the CFD results with the experimental data of Seifert et al. [8]. The CFD simulations were performed using the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations in conjunction with a two-equation realizable k-ε model. Figure 14 shows the three

AFC configurations employed in the study. The study was performed at free-stream velocity of 10, 20 and 30 m/s (22, 44 and 66 mph) with corresponding Reynolds numbers of 3.08 x 10^5, 6.16 x 10^5 and 9.24 x 10^5 respectively. The synthetic or oscillatory jet actuator is defined by $Vjet = V_0 \sin(2\pi f t)$ with f = 100 Hz and V_0 = 0.5 x free-stream velocity. Figure 15 shows a typical adaptive grid around the 2D truck configuration. Figure 16 shows the static pressure on the rear face of the truck. It is clear that the use of AFC increases the static pressure compared to the baseline (without AFC). This increase in pressure is responsible for 15 to 20% reduction in drag. Figures 17 and 18 show a snapshot of velocity contours in the flow field behind the truck. Without AFC, the asymmetric Karman vortices are shed as expected (Figure 17). With AFC (case 1 of Figure 14), the flow structure changes in the near wake region, resulting in increased pressure on the rear face (Figure 16). This mechanism is also seen in simulations for other 2D and 3D body shapes [9].

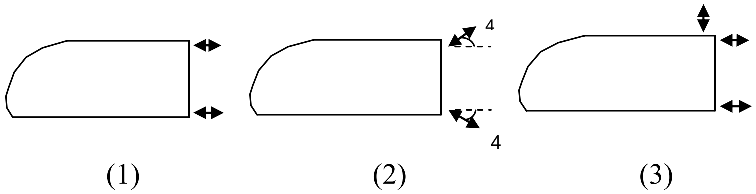


Figure 14. Three oscillatory jet configurations employed in the drag reduction study [9]

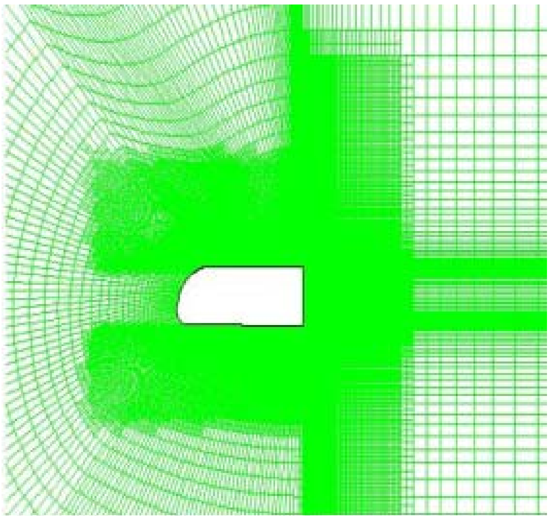


Figure 15. Adaptive mesh around the 2D truck [9]

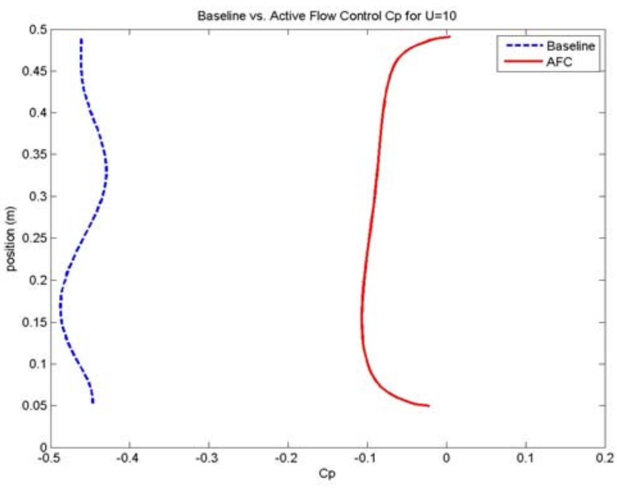


Figure 16. Static pressure at the rear face of the truck; Blue – without AFC, Red – with AFC for case 1 of Figure14 [9]

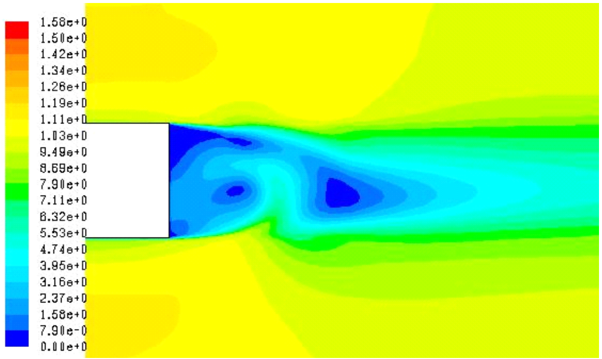


Figure 17. Velocity contours without AFC for Re= 3.08 x 10^5 [9]

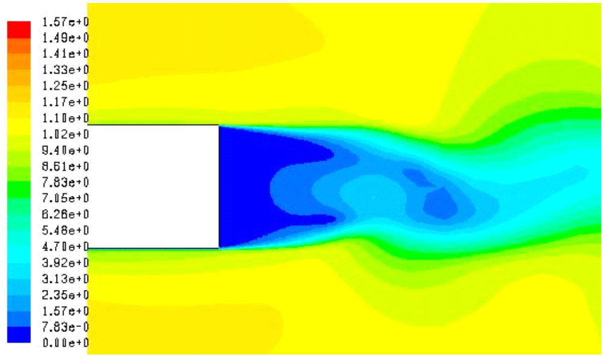


Figure 18. Velocity contours with AFC for Re= 3.08 x 10^5 for case 1 of Figure14 [9]

Figure 19 shows the reduction of drag with Reynolds number using three different configurations of AFC, shown in Figure 14, compared to baseline configuration without AFC. The agreement between the calculations and experiments is excellent. Figure 19 shows that 13-15% reduction in drag can be achieved at higher Reynolds numbers (close to highway speed of 55mph).

