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Review of CO_2 Emissions and Technologies in the Road Transportation Sector

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ABSTRACT

The topic of CO_2 and fuel consumption reductions from vehicles is a very broad and complex issue, encompassing vehicle regulations, biofuel mandates, and a vast assortment of engine and vehicle technologies. This paper attempts to provide a high-level review of all these issues.

Reducing fuel consumption appears not to be driven by the amount of hydrocarbon reserves, but by energy security and climate change issues. Regarding the latter, a plan was proposed by the United Nations for upwards of 80% CO_2 reductions from 1990 levels by 2050. Regulators are beginning to respond by requiring ~25% reductions in CO_2 emissions from light-duty vehicles by 2016 in major world markets, with more to come. The heavy-duty sector is poised to follow. Similarly, fuel policy is aimed at energy diversity (security) and climate change impacts. Emerging biofuel mandates require nominally 5-10% CO_2 life cycle emissions reductions by 2020. Processes that utilize plant cellulose and waste products show the best intermediate term potential for meeting these goals, but long term trends are towards biofeedstocks for refineries.

Vehicle technologies are emerging to meet the regulatory mandates. Light-duty engine efficiency gains will result in about 30% fuel and CO_2 reductions by 2015. Many of the reductions will come from the use of direct injection technology in gasoline engines, and downsizing diesel and gasoline engines for more specific power. CO_2 savings shows a general linear relationship with cost. Diesel hybrids offer the greatest CO_2 reduction potential. Plug in hybrids can lead to heavy electrification of the fleet for energy diversity and greenhouse gas reductions, but their CO_2 reductions are moderate and expensive. Battery performance is generally acceptable, but cost will be a recurring issue. Most light-duty efficiency technologies return money to the consumer over the life of the vehicle, so the CO_2 reductions also come with an economic gain to the owner.

In the heavy-duty sector vehicle and operational improvements offer the best gains at 16 to 28% fuel reductions. Engine technology trends are indicating nominally 15% reductions using advancements in currently utilized technologies. Research is shifting to gasoline engines, wherein upwards of 20-25% CO_2 reductions might be realized. Heavy duty hybridization is emerging for vocational and urban vehicles, and can offer a 2 to 4 year payback period.

Black carbon reductions from vehicles can have a profound effect on GHG impact, accounting for upwards of ~20% of CO_2 reductions proposed by the Intergovernmental Panel on Climate Change (IPCC) by 2050.

INTRODUCTION

For more than 35 years vehicle emissions regulations have focused primarily on criteria pollutants, such as hydrocarbon (HC), NOx, CO, and particulate matter (PM). These regulations had and still have a profound impact on powertrain technologies, ranging from fuels and lubrication oils, to engine technologies and emission control systems, across all vehicle and equipment categories. Many argue that no other trend has influenced powertrain technology more than this 99% tightening (nominal) of pollutant emissions. However, in some sectors, such as for gasoline multi-port injection engines, the rate of emissions technology progress has slowed as a result of maturity. For example, in 1999 there were roughly 30-40 SAE papers related to advanced catalysts for gasoline engines. In 2009, the number was about a quarter of this.

On the other hand, tightening CO_2 regulations are just starting and are poised to have a similar impact on powertrain technologies as the historic tightening of criteria pollutants. California regulators finalized the first CO_2 regulations for passenger cars in 2005, followed by Europe in 2009. (In both cases, proposals were made much earlier.) The US Environmental Protection Agency (EPA) is proposing similar regulations through 2016. The United Nations Intergovernmental Panel on Climate Change (IPCC) is proposing CO_2 targets for 2050 and beyond, which will likely drive CO_2 regulations into other vehicle and equipment segments. As such, it is reasonable that it could be more difficult to meet emerging CO_2 regulations than emerging criteria pollutant regulations.

There are numerous technologies being considered to reduce CO_2 emissions. These included low carbon fuels, (e.g. biofuels); advances in engine technologies, like direct injection gasoline engines, cooled exhaust gas recirculation (EGR) for gasoline engines, and downsizing; and electrification of the drivetrain, such as with hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV).

The objective of this paper is to provide an introductory, high-level review of the current status of mobile CO_2 regulations and technologies to address them. The paper is intended to provide a broad perspective on the topic rather than a deep analysis on any given topic. It should be noted that one can look at reducing CO_2 emissions more broadly - reducing energy consumption, increasing fuel diversity and energy security, and improved efficiency. The points made in this paper are generally applicable to all these issues.

Because fuel diversity and CO_2 emissions directions are being driven by fossil fuel availability and climate change issues, the review begins with global fuel production and consumption trends, along with CO_2 projections proposed by the IPCC, followed by the regional regulatory response. Then comes a technology overview on fuels, and light-duty and heavy-duty engine technologies, including powertrain hybridization.

REGULATORY OVERVIEW

This section will summarize the environmental and resource drivers for reducing CO_2 and fuel consumption, and the regulatory framework for moving forward.

The first subsection outlines issues regarding petroleum reserves and consumption, which, via energy diversity and energy security arguments, drive fuel economy regulations. The second subsection covers climate change drivers behind specific CO_2 emissions regulation, or "equivalent" CO_2 regulation, which encompasses most climate change agents. The third subsection will summarize fuel economy or CO_2 emission regulations.

PETROLEUM

Dwindling oil reserves and expected increases in global consumption are part of the argument for the need to regulate fuel consumption (and thus CO_2) in the transportation sector. The availability of oil is a complex dynamic of economics, technology, and distribution. This section will look at the gross impacts of oil reserves and consumption.

Global oil consumption is about 85 million barrels per day or 31 billion barrels per year. As shown in Figure 1, non-OECD (Organization of Economic Cooperation and Development) oil consumption is increasing at more than 3X the rate of OECD countries (1). Given that half of oil production goes to transportation, and that vehicle penetration rates in non-OECD countries is very low compared to OECD countries, significant future oil demand will come from the developing countries. Globally, oil consumption is predicted by EIA (US Energy Information Administration) to grow from 0.5 to 1.5% per year, and reach about 33 to 44 billion barrels per year by 2030, depending on price (2).

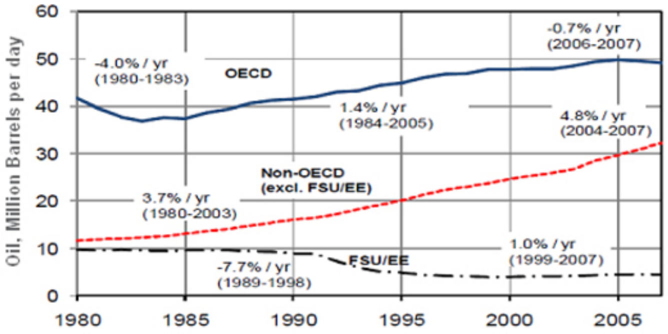


Figure 1. Non-OECD countries' oil consumption has been growing ~3X faster than OECD countries.

On the other hand, largely due to technology advancements in discovery and recovery, proven oil reserves have increased from 998 billion barrels in 1988, to 1068 billion barrels in 1998, to 1261 billion (excluding 150 billion barrels of Canadian oil sands) in 2008 (3), for an average growth rate of 1% per year. This is similar to the consumption rates. As such, the proven oil reserves to production ratio has held relatively constant at 40-43 years since the mid-1980s, excluding the oil sands. (Pre-1980 the ratio was at the mid-30 year level.)

Looking forward, insights can be made by stepping away from the conservative "proven reserves", which have a >90% probability of being exploited with current technology at current prices, to "probable reserves", which have a >50%

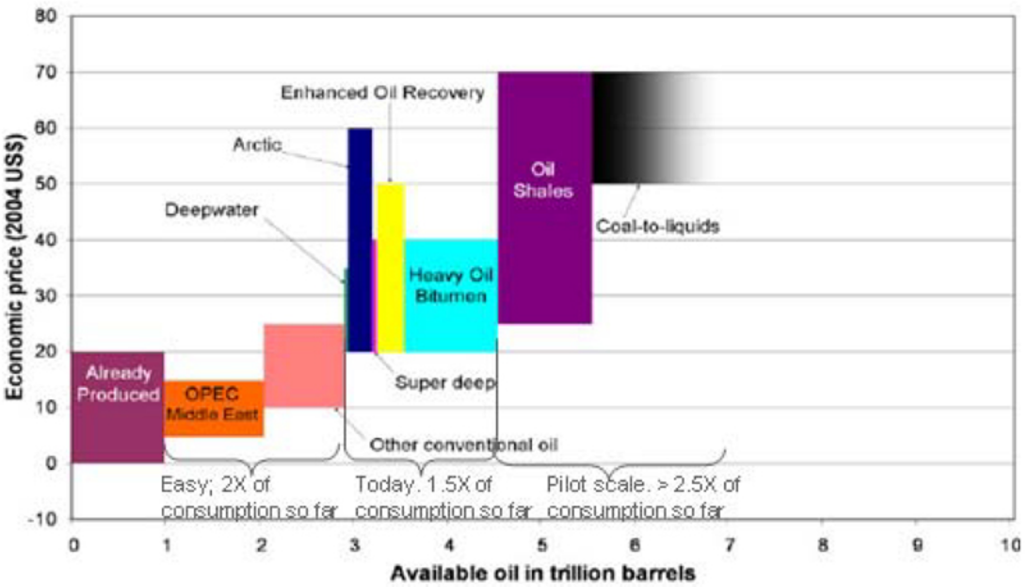


Figure 2. Estimates of probable oil reserves as a function of price (4). Notes were added by author. At EIA consumption estimates for 2030 of 44 billion barrels per year, these reserves would last >100 years.

probability of being extracted. Figure 2 shows one such estimate (4). At today's price of about $85 per barrel, reserves might be on the order of 6 trillion barrels, or 6X what we've consumed thus far. At oil consumption rates of 44 billion barrels per year (year 2030, EIA high consumption), the probable reserves to production ratio is >130 years.

