



## **Light Vehicle Alternative Fuels and Fuel Economy Related Technologies**

### **Overview**

Economies throughout the developing world have been undergoing rapid growth over most of the last 20 years, notably China and India. Increasing economic growth is leading to increased global transportation demand. Since most means of transportation currently use petroleum-based fuels, there is an increasing demand for petroleum resources. At the same time, security issues and environmental concerns are calling for lessening dependence on petroleum. With these growing demands on a global basis, it is not surprising that alternative fuel technologies in the automotive sector are rising in importance.

This paper reviews major light vehicle (car and light truck) fuel and fuel saving technologies either currently available or on the horizon that can be employed to reduce global petroleum demand including: diesel, alcohols (butanol and ethanol), biodiesel, straight vegetable oil, biomass-based diesel and gasoline, coal- or natural gas-based diesel and gasoline, natural gas, hybrids, plug-in hybrids, electric vehicles, hydrogen fuel cell vehicles, electrification of accessories, vehicle light weighting, advanced drive train technologies, as well as vehicle use technologies.

### ***Fuels***

#### **Diesels**

Today, diesel is the main alternative fuel to gasoline worldwide. While it is still petroleum-based, the technology for its use is widely available and increasing its use can reduce oil consumption. Diesel engines can provide 25 percent more fuel efficiency and more torque at lower rpm than gasoline engines. Due to thicker castings and higher quality components needed to withstand the higher pressures and torque of diesel combustion, comparative diesel engines tend to be more expensive to produce and have higher upfront costs for consumers though the lower fuel costs from increased efficiency can usually payback those increased upfront costs in a few years.

While diesel engines account for approximately half of the European market, they have not been popular in the United States, accounting for less than one percent of light vehicle sales. Some of the reasons for this discrepancy have been the U.S. diesel fuel's historically higher sulfur content (compared to Europe), strict U.S. air pollution regulations for nitrous oxides and particulates, and European tax advantages for diesel-fuelled vehicles (making diesel fuel cheaper versus gasoline in Europe). In addition, U.S. consumers have not been interested because they remember the noisy, smoky, unreliable diesel engines offered in the 1980's; therefore bad associations remain in consumer perceptions regarding diesels, despite significant improvements made in diesel technologies over the past 25 years.

However, federal rules will require refiners to sell only ultra-low-sulfur diesel fuel in the United States by December 1, 2014. This change was already substantially met for on-road diesel by

late 2006. Combined with improvements in diesel engine technology, it enables diesel engines to meet tough new emission standards that began for on-road diesels at the beginning of 2007.

The Environmental Protection Agency (EPA) estimates that if one-third of U.S. light vehicles had diesel engines, the United States would save 1.4 million barrels of oil per day, roughly the amount of oil the United States currently imports per day from Saudi Arabia. Unfortunately there are several challenges to future diesel sales. These challenges include: the additional costs associated with developing the technology to comply with strict state and federal emission standards; high relative market prices for diesel fuel; overcoming diesels' poor reputation with consumers; and, marginally by the still developing nationwide availability of ultra-low-sulfur fuel.

### **Alcohols – Ethanol, Butanol**

Ethanol is usually produced by fermenting plant sugars but can also be created by thermal-chemical reaction, or perhaps more directly through biological means. Most ethanol in the United States is made from corn. It can also be made from cellulosic materials such as trees, grasses, and forestry residues. For many years corn ethanol has been used as an additive to gasoline but it is also available as a primary fuel, most commonly as a blended mix of roughly 85 percent ethanol and 15 percent gasoline (E85). There is limited availability of E85 on a national scale. At the beginning of 2007, there were only about 1,100 E85 fuelling stations nationwide. There are currently 2,200 stations, which is still quite low. By comparison, there are roughly 170,000 gasoline stations in the United States today.