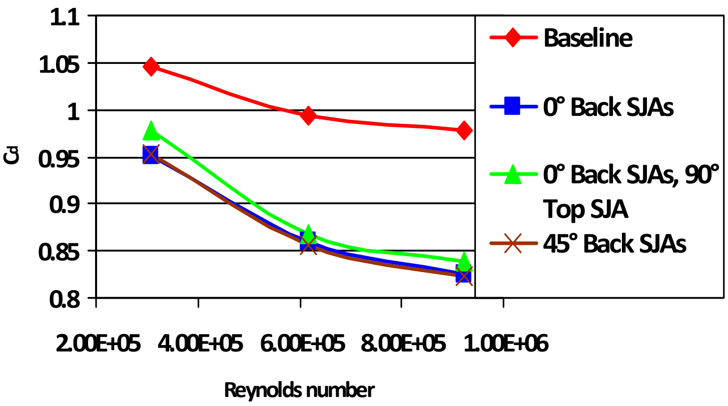


Figure 19. Variation of drag coefficient with Reynolds number without and with AFC [9]

2.1.2 Effect of vehicle spacing on aerodynamic drag

It has been shown by Browand [6] that the spacing between the vehicles on the road affects the aerodynamic drag. At large spacing between the vehicles, the vehicle following the vehicle in front experiences less drag due to lower dynamic pressure in the wake. The two vehicles collectively have less drag than the corresponding drag of the vehicles in isolation. At small spacing (less than one vehicle length, there is a cavity flow with higher pressure resulting in lower drag for the two vehicles. Figure 20 shows a schematic of the two vehicles on the road [6]. Figure 21 shows the drag coefficient of two vehicles as a function of spacing between the two. C_{D0} is the drag coefficient of a single vehicle in isolation. At a spacing of one vehicle length, the drag of the trailing vehicle reduces by 25 ~ 30%. The effect on drag of three vehicles in a lane is shown in Figure 22 [6]. The savings in average fuel consumption for three vehicles at 0.8 car length spacing is ~ 6 -7%.

Figure 20. The second vehicle experiences the wake of the first vehicle (with lower dynamic pressure) resulting in lower total drag for the two vehicles [6]

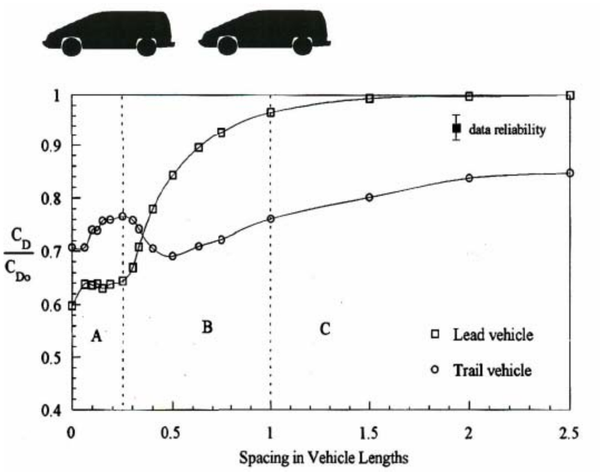


Figure 21. Variation in drag coefficient of two identical vehicles as a function of spacing between them [6]

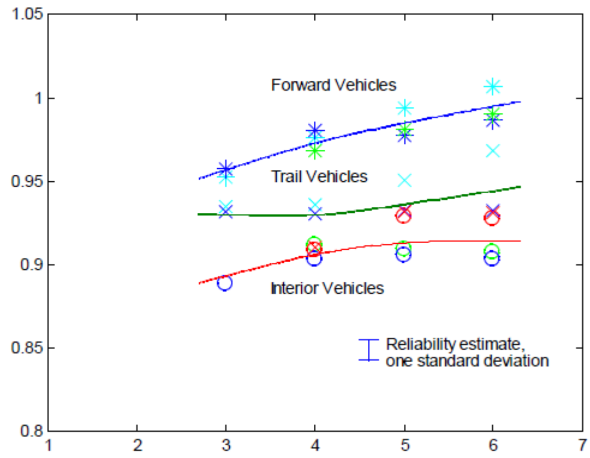


Figure 22. Variation in drag coefficient of three identical vehicles as a function of spacing between them [6]

2.2 Effect of operational speed profile of the vehicle on fuel efficiency

Barth [11] has shown that the operational speed profile of the vehicle has an effect on its fuel efficiency. In particular, the acceleration at higher speeds can substantially increase the fuel requirement as shown in Figure 23 [11]. Therefore, the sudden acceleration of the vehicle should be avoided especially on the highway. Figure 24 shows the effect of congestion on fuel efficiency for a heavy duty truck [11]. It is clear that the congestion reduces the fuel efficiency over most of the speed range.

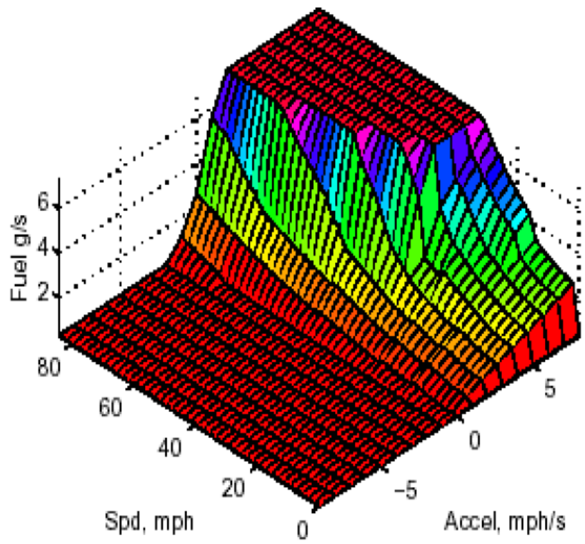


Figure 23. Effect of speed variation on fuel efficiency [11]