From this perspective, it appears that there are enough hydrocarbon reserves to last for the foreseeable future. However, political, environmental, resource (like water) and other constraints might limit production, reducing these reserves considerably. Also, energy diversity and security issues are significant motivations for tightening fuel consumption standards.

<figure 2 here>

CLIMATE CHANGE AND REGULATORY RESPONSE

Given the UN IPCC consensus statement that there is a >90% chance that anthropogenic greenhouse gases are warming the globe (5), CO_2 emissions from the burning of fossil fuels would appear to drive vehicle fuel consumption and CO_2 regulations more than depletion of hydrocarbon reserves. This subsection will look at the climate change issues and the regulatory response.

Climate Change

Figure 3 summarizes the IPCC's analyses on anthropogenic CO_2 and the impact on CO_2 concentrations in the air (5). The Panel's analyses show that the 450 ppm goal for CO_2 in the atmosphere is the best balance of warming potential (40-60% probability of stabilizing at ~2C° above pre-industrial levels) and reasonable reduction measures (−3% per year to 2050). To attain this point of stability, nominally 80% CO_2 reductions are needed by about 2050. This brings total global emissions roughly equivalent to 1910 levels. From a vehicle industry perspective, to do its share the 80% reduction is for the whole in-use fleet, not just new vehicles.

At the 2009 UN Climate Change Conference in Copenhagen, the US pledged (nonbinding) to drop CO_2 emissions by 1.3% by 2020, 3.1% by 2030, and 80% by 2050 versus 1990 levels; the EU pledged unconditional 20% reductions by 2020, and 30% if other developed countries follow; Japan: 25% by 2020; China: 40-50% reductions in carbon intensity (CO_2 normalized to GDP) versus 2005 levels, by 2020. All these proposals are nonbinding and will be negotiated in subsequent meetings. However, the pledges suggest CO_2 reductions are in serious discussions and now a matter of negotiation.

The IPCC also made estimates of greenhouse gas (GHG) sources and proportional impact. About 13% of GHGs come from the transportation sector. About 77% of all GHG contributions are from CO_2, 14% from methane; and 8% from N_2O. About 57% of the CO come from fossil fuels, while most of the CO_2 balance is from deforestation.

<figure 3 here>

Black carbon is a short-lived climate-forcing agent, staying in the atmosphere for weeks. However, the IPCC estimates it is

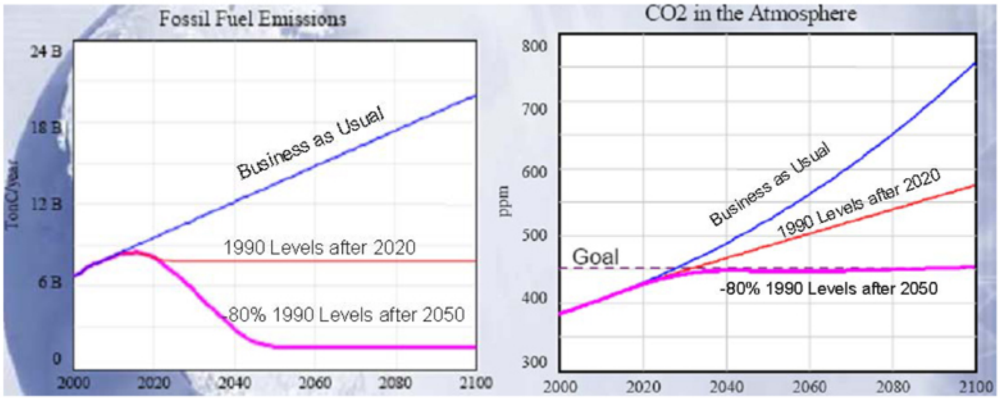


Figure 3. The UN IPCC models show that 80% reductions in anthropogenic CO_2 are needed to stabilize CO_2 levels to 450 ppm in the atmosphere (5).

roughly equivalent to methane in its warming potential at present levels. Because of its impact on snow melting and in the atmosphere, in the arctic black carbon might represent about 20% of total GHG impact (6). Globally, about 17% of black carbon emissions come from transportation (7). As black carbon has about 2000X more atmospheric warming potential than CO_2 on a mass basis (8), about 20-25% of an unfiltered diesel vehicles carbon footprint is in black carbon. Remediation of diesel soot today is primarily done to minimize the adverse health effects, but the climate forcing impact could further increase interest.

Regulatory Response

In Europe, road transportation accounts for about 20% of CO_2 emissions, and passenger cars are about 60% of this or 12% of the total inventory (9). In the US, road transportation is about 28% of GHG emissions with about 15% coming from light duty trucks and passenger cars (10). From 1990 to 2004, transportation GHG emissions increased 24% (11). As such, and provided that emissions from passenger cars and trucks are closely regulated with an established framework, the industry has emerged as the first industry to have binding CO_2 regulations. California emerged first with automobile regulations in 2004, dropping emissions from about 240 g CO_2 (equivalent - includes all GHG normalized to CO_2) per km in 2009 to 170 g/km in 2016. However, these required a waiver from the US EPA before they could go into effect. The waiver was granted in 2008 and the regulations went into effect. However, the US government put forth a Notice of Proposed Rulemaking (NPRM) in September 2009 that tightens average new vehicle fleet requirements 25% to 170 g CO_2 (equivalent) per km in 2016 for all of the US. The goal is to have this regulation finalized in March 2010. If implemented as planned, California agreed to forego their requirements as the EPA requirements require very similar reductions. As such, a 50-state CO_2 regulation would be in effect. (Note: To provide the reader with an equal basis of comparison, the CO2 values were normalized to the New European Drive Cycle using the methods developed by F. An, et al. (12).)

Europe finalized their first CO_2 mandates in March 2009 at 130 g CO_2/km for an average sized car of 1372 kg in 2015 (13). In the next round of tightening the European Union set a target of 95 g CO_2/km for 2020 (12), to be reviewed in 2013. Similarly, California (and 13 other states following its lead; about 40% of the US market), is targeting 40-50% reductions from 2009 baseline levels by 2025 (14).

F. An, et al. (13), compared the fuel economy and CO_2 standards around the world on a normalized basis - CO_2 emissions on the New European Drive Cycle (NEDC). Results are shown in Figure 4. On this basis, Japan's fuel consumption regulations are similar to Europe's CO_2 regulations. The US is about 30% higher than Europe or Japan. The US CO_2 regulation is based on a vehicle's footprint (area between the tires), while that in Europe are based on a vehicle's mass. (Every automaker will have a different fleet average CO_2 emission dependent by mix.) However, when this author looked at about 20 automobiles for footprint and weight, and adjusted for test cycle differences using An's method, the European regulation is about 15% tighter car-for-car than the US regulation. So, roughly half of the difference between the US levels and those in Europe is due to larger vehicles in the US fleet.

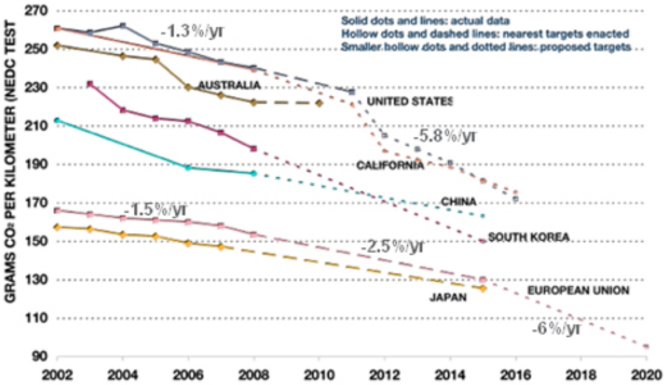


Figure 4. Historic CO_2 emissions (solid lines), and enacted (dashed lines) or CO_2 regulations (dotted line) for various countries with fuel consumption or CO_2 regulations (13). Data were normalized to CO_2 emissions on the NEDC test. Percent improvements per year were added.

Also shown in Figure 4, without mandated regulations the average rate of improvement shown here is about 1.5% per year. This might be regarded as a market rate of improvement that is largely consumer driven. Note that moving forward, the regulations are forcing much greater rates of improvement, up to 6% per year reductions. In other words, the governments are requiring greater improvements than the automotive companies perceived were needed from market forces. In this way, CO_2 reductions are being mandated similarly to criteria pollutants, a paradigm shift that should result in faster technology evolution.

Heavy Duty

In 2006 Japan introduced the first heavy-duty vehicle fuel economy standards in the world (15). It calls for nominally 12% increases in fuel economy (km/liter) from a 2002 baseline by 2015. To estimate improvements, computer simulations of various vehicles are used to conduct and analyze engine dynamometer tests. Most of the reductions are expected to come from engine improvements.