Ethanol is currently not cost-competitive with gasoline or diesel as a primary fuel. The cost of corn feedstock accounts for approximately 75 percent of corn ethanol's production costs. Competing demand for agricultural land uses and the corn itself, primarily as livestock feed, hampers major feedstock cost reductions. Government subsidies play a huge role in generating the necessary crops. For example, the federal government provides a 45-cent per gallon subsidy to help make ethanol cost competitive along with a 2.5 percent ad valorem tariff and a 9-cent per gallon effective duty on imports.<sup>1</sup>

Ethanol has a lower energy content than regular gasoline returning fewer miles to a gallon in a similarly sized gasoline engine. Due to its higher octane, smaller, higher compression engines optimized for ethanol could maintain similar power and mileage results versus larger gasoline-based engines. (Engines optimized for ethanol can achieve over 40 percent thermal efficiency. Gasoline engines currently reach about 25 percent thermal efficiency.<sup>2</sup>) Turbochargers or superchargers fitted in slightly smaller engines could allow manufacturers to attain some of that optimization in a flexible format. They could do that by allowing engineers to change cylinder pressures depending upon the fuel. Variable compression engines could also provide some of

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<sup>1</sup> In addition to a 2.5 percent ad valorem tariff, the U.S. has a 54-cents per gallon duty surcharge designed to offset the 45-cent subsidy on ethanol blending.

<sup>2</sup> "Economical, High-Efficiency Engine Technologies For Alcohol Fuels," Brusstar and Bakenhus, <http://www.epa.gov/otaq/presentations/epa-fev-isaf-no55.pdf>

that optimization while maintaining flexible fuelling capability but the technology is not currently commercialized in production automobiles.<sup>3</sup>

Due to the much more abundant feedstocks (because any type of plant matter is potentially a feedstock), cellulosic ethanol could eventually be produced in much higher quantities than corn ethanol. However, large reductions in the production costs of cellulosic ethanol are needed to make it commercially viable. Cellulosic ethanol production is currently more costly than corn ethanol production because the cellulose must first be broken down into fermentable sugars that can be converted into ethanol, an extra processing step or it has to be treated via currently more expensive thermal-chemical reactions. In addition, cellulosic materials have less energy content per pound than corn, thus requiring larger quantities of feedstock to produce equivalent output yields. The increase in quantity for equivalent yields results in significantly higher transport and handling costs.

Moreover, because ethanol retains water, it is more corrosive than petroleum-based fuels. The widespread commercialization of ethanol will require substantial retrofitting of the refueling infrastructure. Investments will be needed to upgrade pipelines, storage tanks, and filling stations. For instance, gasoline stations may have to replace their storage tanks, at an estimated cost of \$100,000 per tank. In addition, most current vehicle fuel systems and engines cannot effectively handle high concentrations of ethanol. Generally U.S. automotive fuel systems are engineered for less than 10 percent by volume (E10) fuel. Raising the level in the general gasoline pool may present problems for standard gasoline engine fuel systems.<sup>4</sup> Therefore widespread use of ethanol as a primary fuel would require a turnover in the vehicle fleet or substantial retrofitting.

Fleet turnover would not be an issue for other alcohols such as butanol. Butanol can be made from the same feedstocks as other alcohols such as ethanol. Butanol does not retain water and can be readily used in our current fuelling infrastructure. Butanol is also much more similar to gasoline in energy content per gallon requiring little additional engine optimization, but like cellulosic ethanol it is not currently cost effective to produce. Several companies are working to make commercial butanol production cost competitive.

### **Biodiesel**

Biodiesel has similar properties to petroleum diesel but can be produced from vegetable oils or animal fats. While similar to petroleum-based diesel fuel, biodiesel is chemically distinct. Because it is chemically different, biodiesel presents problems to the complex emissions reductions equipment in modern diesel powered vehicles. In addition, vehicle manufacturers are not as familiar with the long-term effects of biodiesel on the reliability of their engines. Due to warranty concerns, many vehicle manufacturers only certify their products for use with five