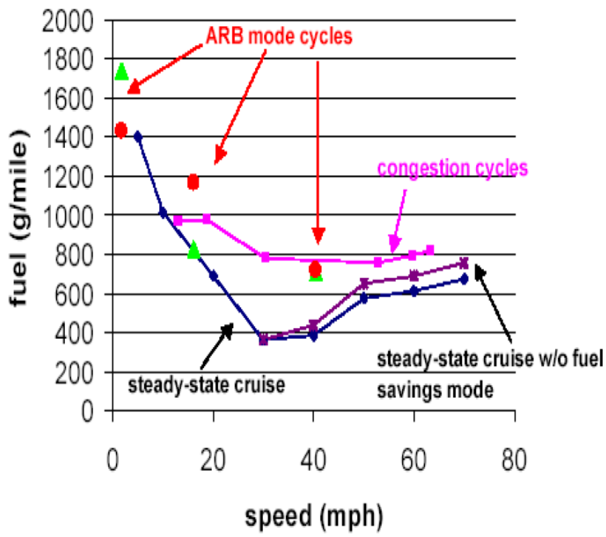


Figure 24. Effect of congestion on fuel efficiency [11]

It is clear from the discussion above that by proper spacing of the vehicles, smoothing the speed profile in driving (avoiding sudden acceleration and deceleration especially on slopes), avoiding congestion on the roads (especially important in big cities with heavy traffic such as New York City area, Bay area and Southern California region etc.), it is possible to achieve significant saving in fuel consumption. However, these goals will not be possible to achieve by simply hoping for a change in the driving habit of the people through some sort of information campaign (?).

It has been suggested that automation of various aspects of road transportation can not only improve the fuel efficiency but can also contribute to more efficient use of road infrastructure as well as improve safety [12]. The automation can improve the fuel efficiency by (a) regulating the spacing between the vehicles to reduce drag, (b) profiling the acceleration and deceleration maneuvers and adjusting them for slopes, (c) increasing the lane capacity and instituting the metered access to reduce congestion (it has been implemented and is being implemented on many highways with heavy traffic near large metropolitan areas), (d) ensuring that the automated lanes cruise at constant speed (without acceleration and deceleration), and (e) avoiding traffic shock waves (stop and go) and idling losses due to congestion in city driving.

Additionally, the automation will relieve stress on parallel (non-automated) roads. The automation will also significantly improve safety by (a) detecting problems faster than the drivers can, (b) measuring the driving conditions (lane position, distance to other vehicles) more accurately than drivers are able to, (c) controlling the vehicle motions (lateral and longitudinal) more accurately than drivers can, (d) not being vulnerable to distraction and impairment that the drivers are, and (e) ensuring consistent behavior among vehicles over time. The automation can be accomplished by using the existing technologies of cooperative control. The autonomous control of the vehicles is not needed for the purpose of improving the fuel efficiency and the safety.

2.3 Efficient utilization of costly infrastructure

Shladover [12] has pointed out that the infrastructure for road transportation (primarily the roads) is not being efficiently utilized. It is very expensive to build highways and their construction requires energy and therefore they also contribute to environmental pollution. In U.S, standard highway lane is 3.6m in width, and large passenger cars are only 1.8m in width; therefore we use only half the lane width. On a typical highway, we use only one ninth of the length of the lane, the maximum throughput is 2200 vehicles/hr which represents headway of 1.64 sec. Los Angeles region freeway performance measurement system (PeMS) data shows that this throughput is reached at speed around 100km/h for vehicle length of 4.6m with average separation distance of ~ 40m. Therefore, net utilization is 5.5% of road surface occupied by the vehicles even at highest efficiency. The automation can lead to more efficient utilization of the roads. The future construction of highways and city roads may be based on less surface requirement without compromising safety.

2.4 Savings in fuel consumption by vehicle weight reduction

It is well known that substantial savings in fuel can be achieved by reducing the vehicle mass. It can be accomplished by the use of light metals such as aluminum and ultralight steel and stronger and lighter advanced carbon composites. The issues that may need to be addressed are crashworthiness and the manufacturing cost. According to Lovins [5], the use of carbon composite would be most promising since they can absorb six to twelve times more energy per pound than steel; it will make the cars not only lighter but also bigger and safer. It will also make them simpler and therefore potentially simpler to manufacture. There are several examples of cars (e.g. GM Ultralite 1991, Opel Eco Speedster 2002, Toyota Allesandro Volta 2004 etc.) and trucks that have been built using carbon composites; however none of them has been mass produced [5]. Figure 25 shows that the fuel used in U.S. gallons per year by a baseline SUV vehicle (Audi AllRoad 2.7T) for a typical U.S driving pattern is ~ 956 gallons. As shown in Figure 25, 51% reduction in mass of this vehicle can result in approximately 50% in fuel savings requiring only 495 gallons. Better integration of aerodynamics, tires and power train can further reduce the oil consumption by 105 gallons and the hybridization (part of the power source being electric – battery or fuel cell) can additionally reduce the oil consumption by 111 gallons [5]. It is important to note that these are theoretical estimates by Lovins [5] and may not be easily realizable in practice.

In previous sections, we have discussed a number of approaches for reducing the fuel consumption of a road vehicle based on the available technologies of passive and active flow control and shape optimization for drag reduction, and utilization of automatic control technologies for efficient vehicle movement and control. In addition, we have emphasized the use of advanced composite materials and light weight metals for mass reduction which have a major impact on fuel efficiency. Figure 26 shows the propulsive energy requirement sensitivity of various road vehicles with respect to mass of the vehicle, the operational speed profile, rolling resistance and aerodynamic drag. It is also compared with low and high speed trains [13]. The numbers at the top of the bars indicate % decrease in the energy requirement with 1% change in one of the parameters (mass, speed profile, rolling resistance and aerodynamic drag). As an example, if mass of the automobile on the highway decreases by 20% (it includes all weights - the body weight, passengers and cargo weight, and fuel), it will decrease the energy requirement by 8%.

In previous sections, we have discussed various technological solutions for improving the energy efficiency of road vehicles. The energy efficient vehicles not only require less fuel (and therefore reduce consumption of energy resources and save money), the by product is less pollution and environmental impact. In the following sections, we discuss alternative fuels and power sources for reducing the emissions due to the use of fossil fuels (primarily the petroleum and diesel).