In the US, in July 2008 the EPA published an Advanced Notice of Proposed Rulemaking (ANPRM) concerning vehicle CO_2 regulations, and requested comments on regulating the heavy duty truck and non-road sectors (16). Based on this information, the EPA is targeting a proposal in the first half of 2010 for regulating CO_2 from heavy-duty trucks. Converse to light-duty applications, wherein vehicle weight and engine technologies can have the biggest impacts, for trucks, chassis and vehicle improvements, like aerodynamic cowls and low rolling resistant tires can have the biggest impacts. In this regard, the EPA has proposed fuel consumption chassis test cycles for a variety of applications as part of their Smartway program. Also, in December 2009 California finalized HD tractor-trailer truck greenhouse gas regulations, with phase-in beginning in 2010 and proceeding through 2017 (17). The rule requires EPA Smartway cowling and tire technology on all such trucks operating in the state. Smartway is the US EPA program that encourages adoption of fuel efficient technologies.

REGULATORY CONCLUSIONS

Regulations governing vehicle emissions of CO_2 (eq.) are just now emerging, but are poised to be a long term trend. They are primarily being driven by increasing concern about anthropogenic impacts on climate change, but are also synergistic with energy diversity policy (e.g., EISA). The long term regulations will directionally follow the IPCC's recommendation to drop CO_2 (eq.) emissions by 80% from 1990 levels by 2050 for the entire in-use fleet. In the US and Europe, light duty regulations are in place or being proposed to drop new vehicle emissions about 20-25% from 2008 levels by 2015-16, with increased annual percentage reductions targeted through 2020 in Europe. Given that technologies for reducing criteria pollutants, like NOx, hydrocarbon, particulates, and CO, have been commercialized for more than 30 years, it is reasonable that meeting the future CO_2 emissions standards will be more challenging than future criteria pollutant standards.

BIOFUELS

One of the cornerstones to decreasing transportation CO_2 emissions and reducing dependency on petroleum is to move towards low-carbon fuels. This can mean such diverse fuels and sources as low-carbon intensity electricity, hydrogen, and natural gas. Given the interest, legislation, and attractive short term potential of biofuels, this section will deal exclusively with this low-carbon fuel and petroleum replacement. The more significant mandates that will drive the field are in the US and Europe.

GOVERNMENT MANDATES

In November 2007, the US passed the Energy Independence and Security Act (EISA). It calls for 36 billion gallons of biofuels per year (~20% penetration) for the transportation sector by 2022. Figure 5 shows the general requirements for the fuels that can be used (18). In May 2009, as required by the act, the EPA proposed annual ramp up rates for each fuel type, and life cycle GHG calculation methodologies (19). Significant additional GHG is emitted for land use changes, but with time, the CO_2 reductions make up for this. As such, the time horizon and a way to compensate for early reductions versus later ones (discount rate) becomes important. Figure 6 shows the results of the full net CO_2 life cycle analyses for a 100 year time horizon at a 2% discount rate for a variety of biofuels. In these analyses, corn ethanol using combined heat and power (CHP) and sugar cane

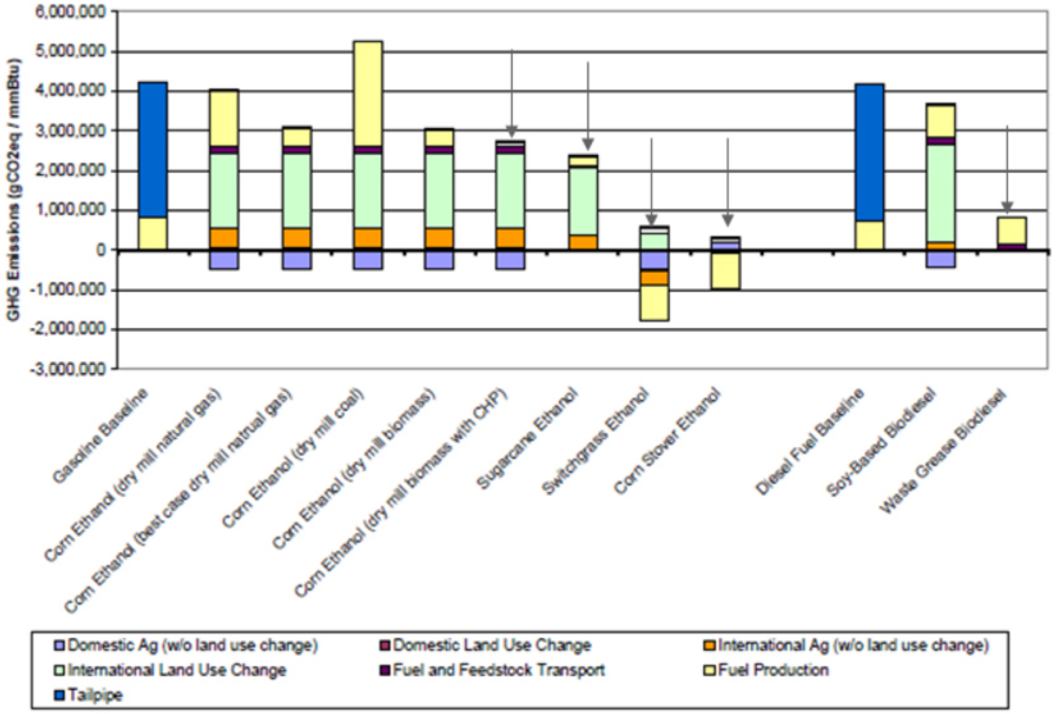
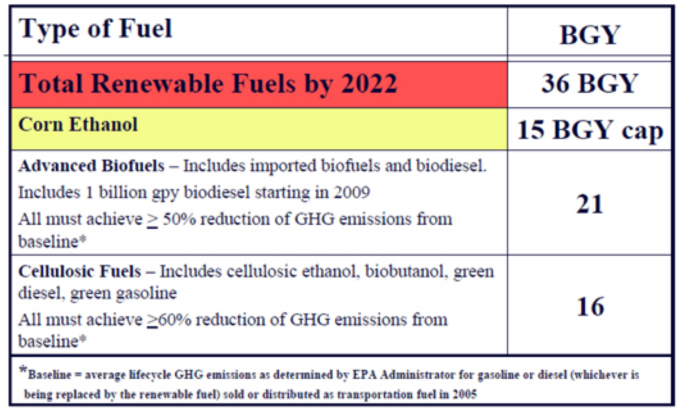


Figure 6. CO_2 life cycle analyses for various biofuels over a 100 year time horizon at a 2% discount rate (19). Using these analyses, the identified fuels meet the cellulosic (>50% reduction) or advanced biofuel (>60%) requirements of EISA.

ethanol meet the cellulosic fuel requirement (>50% GHG reduction) of EISA, and cellulosic ethanol from switchgrass and corn stover, or biodiesel from waste grease meet the advanced biofuel requirement (>60% reduction). Economic impacts are estimated from $4 to $18 billion per year or < $0.11 per gallon for oil priced at >$53 per barrel.

California adopted the Low Carbon Fuel Standard (LCFS) in April 2009 (20). Its aim is to reduce greenhouse gas emissions from California's transportation fuels by 10% by 2020. The standard sets carbon intensity (CI) targets for each year and is phased-in gradually, with the bulk of the reductions required in the last five years (3.5% penetration in 2016 going to 10% in 2020). This allows for the development of advanced, lower CI fuels and more efficient advanced-technology vehicles. The baseline gasoline fuel consists of reformulated gasoline containing 10% corn ethanol and ULSD is the baseline diesel fuel. The LCFS takes a cradle-to-grave model analysis to calculate full life-cycle GHG emissions associated with producing, transporting, and burning the fuels, including both direct and indirect land-use effects. In December 2009, governors of 11 Northeast states signed a memorandum of understanding to develop a regional LCFS, with the goals to be determined.



Type of Fuel	BGY
Total Renewable Fuels by 2022	**36 BGY**
Corn Ethanol	**15 BGY cap**
Advanced Biofuels – Includes imported biofuels and biodiesel. Includes 1 billion gpy biodiesel starting in 2009 All must achieve ≥ 50% reduction of GHG emissions from baseline*	**21**
Cellulosic Fuels – Includes cellulosic ethanol, biobutanol, green diesel, green gasoline All must achieve ≥60% reduction of GHG emissions from baseline*	**16**
*Baseline = average lifecycle GHG emissions as determined by EPA Administrator for gasoline or diesel (whichever is being replaced by the renewable fuel) sold or distributed as transportation fuel in 2005	

Figure 5. Biofuel mandates (BGY, billion gallons per year) by the US Energy Independence and Security Act (EISA, November 2007). The mandate represents about 20% of transportation fuels (18).

<figure 6 here>

In December 2008 the European Council approved the Renewable Energy Directive, which will be implemented by November 2011 (21). It calls for >10% biofuel mandate in the transportation sector, and each member state needs to implement it into law (ramp up rates etc) by November 2010. The biofuel must be sustainable and decrease GHG emissions by 35% in 2010 and 50% by 2017 (60% for new installations). Second generation biofuels (cellulosic and wastes) get a 2X credit, and renewable electricity gets a 2.5X credit. The GHG reductions include cultivation, processing, and land use changes, but do not encompass indirect land use changes, which are being analyzed. Examples of default GHG reductions range are 19% for palm oil biodiesel, 52% from sugar beet ethanol, and 83% from bio-waste biodiesel. Given that the EU imports diesel fuel and has an excess of gasoline for export, current biofuel production splits are about 75% biodiesel and 25% ethanol.