<sup>3</sup> Examples: “Saab Reveals Unique Engine Concept that Offers High Performance and Low Fuel Consumption,” <http://www.saabnet.com/tsn/press/000318.html>; “The Engine of the Future,” [http://www.sandersonengine.com/html/the\\_engine\\_of\\_the\\_future.html](http://www.sandersonengine.com/html/the_engine_of_the_future.html); “New Engine Design Adjusts Compression to Meet Driving Conditions,” [http://www1.eere.energy.gov/vehiclesandfuels/pdfs/success/vcr3\\_29\\_01.pdf#search=%22%22variable%20compression%20ratio%22%20engine%22](http://www1.eere.energy.gov/vehiclesandfuels/pdfs/success/vcr3_29_01.pdf#search=%22%22variable%20compression%20ratio%22%20engine%22)

<sup>4</sup> There are studies underway to determine if higher blend levels can be achieved without compromising fuel system safety.

percent biodiesel blends (B5). Biodiesel manufacturers have developed industry standards to help maintain product quality and they are working with vehicle manufacturers to help certify engines for higher level blends.

Like corn-based ethanol, the cost of biodiesel feedstocks (largely soybean oil in the U.S) is the largest component of production costs. The cost of soybean oil is not expected to decrease significantly in the near-term owing to competing demands for animal feedstocks and land for feedstock production.

Several firms are exploring algae production for fuels including biodiesel and ethanol. Although production has not been economical to date, algae production could make sufficient vegetable oil available for significant bio-diesel or alcohol production in the future.

### **Straight Vegetable Oil (SVO)**

Vegetable oil can be used as a primary fuel in diesel engines without further conversion. Fuel more similar to petroleum diesel is needed to start the engine, but the engine can continue to function on straight vegetable oil (SVO). Like all fuels there are potential emissions concerns and potential trade-offs. For example, research into the emissions impact on the use of rapeseed oil (RSO) as SVO found it to be more likely to induce cancer than petroleum-based diesel and other fuels.<sup>5</sup>

Feedstock production constraints for SVO are similar to those of biodiesel, but vehicle producers have even greater concerns about the long-term reliability of their products running on SVO. The lack of fuel standards and the extremely wide variety of vegetable oils make certifying engines for their use extremely cost prohibitive. No manufacturers currently warranty vehicles running on SVO.

### **Biomass-based Diesel and Gasoline**

It is also possible to use biomass (vegetation and animal wastes) to produce biomass-based gasoline and diesel. These fuels have the same basic fuel properties (range of carbon chains) of current petroleum-based fuels.

One way to do this is via the “Fisher-Tropes” thermal-chemical method.<sup>6</sup> The resulting fuel is sometimes known as “renewable diesel.” The process is generally known as biomass-to-liquids (BTL). No company currently commercially produces fuel this way from biomass but several test plants are in operation and the process is used commercially on natural gas and coal (see below) in various countries around the globe. Still, a number of technological and economic challenges need to be overcome for this process to achieve commercial viability using biomass.

Another way to produce biomass-based petroleum fuels is via hydrocracking to produce diesel or catalytic cracking to produce gasoline. These fuels are sometimes called “green diesel” or “green gasoline” respectively. Hydrocracking is similar to the catalytic cracking which is the

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<sup>5</sup> “Strong mutagenic effects of diesel engine emissions using vegetable oil as fuel”, Bunker, Krahl, Munack et.al., February 2007, <http://www.bv-pflanzenoele.de/pdf/ArchTox.pdf> , pg. 1

<sup>6</sup> The Fisher-Tropes process builds up the hydrocarbon chains from the carbon and hydrogen present in gasified carbon feedstocks.

refining method currently employed to produce petroleum-based fuels. Like the Fisher-Tropes method noted above, the resulting fuels are the same as petroleum-based fuels. A European refiner has recently installed a hydrocracking “train” (unit) for the European market.

A third way is to engineer biological organisms to excrete these fuels directly. Several firms are experimenting with microorganisms that produce similar chemicals in the same way that ethanol is excreted in traditional fermentation.