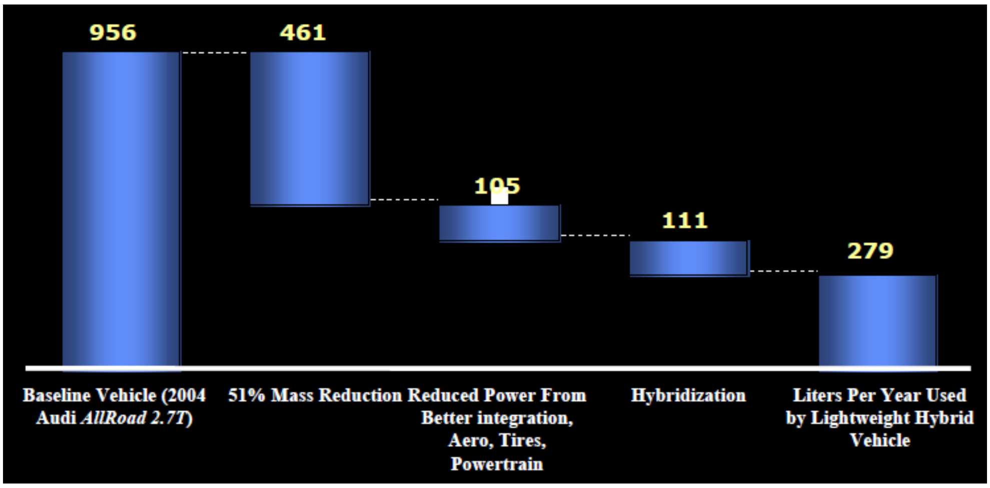


Figure 25. Effect of mass reduction and other technologies on fuel consumption of a typical SUV for a typical driving pattern in U.S. [5]

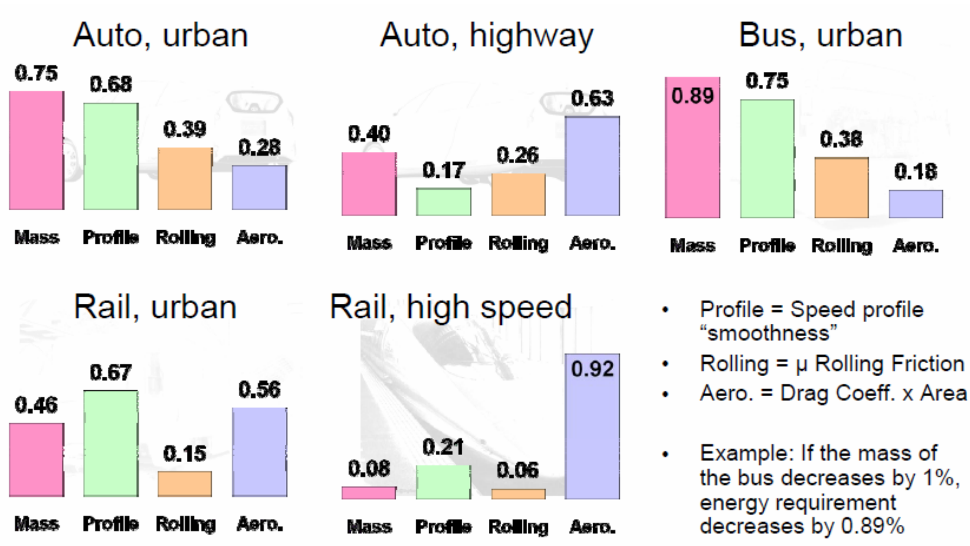


Figure 26. Propulsive energy requirement sensitivity of automobiles, buses, and rails with respect to mass, speed profile smoothness, rolling resistance and drag [13]

2.5 Alternative fuels and power sources

2.5.1 Biofuels

There is considerable push worldwide to explore alternative sources of energy with low carbon foot print for road transportation. Biofuels are increasingly being used as replacement of liquid fossil fuels. It is forecasted that by 2030, 15 to 25% of the petroleum based fuel will be replaced by biofuels. In addition, efficient and cost effective energy storage technologies such as batteries and hydrogen fuel cells (which require hydrogen production and storage technologies) are being developed; the energy for these sources of mobile energy will be obtained from emission free sources such as solar, wind etc. In this section, we first briefly discuss the biofuels followed by the energy storage technologies.

There are three types of biofuels that can be created from the type of biomass used: (a) Ethanol: It is made by converting the carbohydrate portion of biomass into sugar, which is then converted into ethanol in a fermentation process similar to brewing beer. Ethanol is the most widely used biofuel today with current capacity of 55 billion liters per year based on starch crops such as corn and sugarcane. Ethanol based on Cellulosic biomass is currently the subject of extensive research, development and demonstration efforts because it can be produced from non food crops such as switchgrass, miscanthus, jatropha, hemp etc. as well as wood and other agriculture residues. Brazil is currently the biggest producer of ethanol from sugarcane (~ 20 billion liters) followed by the U.S and the European Union, China and India. Ethanol supplies about 20% of the road fuel in Brazil while it supplies only 3% of the road transportation fuel in U.S. But its use will continue to increase as mentioned before. (b) Biodiesel: It is produced through a process in which organically derived oils are combined with alcohol (ethanol or methanol) in the presence of a catalyst to form ethyl or methyl ester. The biomass derived ethyl or methyl esters can be blended with conventional diesel fuel or used as a neat fuel (100% biodiesel). Biodiesel can be made from soybeans or canola oil, or waste vegetable oils. The current worldwide biodiesel production is ~ 12 billion liters. Germany is a major producer of biodiesel (~ 3 billion liters) followed by other countries in the European Union (~ 2 billion liters). U.S produces about 2 billion liters of biodiesel. (c) Syngas: Biomass can be gasified to produce a synthesis gas composed primarily of hydrogen and CO, called syngas or biosyngas. Hydrogen can be recovered from this syngas, or it can be catalytically converted to methanol. It can also be converted using Fischer-Tropsch catalysts into a liquid stream with properties similar to diesel fuel, called Fischer-Tropsch diesel. Syngas is not widely produced or used. It can however be used with benefit for heavy duty trucks.