BIOFUEL TECHNOLOGIES AND PROPERTIES

Biofuel technology is rapidly evolving to try to meet the regulatory mandates outlined in the previous section. The technology is quite diverse and dynamic. This is illustrated in Figure 7 (22). Feedstocks range from sugar sources (cane, beets, corn) to organic waste to "designer" crops like algae. Processing routes evolve from the current ethanol processes (fermentation and purification) and biodiesel route (vegetable oil esterification and purification), to second generation processes using enzymes or thermal processing to utilize plant cellulosic materials. Third generation systems use energy crops (like algae) and biofeedstocks that are integrated into the refinery process.

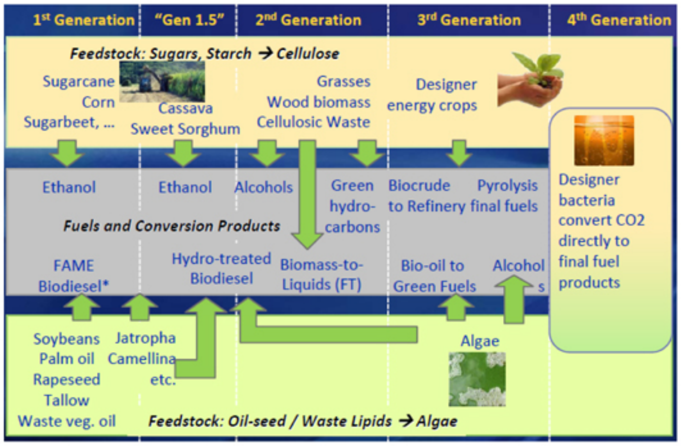


Figure 7. Illustration of biofuel process diversity and evolution (22). Gasoline based fuels are on the top, and diesel fuels are on the bottom. Eventual evolution of biofuels could be to biocrudes for refinery feedstocks.

Virtually all of the engine manufacturers and oil companies desire a refinery-integrated biofuel approach. Engine makers favor this approach because most gasoline engines are designed to operate on <10% ethanol, but higher blends will be needed to meet EISA targets. This potentially can cause backward compatibility issues in a wide variety of applications. Examples might be difficulty in air:fuel management for open-loop control automotive engines (23); too lean operation of fixed carbureted small non-road engines; fiberglass fuel tank failures in marine applications; and a variety of other material compatibility issues (24). Glycerine in biodiesel blends can precipitate out in cold conditions, plugging fuel filters. Ash can cause fuel injector corrosion or fouling and prematurely plug diesel particulate filters. Also, biodiesel can cause higher levels of lube oil dilution because it has a higher distillation temperature (more heavy hydrocarbons) than diesel fuel. On the refinery side, biofuel blends need to meet standards to allow transport by pipeline, requiring terminal blending; and in general, oil companies desire efficiencies of scale offered by refinery operations.

These potential problems are addressed if biofeed stocks are catalytically hydroprocessed to produce biodistillates, generally known as renewable diesel. Several processes for renewable diesel production are now in commercial use. These include stand-alone processes by Neste Oil (to produce NExBTL™) and UOP (Ecofining™), as well as ConocoPhillips' co-processing of triglycerides with petroleum diesel feedstocks. All these processes require hydrogen and are conducted under high pressure. The products are hydrocarbons (not oxygenates), that are very similar to those found in petroleum diesel (25).

One issue with this approach is that most raw biofeedstocks are not efficiently transported more than about 100 miles before CO_2 benefits are consumed by transportation emissions. To expand feedstock access to processing facilities, they are concentrated close to the source. Such a scheme is depicted in Figure 8 (26), wherein Archer Daniels Midland (ADM) is teaming with ConocoPhillips (COP).

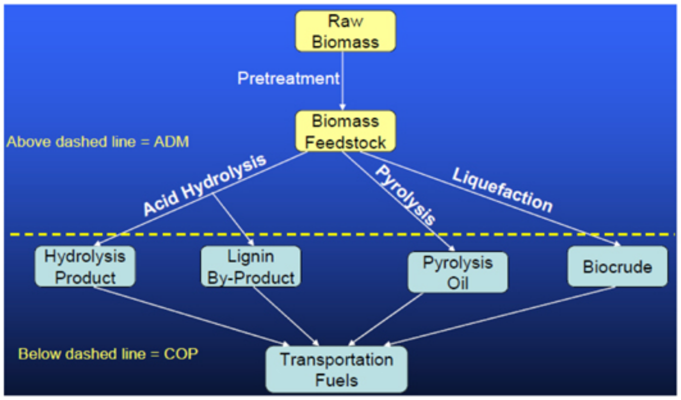


Figure 8. Schematic of a joint effort by Archer Daniels Midland (ADM) and ConocoPhillips (COP) to synthesize and process biocrude (26).

Regarding properties, biofuels have a range of energy densities. Figure 9 shows comparisons of the energy density of a variety of transportation fuels (27). Because it has more oxygen and lower carbon and hydrogen contents, biodiesel is variable but has up to 10% lower volumetric energy density, as shown here, but is more typically 5 to 6% lower than

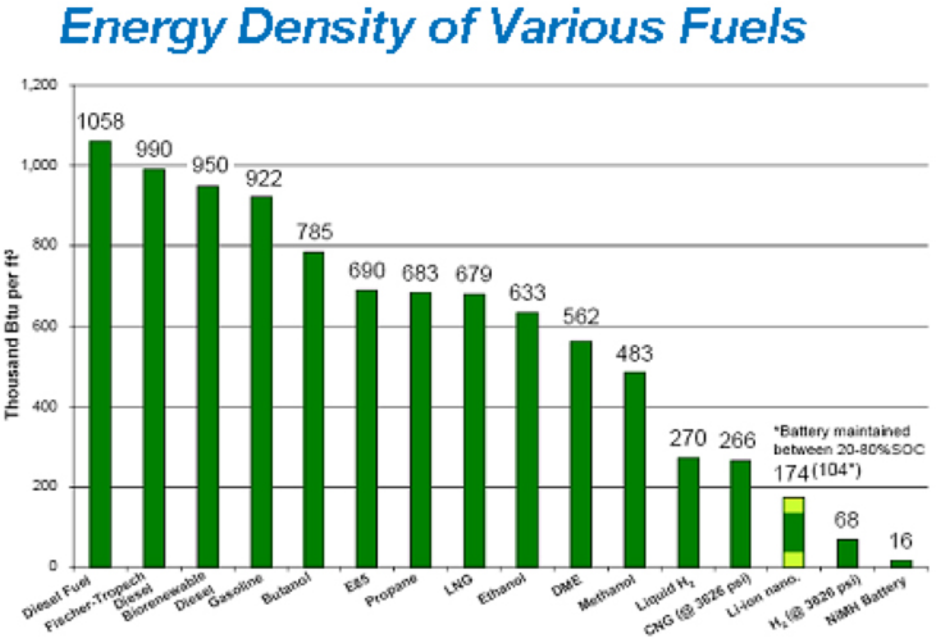


Figure 9. Comparison of volumetric energy densities of a variety of current and potential transportation fuels (27). Biodiesel has 5 to 10% lower volumetric energy content than diesel, while ethanol has 30% lower energy content than gasoline.

diesel, according to a literature survey by the CRC (25). When blended with petroleum fuels, B20 (20% biodiesel) will have very similar fuel economy (e.g., miles/gallon) as diesel fuel. Conversely, ethanol has 30% lower volumetric energy than gasoline so E85 will have nominally 25% lower fuel economy than gasoline.

Figure 10 shows a comparison of key properties of fatty acid methyl ester based biodiesel (FAME) and renewable biodiesel with No.2 ultra-low sulfur diesel fuel (25). Noteworthy is the increased cetane level of both biodiesel and renewable diesel relative to diesel. Emissions of CO, particulate matter (PM), and hydrocarbons are generally reduced about 10-20% for B20. NOx emissions are roughly the same as with diesel.

Ethanol has an octane number, (R+M)/2, of about 100, so it is an octane enhancer to gasoline. When used with legacy vehicles, there is a trend towards lower non-methane hydrocarbon, PM and CO emissions, but acetaldehyde and formaldehyde emissions increased (28). Catalyst temperatures for engines with closed-loop control decrease. The vapor pressure of E3 is about 13% higher than that of gasoline, but then is flat up to E20 levels (29). Hot soak and diurnal evaporative emissions were tied to the vapor pressure but were ~6X higher for E3 than for the base fuel. However, they were still within the 2 gram/test regulatory requirement for the vehicles.