These biomass-based fuels tend to have much fewer impurities than petroleum-based fuels leading to lower emissions when used as an additive. Additionally, vehicle manufacturers have much more experience developing engines that operate on these types fuels and the current fleet is generally optimized for their use. Ironically, vehicle manufacturers depend upon some of the impurities (largely the waxes) found in conventional fuels for lubrication there are potential reliability concerns for automakers with these fuels used in very high levels but they will still generally tend to improve the quality of traditional petroleum fuels when blended. There are no separate fuel standards for these fuels.

### **Coal- or Natural Gas-Based Diesel and Gasoline**

As mentioned above, coal and natural gas can also be converted into petroleum-like fuels. Germany produced large quantities of diesel fuel from coal during the Second World War and South African firms did the same under apartheid. South African facilities continue to operate and Chinese firms are adding significant production of coal-based fuel production.

Production of natural gas-based versions of these fuels is limited. Strong worldwide demand for natural gas makes it generally too expensive to use as a feedstock.

The properties of the fuels produced from either coal or natural gas are similar to biomass-based, renewable diesel and likewise vehicle emissions are generally lower than standard petroleum-based diesel. The production of fuel from coal in particular releases significant quantities of the principal greenhouse gas CO<sub>2</sub> that would worsen climate change impacts unless provision is made to capture and then permanently sequester the gas.

### **Natural Gas and Natural Gas Vehicles**

Natural gas can be used as a vehicle fuel either compressed or liquefied. Natural gas vehicles are currently available in the United States and have been for many years. While natural gas vehicles have fewer emissions, their use is currently limited in the United States.

Gas-based fuels present on-board storage problems due to their low density. The low density currently necessitates relatively expensive and large high-pressure tanks which have significant packaging issues. Current automotive conversions generally lose much of their trunk volume. The low density also leaves these vehicles with limited range. Natural gas vehicles also face considerable infrastructural barriers. Retrofitting refueling stations could cost from \$100,000 to \$1 million per station, and home-refueling devices can cost around \$2,000 each.

Use of natural gas as a vehicle fuel is currently substantial in Germany, Argentina, Brazil, India, Pakistan and Iran. In addition, Venezuela mandated as of January 1, 2008 that all light vehicles sold there be capable of running on both natural gas and gasoline.

### *Electrics*

#### **Hybrids, Plug-In Hybrids and Electric Vehicles**

Hybrid vehicles have become of significant interest to American consumers. They currently represent about two percent of new light vehicle sales. Hybrid power systems combine small engines with battery packs and electric motors. Current hybrid vehicles use their electric drive components to recapture energy and to augment their petroleum-fueled engine allowing the engine to operate in higher efficiency ranges. Hybrid electric vehicles are now cost effective, proven technologies. Like most efficiency related technologies, the added costs of the technology are faced at the time of purchase while lower operating costs are seen over time. While hybrids provide substantial improvements in efficiency over internal combustion engine driven vehicles, even greater reliance on electrical energy to drive vehicles could provide much greater gains in transportation efficiency and fuelling costs.

Batteries and electric motors are highly efficient in their storage and use of electricity. Likewise, the large turbines at electrical power generation stations achieve much greater efficiencies than the internal combustion engines found in regular automobiles. Charging vehicles from the electrical grid allows them to benefit from the greater efficiencies of the large power generation stations. The result is a much lower energy requirement per mile. This results in plug-in vehicles having lower emissions per mile using the average U.S. power generation mix of electricity than typical hybrid vehicles which are already much lower than traditional engine driven vehicles.<sup>7</sup> Electric energy is much less expensive than petroleum-based fuel, so the per-mile cost of electric power is also much lower. In addition, since so many different fuels can be used to produce electric power, grid-based electric propulsion allows much greater macro-level fueling flexibility. Any fuel producing electricity is capable of producing electricity to power an electric vehicle.

Unfortunately, the cost and limitations of battery storage technologies have acted to limit the utility of battery powered vehicles and thereby consumer acceptance. Deep cycling batteries (charging and discharging batteries toward their extremes) has tended to have a considerable negative impact on their useful life. Hybrid vehicles tend to use only a shallow portion of their batteries' potential energy storage to help preserve them. In addition, batteries have historically held limited power and they were heavy. The low power per pound limited their range. The limited utility posed by limited range was compounded by the long time it took to recharge batteries. Considerable research is underway to address these limitations.