The blends of ethanol, known as E10 (10% ethanol and 90% gasoline) and E85 (85% ethanol and 15% gasoline) are becoming increasingly available at gas pumps in U.S, Brazil, and in many countries in Europe and other parts of the world. E10 can be used with any existing vehicle while the use of E85 requires a Flexible Fuel Vehicle (FFV) which requires some modifications in the existing vehicles. Wang [14] has done an extensive analysis of the benefits of E10 for a general vehicle (GV) and E85 for a FFV vehicle as a replacement of conventional gasoline and also for reducing the GHG emissions. Figure 27 shows the change in per-mile energy use by ethanol blend to displace gasoline [14]. The left column of the figure shows that overall energy use per-mile of transportation increases by use of ethanol blends compared to fossil fuel based energy. The energy required for producing the ethanol from corn or cellulosic biomass is included in the calculation of total energy change per mile with the use of Ethanol blend. For example, the use of E85 blend from cellulosic biomass for a FFV vehicle requires 52.3% extra energy compared to fossil fuel based energy for one mile of transportation. The middle and last column of Figure 27 show change in fossil energy or petroleum energy (the energy required for refining the crude oil is included in this) needed for one mile of transportation using the ethanol blend. For example, with the use of cellulosic E85 blend, 70% less energy from petroleum is needed for one mile of transportation (or in other words, 85% of ethanol in the blend contains equivalent of 70% energy in the petroleum).

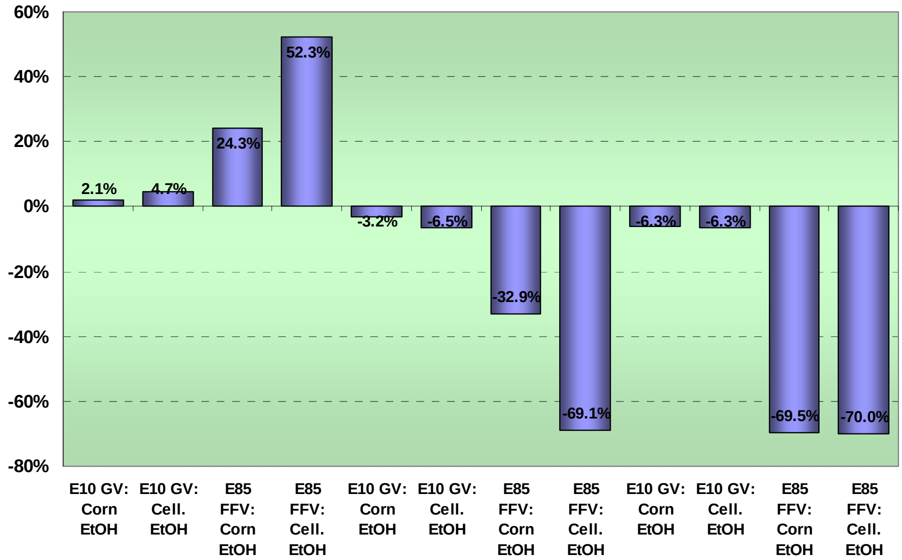


Figure 27. Change in per-mile energy use by ethanol blend to displace gasoline [14]

Figures 28 and 29 show that the use of cellulosic ethanol can indeed reduce the GHG emissions significantly, especially the use of E85 blends. However, the use of corn based ethanol has a much smaller effect in reducing the GHG emissions. Figure 28 shows the reductions in per-mile GHG emissions by ethanol blend to displace gasoline. Figure 29 shows GHG emission reductions per gallon of ethanol to displace an energy-equivalent amount of gasoline.

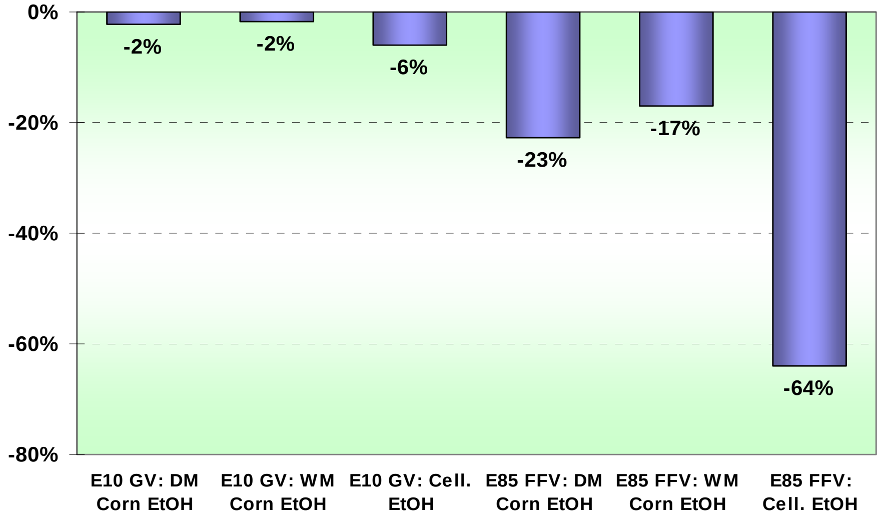


Figure 28. Reductions in per-mile GHG emissions by ethanol blend to displace gasoline [14]