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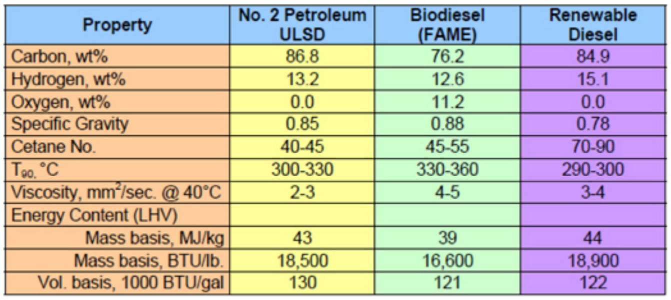


Property	No. 2 Petroleum ULSD	Biodiesel (FAME)	Renewable Diesel
Carbon, wt%	86.8	76.2	84.9
Hydrogen, wt%	13.2	12.6	15.1
Oxygen, wt%	0.0	11.2	0.0
Specific Gravity	0.85	0.88	0.78
Cetane No.	40-45	45-55	70-90
T_{90}, °C	300-330	330-360	290-300
Viscosity, mm²/sec. @ 40°C	2-3	4-5	3-4
Energy Content (LHV)			
Mass basis, MJ/kg	43	39	44
Mass basis, BTU/lb.	18,500	16,600	18,900
Vol. basis, 1000 BTU/gal	130	121	122

Figure 10. Some general properties comparisons between diesel fuel, FAME, and renewable diesel. Cetane levels are increased for the biofuels, but renewable diesel has more-similar properties to diesel (25).

BIOFUEL CONCLUSIONS

Governments are beginning to address energy diversity, energy security, and climate change issues with biofuel mandates. The US will be requiring that about 20% of the transportation fuels have >50% of the GHG emissions reductions of conventional fuels by 2022. Europe will require 10% penetration of similarly effective fuels by 2020. Methods for determining the carbon intensity of the fuels are in the proposal stage. Candidates to meeting these requirements use the plant cellulose or are based on waste products. It appears that the long term trend is towards integrating biofeedstocks into refinery operations. Biodiesel has about 5-10% lower energy content than diesel but a higher cetane value. Fuel economy impacts will be negligible for common blends. HC, CO, and PM emissions are about

10-20% less for B20 than for diesel fuel, but NOx emissions are roughly similar. Ethanol has about 30% lower energy content than gasoline, but higher octane levels. Similar to biodiesel, HC, PM, and CO emissions trend lower as ethanol levels increase, but evaporative emissions go up.

LIGHT DUTY POWERTRAIN TECHNOLOGIES

This section will summarize the developments on engine performance and hybridization. The regulatory mandates governing fuel economy and CO_2 are forcing the automotive companies to aggressively move to increase efficiency. Leading approaches involve improving the powertrain with improved engine performance, hybridization, and new transmissions; and improving vehicle performance by reducing weight, reducing drag and reducing rolling resistance.

IMPROVED ENGINE PERFORMANCE

The opportunities for improved efficiency are illustrated in Figure 11 for a diesel engine (30), but the general breakout is similar for gasoline engines. Most of the reductions, upwards of 65 to 75%, come from improved combustion and thermal management. As such, this section will focus on this opportunity.

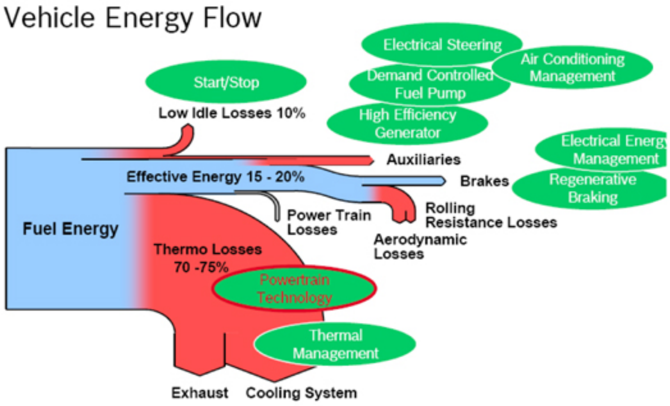


Figure 11. Most of the light-duty vehicle efficiency improvement opportunities reside with engine combustion and thermal management (30).

Measured fuel efficiency depends on the drive cycle being used. Figure 12 shows simulated fuel economy values for an E-class Mercedes equipped with a gasoline or diesel engine and a full hybrid (110 kW engine, 31 kW electric motor), driven on city and highway certification cycles, and on the high load US06 cycle (31). A full hybrid approach uses the engine and battery to the full synergistic extent, but has low or no all-electric range. The diesel performs best in the high-load operation, and the hybrid performs best in the stop-go urban cycle. The US Corporate Average Fuel Economy (CAFE) and CO_2 values for certification are based on a weighting of 55% city and 45% highway driving. On the other hand, surveys from electronically monitored real-world driving show most of the driving falls between the highway and US06 tests (32). The connection between test cycle CO_2 measurements and real-world emissions will depend on vehicle choice and driver patterns.

In a similar context, it should be noted that certified CO_2 emissions could vary from actual real world emissions due to fuel differences. Certification fuel is often much different from fuels on the market.

The leading gasoline and diesel technology choices for meeting the tighter European and US CO_2 standards include direct injection gasoline, gasoline turbocharging, dual clutch transmissions, and stop-start systems (33, 34). Enablers to these technologies are cooled-EGR (exhaust gas recirculation) for gasoline engines, cylinder de-activation, and variable valve technology. Overall, specific power will increase, enabling significant engine downsizing.

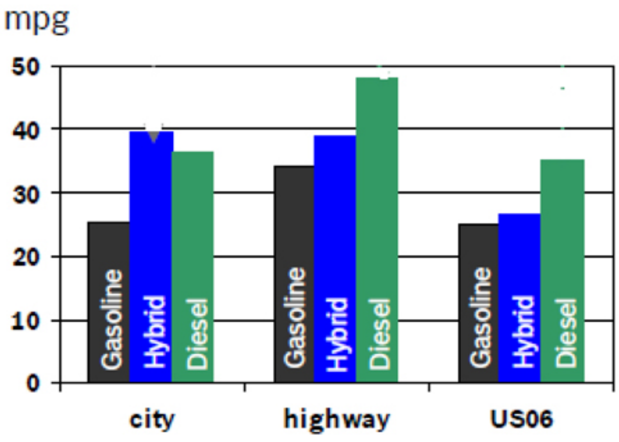


Figure 12. Simulated test results on a Mercedes E-class with the same powertrain power, showing the importance of drive cycle in measuring fuel economy (30). MGP is miles per gallon.

In that regard, engine downsizing is emerging in Europe as a significant technology package for meeting the 2015 regulations. The principle is to run the engine at higher Brake Mean Effective Pressure (BMEP; or load) for lower fuel consumption per unit of energy. As shown in Figure 13, this allows reduced cylinder size to deliver the same net power to the crankshaft (35). In this example at 2000 RPM on a diesel engine, the BMEP is increased from 2 bar to 2.5 bar (+20%) when dropping engine displacement 20%. The smaller engine is consuming 10% less fuel as a result of the more efficient load point. It is estimated this smaller engine will save 20% fuel on the NEDC. (More typical levels are on the order of 10%.) To maintain the same performance as the larger engine

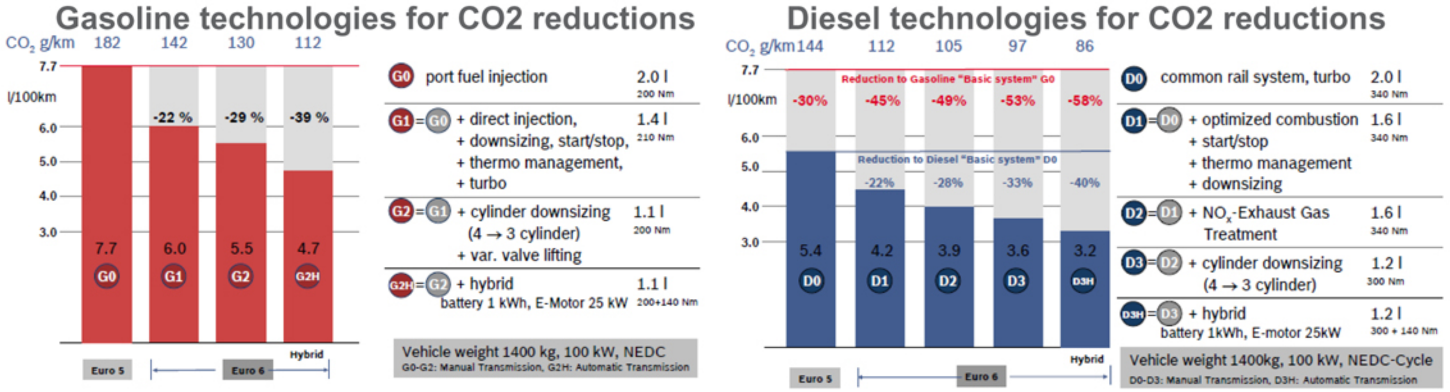


Figure 14. Comparison of incremental gasoline and diesel engine technologies for CO_2 reductions. The diesel 30% CO_2 advantage will be maintained or slightly increase in the near future (31).

at acceptable NOx levels, new technologies for the diesel engine need to be utilized such as increased turbocharging, higher peak cylinder pressure, higher injection pressures, variable valve technology, and more charge air cooling (36). Even so, there are limitations and trade-offs, namely NOx increases may overwhelm the incremental fuel savings, and added cost may limit the technology to higher-priced cars. Also note that the test cycle or drive conditions become quite important. The fundamental fuel consumption savings is limited to low-load operation, as the specific fuel consumption flattens at the higher loads in Figure 13. However, the enabling technologies may offset this, somewhat.