The U.S. Advanced Battery Consortium (USABC) is part of the United States Council for Automotive Research (USCAR). USABC is supported by a cooperative agreement with the U.S.

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<sup>7</sup> Sources: "Sorting Through the Many Total-Energy-Cycle Pathways Possible with Early Plug-In Hybrids," Center for Transportation Research, Argonne National Laboratory, <http://www.transportation.anl.gov/pdfs/HV/458.pdf>, and "Environmental Assessment of Plug-In Hybrid Electric Vehicles," Electric Power Research Institute and the Natural Resources Defense Council, <http://my.epri.com/portal/server.pt?open=514&objID=223132&mode=2>

Department of Energy that provides up to 50 percent of the USABC budget. The Consortium's mission is to develop electrical energy storage for fuel cell, hybrid and electric vehicles. Several manufacturers have batteries undergoing testing at USABC that have met or exceeded initial testing guidelines for plug-in applications.

Even without all of the necessary battery parameters being validated by USABC, GM announced their intention to build plug-in hybrids (contingent on the availability of the batteries). GM showcased their "Volt" plug-in concept at the 2007 North American International Auto Show and it is in the process of conducting the production engineering for the vehicle. As a plug-in hybrid, the Volt will have an electric-only range of roughly 40 miles. Once the batteries are discharged, a small on-board generator (anything from a gasoline engine to a hydrogen fuel cell) can engage to keep the batteries charged. The effect would be to extend the vehicle range for as long as fuel is available for the small engine. The advantage of this plug-in hybrid system is that it would allow roughly 80 percent of U.S. trips to be completed using much cheaper electricity while sidestepping the long recharging and range issues of older battery electric vehicles.

Major advances have been made in the characteristics of batteries which enables the production of vehicles such as the Volt. New, nanoscale production techniques have allowed battery firms such as A123 Systems and Altairnano to produce batteries that can withstand heavy deep cycling and yet still meet vehicle manufacturer warranty requirements. The new batteries can also be safely charged and discharged to high portions of their total capacity in minutes. These advances in battery technology have led virtually every major automotive firm to announce their intentions to produce plug-in vehicles by 2012.<sup>8</sup>

Many of these new vehicles will still have limited range versus traditional internal combustion vehicles and will take significant time to recharge using standard wall sockets. Nonetheless, electrical vehicle charging infrastructure is already significantly further advanced than all the other non-petroleum alternative fuels. Nearly 50 percent of U.S. households have access to outdoor plugs enabling a large potential market for early adoption and the load of a typical vehicle charging to cover 40 miles will be similar to a washing machine running over night. As such, even standard 110 volt outlets can provide enough energy for 80 percent of trips via overnight charging. It is also possible that consumers will view recharging at home or work more convenience than taking side trips to fueling stations.

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<sup>8</sup> Mitsubishi announced in October 2007 that it would start marketing its fully electric "iMiEV" in Japan in 2009. Two months later, Subaru announced that it will also start selling its "R1e" fully electric cars in Japan beginning in 2009. Ford will begin limited sales of fully electric vehicles in 2010 and Chrysler has announced plans to sell an electric sports car starting in 2010. Nissan and Renault have plans to begin selling fully electric vehicles worldwide in 2010. Toyota has announced plans to market a plug-in hybrid in late 2009 and full electric in 2012. Mercedes Benz plans to begin offering an electric version of its Smart car and one of their Mercedes in 2010. India-based Tata Motors has also promised to begin marketing an electric car starting in 2009. Several small firms have led them to market. California-based Tesla Motors began limited production of their electric sports car in March of 2008. They have a stated intention of putting higher volume all-electric vehicles on the road by 2012. China-based BYD Auto, a subsidiary of the BYD Group, is a leading provider of nickel cadmium (NiCd) and lithium-ion batteries. BYD Auto is selling a plug-in hybrid in China and it has announced plans to begin offering the vehicles in Europe in 2010.