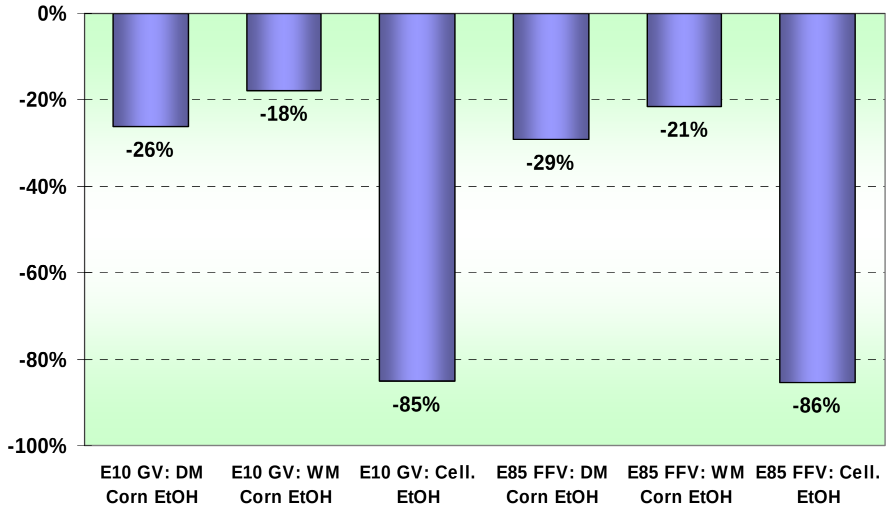


Figure 29. GHG emission reductions per gallon of ethanol to displace an energy-equivalent amount of gasoline [14]

2.5.2 Batteries and fuel cells

As mentioned before, the energy derived from nonrenewable fossil fuels (preferably with carbon capture and sequestration (CCS)) as well as renewable sources such as solar, wind, geothermal etc. can be converted into electrical energy which can be stored in a mobile form so that it can be used in the road transportation. As a result, currently a great deal of research effort is devoted towards the development of high energy, efficient, and stable rechargeable batteries with long life cycle as well as on efficient and cost effective hydrogen production and storage technologies; hydrogen is needed for fuel cells that can be used to power the vehicle. These power sources can be used in an all electric zero-emission vehicle (ZEV) or in a hybrid-electric vehicle (HEV) or a fuel cell powered vehicle (FCV). Figure 30 shows a schematic for on board energy conversion from non-renewable and renewable energy sources [15].

For energy storage, there are basically three mechanisms: (a) electrical energy storage which makes use of batteries and ultra-capacitors, (b) mechanical energy storage which can be accomplished by use of flywheels, hydraulic devices and compressed air, and (c) chemical energy storage in the form of liquid fuels and hydrogen. As shown in Figure 31, the energy storage density of these forms of energy storage devices varies a great deal [13].

It is not surprising from Figure 31 that the carbon based fuel have the highest energy storage density. For road vehicles, batteries and hydrogen (used in fuel cell) are preferred ways to carry energy on board. Figure 32 shows the current state of the battery performance metric [16]. Most of the current research effort is devoted to Li- ion batteries, where the potential for achieving high energy density is greatest.

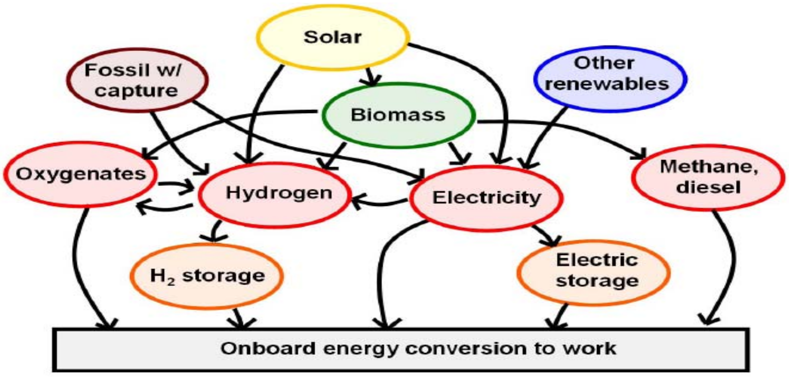


Figure 30. Fuel chain possibilities for carbon free energy for transportation [15]

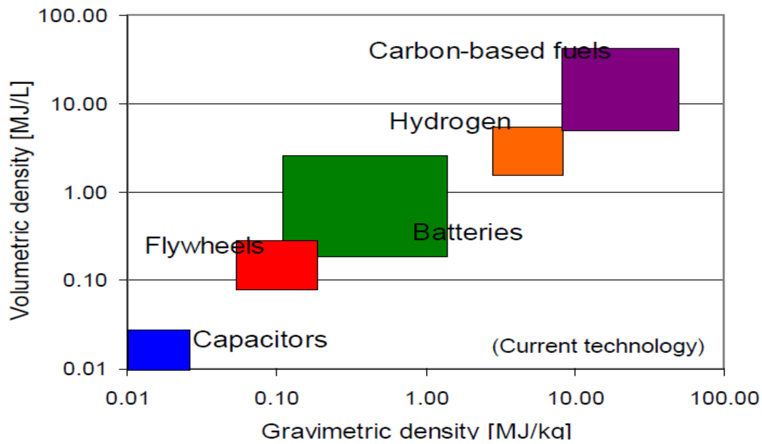


Figure 31. Energy storage density of various energy storage devices [13]

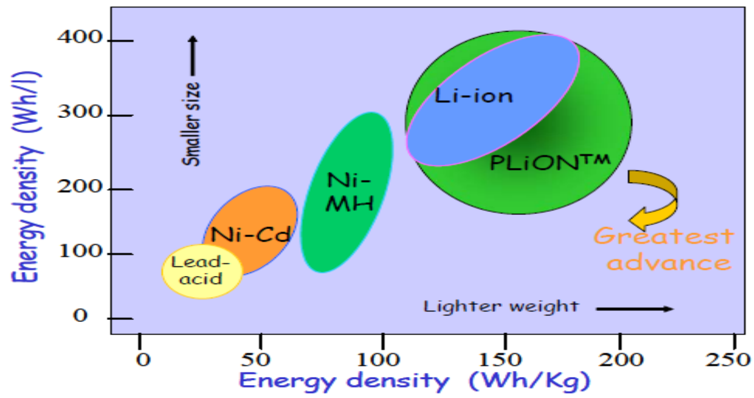


Figure 32. Current state of the battery performance metric [16]

Table 2 shows the specific energies of various batteries in Figure 32 and their comparison with gasoline [16]. Table 3 shows the long term US Advanced Battery Consortium (USABC) performance goals for the batteries [16].