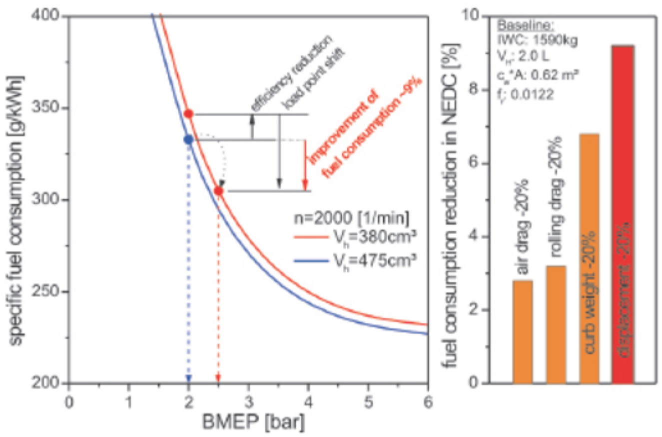


Figure 13. The principle of downsizing a diesel engine. The smaller engine is run at higher BMEP to give a lower specific fuel consumption (35).

Rueger (31) compared incremental technologies for gasoline and diesel engines, and concluded that the diesel advantage on CO_2 (~30%) will be maintained in the near future, albeit with a 9% smaller torque advantage (+100 Nm vs. +120 Nm today). Figure 14 shows the analyses. Note that for an average sized European car (1400 kg), the 2020 CO_2 target value of 95 g/km is nearly attained for the diesel without hybridization.

One of the more attractive gasoline engine technologies is emerging from the SwRI (Southwest Research Institute) research consortium called HEDGE™ (High-Efficiency Dilute Gasoline Engines). Turbocharging is used to improve efficiencies, and a large amount of cooled-EGR, in the range of 25-45% depending on design, is used to reduce auto-ignition under the higher compression ratios (~14:1 vs. 9-11:1 for other gasoline technologies). It is a stoichiometric engine using standard multi-port injection. If the hallmark of the technology is cooled-EGR, as implied by the name, the technology is already being partially implemented in the 2010 Toyota Prius. Figure 15 shows the BSFC (Brake Specific Fuel Consumption) map for a 2.4 liter spark-ignition engine that was retrofit with the technology (37). Given that high-load fuel consumption is 10-30% lower than for the base engine, it has good low-end torque, and peak BMEP is quite high (+25% vs. direct injection engines), the concept is quite amenable to downsizing and downspeeding. Issues to resolve include ignition stability and slow flame propagation caused by high levels of EGR; boosting issues raised by lower exhaust temperatures (EGR), high mass flow, and high pressure ratios; and EGR control.

<figure 14 here>

Looking into the long term, several research efforts are aimed at recovering waste energy from the exhaust. BMW reported on using a Rankine turbo-steamer on a 2 liter stoichiometric gasoline engine (38). Steam is generated in the exhaust heat exchanger, which is then used to power a turbine. The water is cooled and returned back to the heat exchanger. Total engine power was increased ~10% in the mid-speed moderate load regime. Exhaust temperatures dropped 300C°. A more advanced system might increase power by 15%.

Thermoelectrics are also being evaluated. The US Department of Energy sees thermoelectrics replacing generators and air conditioner units in light duty vehicles in 7 to 15 years (39). In the first vehicle tests, 1 to 5% fuel consumption gains were reported, with the higher values coming at high load (40).

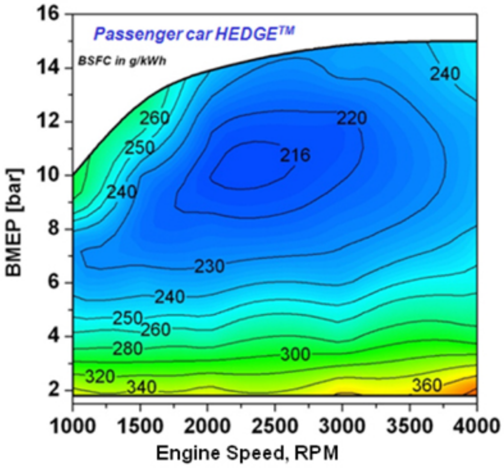


Figure 15. Brake Specific Fuel Consumption (BSFC) map for a 2.4 liter spark-ignition stoichiometric gasoline HEDGE™ engine with multi-port injectors. High load BSFC is 10-30% lower than for the base engine (37).

HYBRIDIZATION

Hybrid electric vehicles (HEVs) are now in their third generation, and have been in the market for 13 years. They are available in virtually every vehicle class. Full hybrids have the lowest CO_2 emissions, with the best delivering >50% reductions from conventional vehicles. However, despite incentives, their market penetration was flat in 2009 at only about 2.5%. Europe is favoring the diesel car over hybrids, and fuel prices are too low in the US to make HEVs appear attractive. As shown in the previous section, they have their best performance in light load, stop-and-go traffic primarily due to their ability to recover braking energy.

Figure 16 shows the well-to-wheel CO_2 emissions estimated using the GREET model (Argonne National Laboratory) for a variety of mid-size HEVs operated on the US city cycle. A number of interesting observations can be made. First, full hybridization drops emissions by about 48% for both gasoline and diesel models. Second, diesel HEVs have the lowest emissions, except for battery electric vehicles (BEVs) on the California grid. For this reason, many European diesel automobile manufacturers are developing diesel HEVs. Under a tight CO_2 regulatory mandate, the diesel HEV looks attractive. Third, the plug-in HEV (PHEV), wherein the electrical grid helps charge the battery, has ~14% higher CO_2 emissions on the US grid relative to HEVs, 5% lower in California, and 5% higher in Europe (not shown). The PHEV modeled here has a moderate battery size in the power split configuration (vs. series) and powers about 1/3 of the travel in EV mode. More recently, Argonne scientists showed PHEVs might get 47 to 62% of its energy from the grid in typical drive patterns if equipped with 4 to 8 kW-hr batteries (41), and close to 90% of energy from the grid for the largest batteries being considered (16 kW-hr). As such, the PHEV has stimulated significant interest in increasing energy diversity. However, despite their CO_2 emissions they are seen as an important step in moving cars toward the grid to help attain the ultimate 2050 goal of 80% reductions (13).

There are several different system architectures and strategies for PHEVs. Figure 17 shows three major types (32), ranging from low or no all electric range (AER) to significant AER, perhaps up to 65 km (40 miles) as in the upcoming Chevy Volt. It is important to note that in all the examples the vehicle reverts to a typical full HEV when the battery reaches a low state of charge (SOC). In the first case with zero or very low AER, the vehicle is closest to an HEV in operation with all blended operation (engine and battery), except the battery is drained to the low SOC and then recharged on the grid. At the other extreme, the last example has the longest AER (biggest battery), and all the needed power in this range comes from the battery/motor, because it is sized for the series configuration with the engine. The Chevy Volt is an example, wherein it has a 136 kW, 16 kW-hr battery (42). The middle example is a compromise, and the most common configuration emerging for PHEVs with moderate AER (8 to 25 km, 5 to 15 miles), requiring a 2 to 6 kW-hr battery. More transportation fuel is shifted to the grid when going from top to bottom in Figure 17. (Some useful parameters in estimating batteries relative to AER are that about 60 to 70% of the battery capacity is used, and a mid-size car will consume about 0.25 to 0.30 kW-hr per mile in normal driving.)

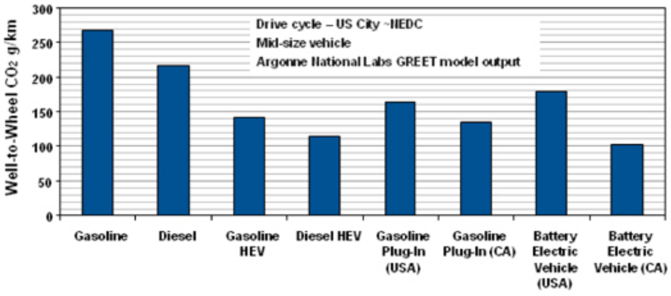


Figure 16. Well-to-wheel CO_2 emissions for various electric powertrains compared to gasoline and diesel vehicles as estimated using the GREET model.