Improvements will need to be made to accommodate very large numbers of plug-in vehicles, but there should be time to accommodate those changes. It takes roughly 15 years to turn over the U.S. vehicle fleet, so even if plug-in vehicles were to be 100 percent of 2012 sales it would be 2027 before the fleet was fully plug-in capable.

### **Hydrogen Fuel Cell Vehicles**

The Detroit 3 initially expressed doubts about recouping the high initial costs of hybrids, and instead chose to focus more attention and R&D budgeting on other long-term technologies such as hydrogen fuel cell vehicles. Fuel cells produce electricity through a chemical reaction. The electricity energizes motors that turn the vehicle's wheels. In this way fuel cells are electric vehicles only with a different energy storage system. Like plug-in vehicles, fuel cells offer low direct emissions compared to conventional vehicles. If pure hydrogen is used the only direct byproduct is potable water vapor. This clean "tailpipe" has long been one of the chief reasons to pursue hydrogen fuel cell vehicles.

Fuel cell vehicles have already been developed in America, Europe and Japan. Most are now on public roads in small numbers for validation and demonstration purposes. These vehicles have similar range and refueling characteristics as current gasoline driven vehicles. GM aims to have a commercially validated fuel cell system available by 2010. GM showed a fuel cell version of the Volt concept vehicle at the 2007 Beijing Auto Show. GM was trying to market these vehicles in China because China has less petroleum-based infrastructure currently in place allowing new investment in hydrogen infrastructure to be made without displacing viable current investments. China also is trying to grapple with how to fuel their fleet into the future. Honda began limited production of their fuel cell vehicle the "Clarity" in June 2008.

Nonetheless, fuel cells remain a longer-term technology. The main technical issue remaining in fuel cells is their extremely high costs although range and performance issues still exist. Honda is leasing its vehicles to selected consumers and commercial fleets for \$600 a month but that amount is likely well below the level necessary for Honda to make money on the vehicles. The auto companies are making headway, but even when these issues are addressed there are other problems waiting in the wings.

One problem is that there are no stores of pure hydrogen in nature similar to pockets of oil or seams of coal. Hydrogen is always bound to other elements such as oxygen in water. It takes energy to create pure hydrogen by breaking the bonds binding hydrogen to other elements. In this way hydrogen is similar to electricity in that it is a carrier of the embodied energy of the source used to break the hydrogen free. Currently most hydrogen is created by reforming natural gas. While running fuel cell vehicles on hydrogen from reformed gas would reduce total emissions compared to current gasoline fueled engines, the process still releases carbon which is one of the key green house gases involved in global climate change.

Another potential source of hydrogen is through the electrolysis of water. Electrolysis uses electricity to break the bonds binding hydrogen and oxygen as water. Electrolysis using only sources such as solar, nuclear or wind power for the electricity reduces the total carbon emissions to almost zero. Of course, the same low emission sources can be used directly by electric vehicles with the same positive environmental effects. However, because energy is expended in



the process of electrolysis, the resulting hydrogen contains less energy than was used to create it (2 to 4 times less using basic electrolysis methods). This means that currently twice as much generation capacity would be required to achieve the same mobility as plug-in vehicles and that vehicles running on electricity can potentially have a cheaper fuel source so long as the electrical energy can be transported to the electrical grid efficiently and cheaply enough. Currently most, if not all, advanced energy technologies can be used to create electricity much cheaper than hydrogen.

Another major issue is the development of a hydrogen refueling infrastructure. There are many independent and sometimes overlapping projects underway to help with this issue. Still, the costs of a national hydrogen fueling system are daunting, with estimates as high as \$40 billion. GM believes it would cost \$12 billion for the necessary 12,000 hydrogen stations to make it possible for customers in the 100 largest metro areas to have to drive no more than 1.25 miles (2 kilometers) to fill up. This may not be enough to provide adequate convenience since there are roughly 170,000 filling stations in the U.S. today. Honda has introduced home hydrogen refueling stations to help address this infrastructure issue, and targeting vehicle introduction into specific markets can allow investments to be made one area at a time.