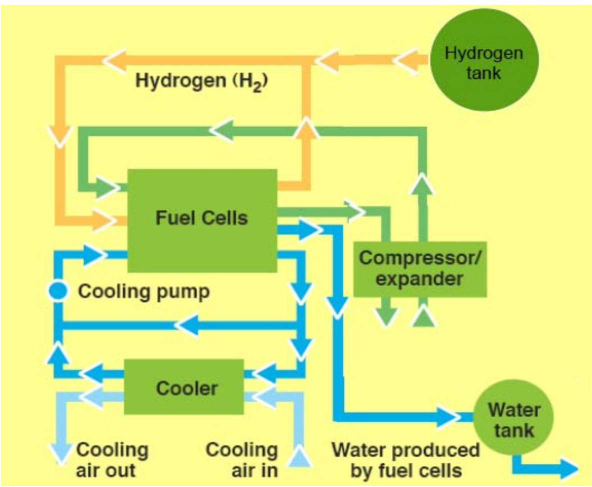
There is general consensus that the Li-ion class of battery is most likely to meet the long term performance goals. For more detailed information on battery technology, the reader is referred to the presentation by Sadoway [16] and the book edited by Yoshio et al. [17]. Another way to carry energy on board a road vehicle is in the form of hydrogen to be used in a fuel cell. Figure 33 (a) shows various components in a fuel cell and Figure 33 (b) shows the schematic of operation of a Proton Exchange Membrane (PEM) fuel cell. There are wide varieties of fuel cells for automotive applications that have been developed over last couple of decades. For detailed information on the fuel cell technology, the reader is referred to the book by O'Hayre et al. [18]. Figure 34 shows other types of fuel cells and their current cost and efficiency.

Table 2. Specific energies of various batteries [16]

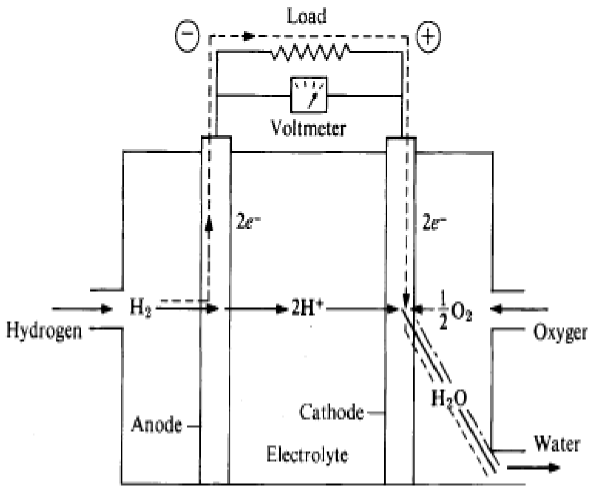
Battery Type	Wh/kg	MJ/kg
Lead Acid	35	0.13
NiCd	45	0.16
NaS	80	0.28
NiMH	90	0.32
Li - ion	150	0.54
Gasoline	12000	43.0

Table 3. USABC long term performance goals for batteries [16]

Operating temp.	-40 to 85°C
Specific energy	200 Wh/kg @ C/3
Energy density	300 Wh/L @ C/3
Specific power	300 W/kg
Power density	600 W/L
Cycle life	1000 cycles @ 80% DOD
Service life	10 years
Ultimate price	~ $100/kWh for 40 kWh packs



(a) Various components in a fuel cell



(b) Operation schematic of a fuel cell

Figure 33. PEM fuel cell using hydrogen as an energy source

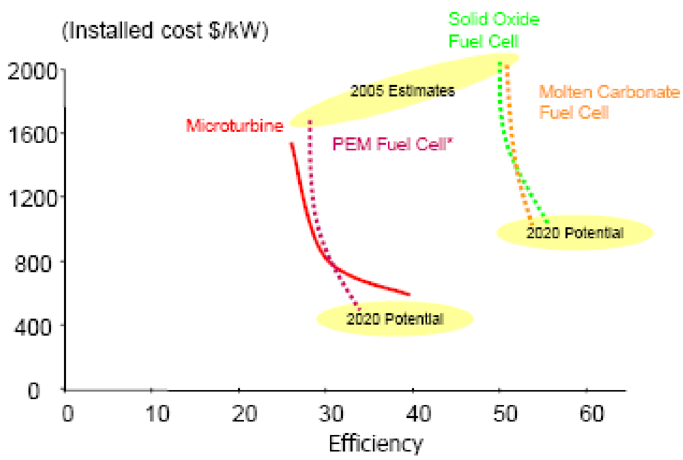


Figure 34. Various types of fuel cells, their cost and efficiency

2.6 Hybrid – electric vehicles (HEV) and fuel cell vehicles (FCV)

Almost all automobile manufacturers around the world are investing in battery and fuel cell technologies with the aim of developing HEV and FCV vehicles. Several HEV, FCV and ZEV are currently being sold by Toyota, Mitsubishi, GM, Ford and other manufacturers. The goal is to eventually replace the conventional vehicles by HEVs and FCVs to reduce the GHG emissions. Wang [14] has estimated the reduction in GHG emissions using the HEVs and FCVs as shown in Figure 35. Figure 35 shows the breakdown between well-to-pump (WTP) and pump-to-wheel (PTW) contributions to the emissions. HEVs substantially reduce both WTP and PTW emissions because they require less gasoline and also less power from gasoline to cover a distance, rest of the power is provided by the battery or another on board energy source. FCV contributes to only WTP emission since natural gas or petroleum/ethanol is required for the production of hydrogen. It does not contribute to PTW emission because all the required power is provided by the fuel cell. Only the FCV in which hydrogen is generated by the renewable carbon free energy source does not contribute to either WTP or PTW emission as indicated by the bottom row of Figure 35.