<figure 17 here>

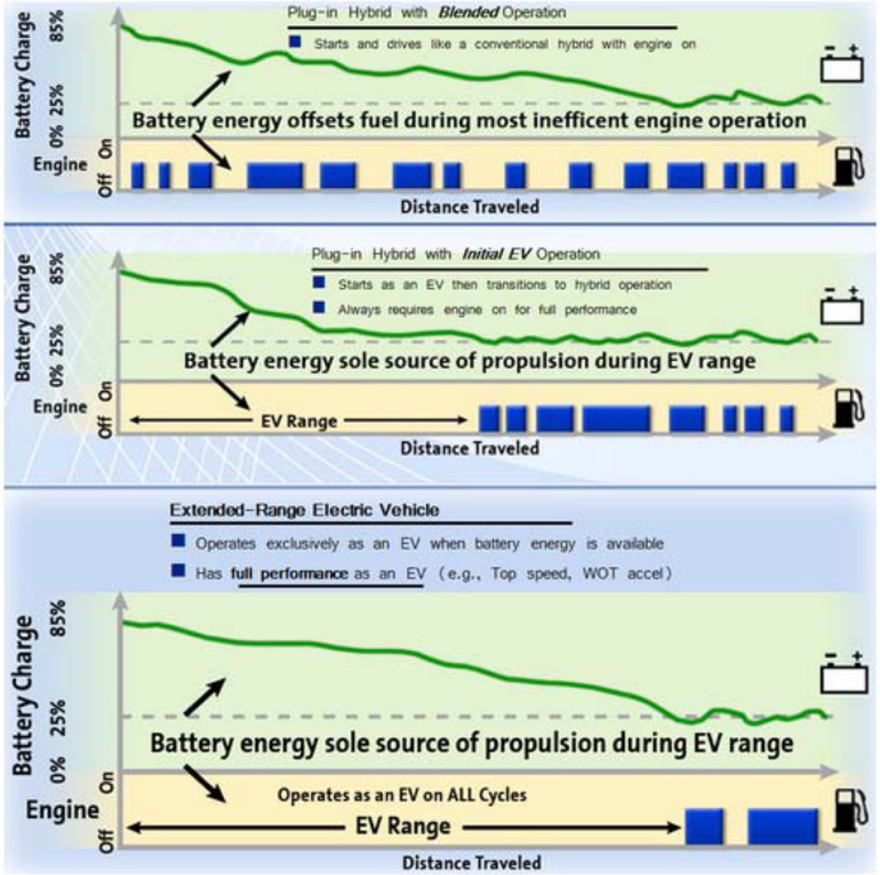
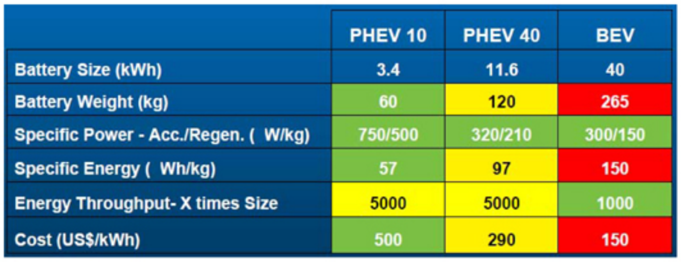


Figure 17. Illustration of the general types of PHEVs being proposed. All concepts revert to HEV mode after the battery is drained to 25% state-of-charge. (13)

Batteries are the single most expensive component and performance determinant in electric drives, thus they are the focus of much work. PHEV lithium ion (Li-ion) batteries are meeting most goals put forth by the US Advanced Battery Consortium (USABC), as shown in Figure 18 for one manufacturer (43), but full electric vehicle batteries fall short on several of these key parameters. The consensus from a 2009 battery workshop concurred with this evaluation, finding that cost was the greatest gap for PHEV batteries; calendar life trends looked good, but there simply was not enough data to confirm attaining the goal (44). Gaps are much more significant on full battery electric vehicles. Weight needs to be taken out, more energy needs to be stored, and costs need to be significantly reduced (~45-50% less than PHEV).



	PHEV 10	PHEV 40	BEV
Battery Size (kWh)	3.4	11.6	40
Battery Weight (kg)	60	120	265
Specific Power - Acc./Regen. (W/kg)	750/500	320/210	300/150
Specific Energy (Wh/kg)	57	97	150
Energy Throughput- X times Size	5000	5000	1000
Cost (US$/kWh)	500	290	150

Figure 18. Current battery status relative to USABC goals for PHEVs and BEVs. Batteries fall short on cost and life (43). Green: goal met; Yellow: goal not yet met but progressing; Red: much more work needed.

Looking further at cost, Nelson (45) evaluated Li-ion battery manufacturing costs for several compositions and capacities. Battery pack costs increased linearly with AER, as shown in Figure 19. Specific usable battery costs for the lowest cost formulation (lithium manganese oxide) decreased from $400/kW-hr for 20 km AER batteries to $300/kW-hr for batteries delivering 65 km AER. Looking at the prognosis for further cost reductions, Nelson estimates abut 47% of the cost is in materials and 17% is in purchased items. Direct labor was only 6% of the total manufacturing cost. Base raw material costs show potential for little change, either way (46, 47). Mock (47) estimated a 90% learning curve for batteries, wherein there is a 10% cost reduction for each doubling of cumulative volume. His survey of costs plateaus at about \$250/kW-hr for the battery pack, (\$360/kW-hr usable battery), agreeing with Nelson.

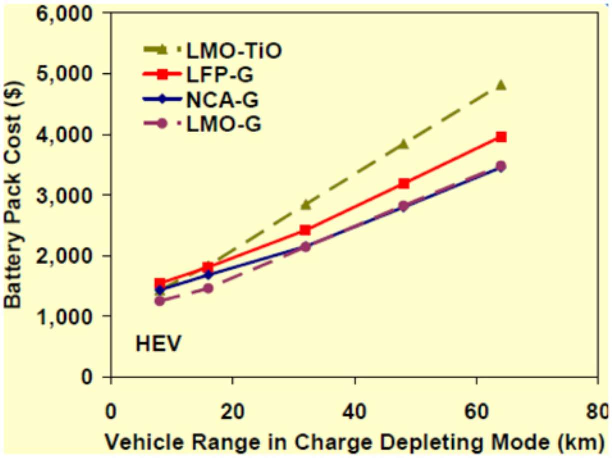


Figure 19. Li-ion battery pack costs increase nearly linearly with AER. 60 kW batteries at 25% SOC. LiMnO, LiFeP, LiNiCoAl; 100,000/yr manufacturing capacity (45)

COST OF FUEL EFFICIENCY FOR LIGHT DUTY APPLICATIONS

There have been numerous studies looking at the cost of fuel savings in the light duty sector. The results are difficult to normalize and assess, as different baselines are used, cost estimates vary, and usually cost values are expressed as percentage increases from the base. Instead of choosing one or two representative studies, the author attempted to normalize baseline comparisons to a mid-sized Tier 2 Bin 5 car and use studies that looked at the different kinds of powertrains, at least to provide internal consistency within each study. The author's estimate of a PHEV with 20 mile AER is also shown. The GREET model provides the CO_2 reductions, and incremental costs to the HEV are for an 8 kW-hr battery at \$360/kW-hr (low end), in addition to an \$800 on-board grid charging system. The results are shown in Figure 20. The first observation is that there is a wide range of expert estimates for both cost and CO_2 reductions within each powertrain group. However, the group averages provide a relatively tight relationship between incremental cost and incremental CO_2 reductions. After an initially high value for advanced gasoline engines, emissions savings increase linearly with cost increase.

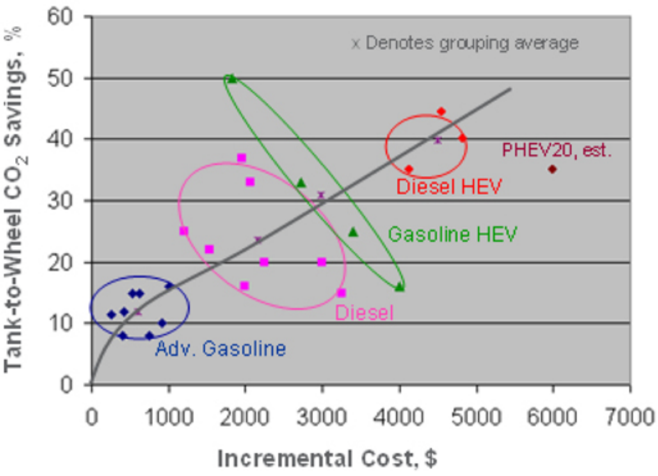


Figure 20. Based on the average results from the literature, CO_2 savings increase linearly with cost. Tier 2 Bin 5 midsize cars.

The above analysis did not take into account fuel savings in the cost estimates, nor did it look at all CO_2 emissions (no well-to-tank or life cycle analyses). In Figure 21 the net cost of well-to-wheel CO_2 (eq) reductions, on a \$/tonne basis, is compared for a variety of powertrain and fueling options (48). As others have found (49, 50), incremental improvements to the powertrains on the road today using standard gasoline or diesel fuels save money, so incremental CO_2 reductions have a negative cost. However, as alluded to earlier in the discussion of Figure 4, these fuel savings might not directly translate into vehicle price increases, and the consumer might not pay for them. Also, not accounted for here is the vehicle resale value and a discount rate, both of which can play into net costs. Cellulosic ethanol and biodiesel also come with a moderate cost or even a savings, depending on petroleum price.

LD VEHICLE CONCLUSIONS

This section reviewed the status of fuel consumption and CO_2 reductions in the light-duty sector. Most of the potential savings comes from improvements in the powertrain. Some of the technologies are favored for light-load or city operation, like hybridization and engine downsizing, and some do better in high-load or highway operation, like diesel. Both the gasoline and diesel engines can improve, on the order of 20-30% from today's engines. These technologies are generally cost effective and will save the consumer money over the life of the vehicle. The greatest CO_2 saving comes for the diesel hybrid. To meet IPCC goals of 80% reductions by 2050, electrification of the vehicle and a green grid are necessary. The PHEV is on the vehicle pathway to accomplish this, but it is a relatively expensive option.