It is possible that hydrogen can become a cheaper energy carrier than electricity. For instance, some of the companies experimenting with microbes that excrete ethanol or gasoline are working on others that excrete hydrogen. Likewise, others are working on solar cells that produce hydrogen directly from water. It may also be possible to site energy production sources such as nuclear, wind, solar or geothermal in very remote locations and cost effectively use electrolysis to transport the resulting energy as hydrogen. There are considerable synergies between plug-in vehicles and fuel cells as well. As mentioned earlier, plug-in hybrids can be equipped with fuel cell range extenders instead of internal combustion engines. Doing so would help alleviate the need for a more widespread hydrogen infrastructure and it would help address the range and recharge issues of many battery technologies. Because fuel cell and plug-ins share most electrical underpinnings, they will also both benefit from increased production volumes of the other allowing manufacturers to spread out the development costs over larger volumes of products.

### *Efficiency Technologies*

#### **Electrification of Accessories**

Electrification of the drive train can result in major fuel economy increases. Similar efficiency gains are available on a smaller scale through the electrification of belt driven accessories such as air conditioning and power steering. Instead of using power from a drive belt that continues to draw some engine power even when the accessory is not in use, the components are driven electrically only when needed. Power steering is the primary target currently because of higher potential efficiency gains. One side benefit of electrifying accessories is that it eases packaging since the components no longer have to be mounted near the engine. It also offers a medium term pathway in a movement toward electrification of drive train components.

### **Light Weight Materials and Components**

Considerable efforts are also going into reducing vehicle weight through such things as advanced composites, high strength metals, and smaller more efficient electronics. Traditionally light weighting vehicles has consisted primarily of reducing vehicle size. There are potential safety impacts of size reduction. By reducing weight without reducing size, light weighting can improve vehicle efficiency while maintaining space for energy absorption thereby maintaining some levels of safety. The advantages of lightweight materials for fuel efficiency are self-reinforcing. Reducing weight lowers the amount of energy needed to move and stop the vehicle for equivalent performance. Each decrease allows further decreases elsewhere, for instance a lower vehicle weight requires smaller brakes allowing yet further decreases in the weight of brake components which further reduces weight.

### **Advanced Engine Technologies**

There are a host of technologies in use or on the near horizon that can be used to increase the efficiency of internal combustion engines. Achieving the same level of power in a smaller, lighter package is one way to increase efficiency. It contributes to the “virtuous cycle” of vehicle light weighting. In addition to the benefits of lighter weight, smaller engines also have lower internal friction and in gasoline engines they have smaller pumping losses.<sup>9</sup>

Turbochargers or superchargers are two technologies capable of enabling engine downsizing. Both technologies increase the amount of fuel and air entering cylinders by pressurizing the intake manifold thereby increasing the amount of air fuel mixture available for any particular engine displacement. Doing so increases the energy available compared with similar sized engines without these components.

Cylinder deactivation or variable displacement is a technology that works to address pumping losses. Cylinder deactivation enables engines to operate on fewer cylinders when driving with low or partial loads. This allows the engines to meet high power requirements, such as gaining speed on an interstate on-ramp when all of the cylinders are active and yet effectively reduce the number of cylinders in operation during low load situations to avoid pumping losses. Variable valve technology and advanced controls are the catalysts for variable displacement technology since they allow engineers to disable and enable cylinders by quickly controlling valve operation depending upon power requirements.