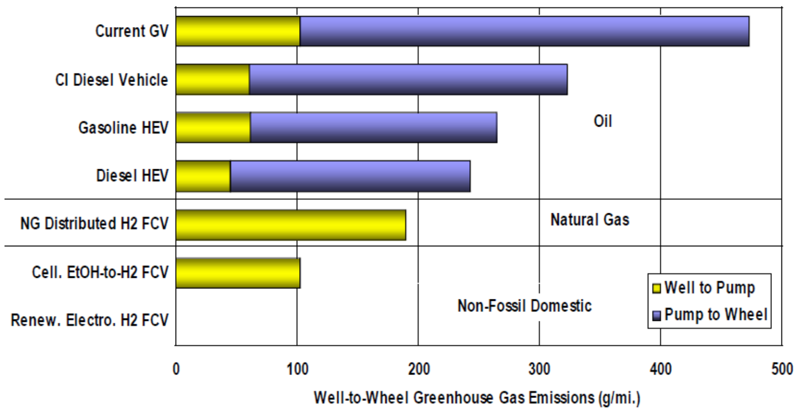


Figure 35. Well-to-Wheel (WTW) emissions for GV, HEV and FCV [14]

3. Challenges and opportunities

In this review, we have identified both challenges and opportunities for improving the energy efficiency of the vehicles by employing technologies for reducing mass (by use of carbon composites), the aerodynamic drag, and the rolling resistance, as well as the automatic control technologies for more efficient and safe operations of the vehicles on the highways. Some of the technologies are currently application ready but several of them require further research and development before mass scale implementation. The energy efficient vehicles will contribute to significant reduction in fuel consumption and as a byproduct reduce the GHG emissions. We have also identified the alternate fuels (biofuels) and other carbon free power sources to reduce the GHG emissions. There are economic, social, and political issues related to the use of biofuels, especially those produced from food crops. Other carbon free power sources such as batteries and fuel cells require more research and development for them to become energy efficient and cost effective. With all the challenges ahead, the future remains bright for technological innovations and their implementation.

Acknowledgements

Majority of the figures used in the section on ‘Sustainable Ground Transportation’ have been taken from the presentations of various authors in the Advanced Transportation Workshop, 10-11 October 2005, organized by the Global Climate and Energy Project (GCEP) at Stanford University. The author would like to thank Professor Raimo J. Hakkinen for reading the manuscript and for making many helpful suggestions that have improved the paper. Finally, it should be noted that the material used in this review paper has been used from a variety of sources listed in the references; any omission is completely unintentional.

References

[1] Schafer, A., Heywood, J.B., Jacoby, H.D., and Waitz, I.A., Transportation in a Climate Constraint World, MIT Press, Cambridge, MA, 2009.

[2] Salari, K., "DOE's Effort to Reduce Truck Aerodynamic Drag through Joint Experiments and Computations," LLNL-PRES-401649, Presentation at Lawrence Livermore National Laboratory, 28 February 2009.
[3] Greene, D.L. and Schafer, A., "Reducing Greenhouse Gas Emissions from U.S. Transportation," Report of Pew Research Center on Global Climate Change, 2003.
[4] www.epa.org
[5] Lovins, A.B., "Technology Integration for Radical and Profitable Transport Efficiency," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/11_Lovins_10_11_trans.pdf
[6] Browand, F., "Reducing Drag and Fuel Consumption," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/10_Browand_10_11_trans.pdf
[7] Agarwal, R.K., Vadillo, J., Tan, Y., Cui, J., Guo, D., Jain, H., Cary, A.W., and W.W. Bower, "Flow Control with Synthetic and Pulsed Jets: Applications to Virtual Aeroshaping, Thrust-Vectoring, and Control of Separation and Cavity Oscillations," in Frontiers of Computational Fluid Dynamics , Chapter 11, D.A. Caughey and M. Hafez Editors, World Scientific, NJ, 2006.
[8] Seifert, A., Stalnov, O., Sperber, D., Arwatz, G., Palei, V., David, S., Dayan, I., and Fono, I., "Large Trucks Drag Reduction Using Active Flow Control," AIAA Paper, AIAA Aerospace Sciences Meeting, Reno, NV, January 2008.
[9] Bellman, M., Naber, J. and Agarwal, R.K. "Numerical Drag Reduction Studies of Generic Truck Models Using active Flow Control," AIAA Paper Number 2009-4013, AIAA Fluid Dynamics Conf., San Antonio, TX, 22-25 June 2009.
[10] Bellman, M., Agarwal, R.K., Naber, J. and Chusak, L. "Reducing Energy Consumption of Ground Vehicles by Active Flow Control," ASME Paper ES2010-90363, ASME 2010 4th International Conf. on Energy Sustainability, Phoenix, AZ, 17-22 May 2010.
[11] Barth, M., in presentation by Shladover, S.E., "Research Challenges for Automated Vehicles," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/06_Shaldover_10_11_trans.pdf (Reference 12).
[12] Shladover, S.E., "Research Challenges for Automated Vehicles," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/06_Shaldover_10_11_trans.pdf
[13] Hermann, W., in presentation by Orr, L., "Introduction to GCEP and Scope of Workshop," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/01_Orr_10_11_trans.pdf (Reference 15)
[14] Wang, M. "Wheel- to- Wheels Results of Advanced Vehicle Systems with New Transportation Fuels," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/03_Wang_10_11_trans.pdf
[15] Orr, L., "Introduction to GCEP and Scope of Workshop," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/01_Orr_10_11_trans.pdf
[16] Sadoway, D., "Advanced Batteries for Automotive Applications," Advanced Transportation Workshop, 11-12 October 2005, GCEP, Stanford University, http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/12_Sadoway_10_12_trans.pdf
[17] Yoshio, M., Brodd, R.J. and Kozawa, A., Lithium-Ion Batteries: Science and Technologies, Springer, 2010.
[18] O'Hayre, Cha, S.-W., Collela, W., and Prinz, F.B., Fuel Cell Fundamentals, 2nd Edition, John Wiley, 2009.

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