Another technology that is dependent on variable valve technology and advanced controls is Homogeneous Charge Compression Ignition (HCCI). HCCI works to blend the efficiency benefits of diesel engines with the lower nitrogen oxide (NOx) emissions and improved response of gasoline engines. Because HCCI engines run without throttles similar to diesel engines, HCCI eliminates pumping losses. Like diesel engines, HCCI engines also use the high temperatures of compression to ignite the fuel mixture (gasoline engines use spark plugs). HCCI operation is limited to lower revolution (RPM), low torque requirements such as interstate cruising because noise and NOx output increases with RPMs. HCCI may be able to equal the benefits of diesel engines because the advanced emissions controls required to meet tough new standards rob some

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<sup>9</sup> Pumping losses are caused in gasoline engines by the partial closure of the throttle butterfly in low load situations. During low load situations such as cruising down the highway, the pistons draw air past the partially closed throttle creating a vacuum in the intake manifold. The pumping action involved in creating the vacuum wastes energy.

of the diesel engine's efficiency.<sup>10</sup> The result is only a 12 to 15 percent efficiency improvement over a standard gasoline engine. HCCI can achieve similar efficiencies at a much lower cost premium.

### **Advanced Transmission Technologies**

Several advanced transmission technologies are currently on the market or are slowly being introduced that can improve the fuel economy of vehicles. Lowering the operating range of an engine (the difference between its fastest to slowest revolutions) generally allows engineers to achieve higher economy from a given engine displacement. One way to lower an engine's operating range is by increasing the number of gears in the transmission. Six and seven speed transmissions allow engines to be designed for a smaller power curve than five or four speed transmissions. The extra gears enable engineers to make fewer of the compromises necessary to operate an engine over a wide power band thereby increasing the fuel efficiency of the vehicle.

Continuously variable transmissions basically allow engineers to tune the engine for constant operation. With continuously variable transmissions, changes in speed and power requirements are handled by changing the transmission ratio instead of varying the power of the engine. Currently, continuously variable transmission technologies are limited to smaller displacement engines and smaller vehicles due to their power handling constraints.

Another potential source of increased vehicle efficiency in transmissions is by reducing the power losses involved in transmitting power to the road. Traditional clutches and torque converters either slip constantly or slip during the changing of gears thereby wasting engine power. Dual clutch transmissions allow transmissions to remain engaged thereby saving energy.

Ford announced their plans at the 2008 auto show in Detroit to use smaller, more powerful engines, electric power assist, vehicle light weighting, and six speed transmissions to improve their fleet economy. This combination of technologies delivered 20 to 30 percent fuel economy increases in the concept Ford Explorer exhibited at the show. Ford calls the combination EcoBoost technology.

### **Vehicle Use Technologies**

In addition to technologies that improve the fuel efficiency or change the fuel that is used, there are also technologies that change how vehicles are used. These technologies can be simple and fairly low tech. Low tech solutions include such things as timing traffic lights and adding additional lanes on overcrowded streets or highways to lower the amount of vehicle idling. It also includes land use planning to reduce demand for vehicle travel. Other solutions can also be fairly high tech. High tech items include such things as "Speed Pass" and smart highways. Like adding highway lanes, Speed Pass helps prevent unnecessary idling at toll plazas. Smart highways are systems that allow vehicles and roadways to communicate. They can work to improve traffic flow and could eventually allow vehicles to travel closer together at high speed thereby enjoying the benefits of slipstreaming<sup>11</sup> the air.

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<sup>10</sup> Oral comments of Bob Lutz on GM's Fast Lane blog, posted July 12, 2007, [http://fastlane.gmblogs.com/archives/2007/07/checking\\_back\\_w.html](http://fastlane.gmblogs.com/archives/2007/07/checking_back_w.html)

<sup>11</sup> Slipstreaming allows a reduction in vehicle drag due to reduced pressure of following another object through the air.

**Conclusions/Implications**

There are many technologies nearing the market which can greatly reduce U.S. transportation demand for petroleum. While virtually all of these technologies are capable of reducing petroleum demand, they are not equally ready for production.

Manufacturers will generally have to make substantial investments to introduce any of the alternatives in volumes needed to spread across their product lines. Some of these alternatives require massive investments in infrastructure as well.

Many of these technologies involve radical departures from current production, potentially requiring large scale retooling and the possible abandonment of current manufacturing investments. Because some of these technologies and fuels are new, manufacturers are not familiar with their reliability and therefore there are potential warranty concerns.

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