<figure 21 here>

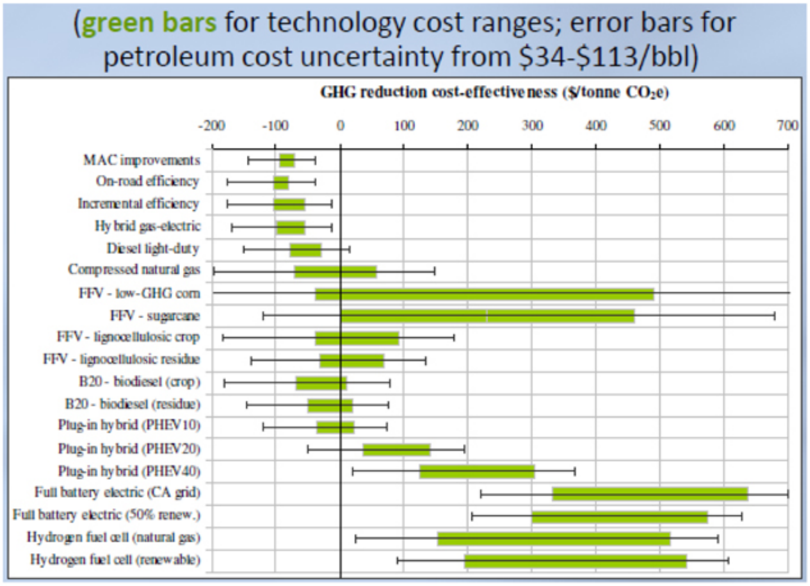


Figure 21. The cost effectiveness of GHG reductions in $ per tonne of CO_2 (eq.) reduced on a well-to-wheel basis. Improvements in powertrains commercially sold today have the lowest costs (48).

HEAVY DUTY POWERTRAIN TECHNOLOGIES

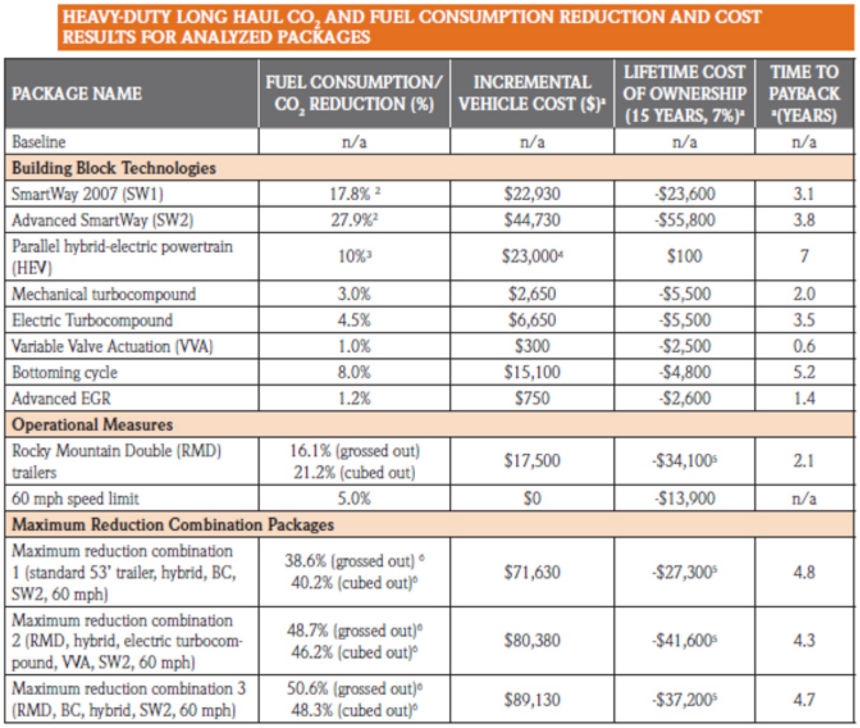
About 6-8% of GHG emissions come from the heavy-duty (HD) truck sectors in the US, Europe, and Japan (51, 52, 53). In the US, about 75% is emitted by the large Class 8 trucks. The HD truck sector is strongly driven to drop fuel consumption, as fuel costs represent 20 to 30% of the total life cycle cost of the truck (second only to wages), and can represent 2 to 2.5X the cost of the truck itself (54). However, many of the fuel-saving technologies have not been introduced to the market because the industry is quite risk adverse, operates on a tight margin, has to face fuel price volatility, and might not have access to good fuel consumption information. For example, many fleet operators require an 18 to 24 month payback period for new technologies, shorter than many feasible technologies can deliver. As such, regulatory pressures are increasing to force fuel savings technologies.

Converse to the light-duty sector, wherein 70% of potential fuel savings comes from engine improvements (Figure 11), in the long haul truck sector 65% potential savings comes from vehicle and operations improvements and 35% comes from the engine(55).

Some examples of technologies and costs for reducing fuel consumption for long haul trucks are reported (56) in an extensive study commissioned by the Northeast States Center for a Clean Air Future (NESCCAF) and by the International Council on Clean Transportation (ICCT). The study evaluated only technologies that are in production or are emerging but have a design specification in the literature. Figure 22 shows a summary of various results. Relative to a baseline 2010 truck with a 13 liter engine and 10-speed manual transmission, between 1 and 10% fuel consumption savings can be realized with engine and powertrain modifications; 5 to 21% savings can come from operational measures, like low speed driving and double trailers; but 18 to 28% reductions can come from vehicle modifications, such as aerodynamic streamlining and low rolling resistance tires. Using combinations of technologies that are already deployed on some trucks can save 8 to 18% fuel. These technologies include hybridization, turbo-compounding, and the modest Smartway 1 package. Up to 50% fuel savings might be realized with the most advanced technology combinations. Deploying technologies with a three-year payback period ($2.50/gallon, 120,000 miles/yr) can save 17% of the long haul fleet fuel in 2030, and 39% would be saved using technologies that pay back in 15 years (1.2 million miles).

<figure 22 here>

Regarding progress on improving engine efficiency, Stanton showed that advanced engine measures, can reduce fuel consumption by 14% relative to a 2007 production engine running at the same NOx level of ~1.3 g/kW-hr (57). Technologies employed include combustion optimization (high pressure and multiple fuel injections, bowl design, variable swirl, variable valve actuation); advanced EGR (low pressure drop, high flow, advanced cooling); air management (2-stage boost, electrically assisted turbocharger); and advanced controls (mixed mode combustion, closed-loop control). Note that these additional technologies are not included in the NESCCAF report, except variable valve actuation and advanced EGR. If exhaust emission control



HEAVY-DUTY LONG HAUL CO_2 AND FUEL CONSUMPTION REDUCTION AND COST RESULTS FOR ANALYZED PACKAGES

PACKAGE NAME	FUEL CONSUMPTION/ CO_2 REDUCTION (%)	INCREMENTAL VEHICLE COST ($)[1]	LIFETIME COST OF OWNERSHIP (15 YEARS, 7%)[1]	TIME TO PAYBACK [1](YEARS)
Baseline	n/a	n/a	n/a	n/a
Building Block Technologies				
SmartWay 2007 (SW1)	17.8% [2]	$22,930	-$23,600	3.1
Advanced SmartWay (SW2)	27.9%[2]	$44,730	-$55,800	3.8
Parallel hybrid-electric powertrain (HEV)	10%[3]	$23,000[4]	$100	7
Mechanical turbocompound	3.0%	$2,650	-$5,500	2.0
Electric Turbocompound	4.5%	$6,650	-$5,500	3.5
Variable Valve Actuation (VVA)	1.0%	$300	-$2,500	0.6
Bottoming cycle	8.0%	$15,100	-$4,800	5.2
Advanced EGR	1.2%	$750	-$2,600	1.4
Operational Measures				
Rocky Mountain Double (RMD) trailers	16.1% (grossed out) 21.2% (cubed out)	$17,500	-$34,100[5]	2.1
60 mph speed limit	5.0%	$0	-$13,900	n/a
Maximum Reduction Combination Packages				
Maximum reduction combination 1 (standard 53' trailer, hybrid, BC, SW2, 60 mph)	38.6% (grossed out) [6] 40.2% (cubed out)[6]	$71,630	-$27,300[5]	4.8
Maximum reduction combination 2 (RMD, hybrid, electric turbocompound, VVA, SW2, 60 mph)	48.7% (grossed out)[6] 46.2% (cubed out)[6]	$80,380	-$41,600[5]	4.3
Maximum reduction combination 3 (RMD, BC, hybrid, SW2, 60 mph)	50.6% (grossed out)[6] 48.3% (cubed out)[6]	$89,130	-$37,200[5]	4.7

Figure 22. Technology assessment for fuel savings from long haul HD trucks. Lifetime cost and payback period estimates are based on high volume technology costs, 1.2 million miles over 15 years (120,000 miles per year for payback time), and fuel priced at $2.50/gallon ($0.67/liter). (56)

achieves 97% deNOx efficiency instead of 80% to attain US2010 NOx standards, an additional 10% fuel consumption reduction might be achieved. This is due to the general inverse relationship between fuel consumption and NOx.

The above technologies are relatively advanced but nevertheless are deployed or moving towards deployment. They are incremental. To look at the longer term, Schmidt did a thermodynamic analysis of engine efficiencies and thus opportunities for improvements (58). Improving combustion efficiency improvements can potentially save 5% fuel; friction reduction and improved gas handling - 2% each; and reducing heat loss to the wall 6 to 18%. Heat losses to the cooling water and exhaust combine for ~55% loss of efficiency.

As with light-duty engines summarized above, heavy-duty waste heat recovery systems based on the Rankine cycle (evaporation of organic working fluid, expansion, condensation, return) are being evaluated (59). Heat is taken out of the EGR loop and exhaust system (after emission control system) and converted to mechanical energy for a 6 to 7% fuel savings, depending on level of EGR. A pathway to achieving a potential 9.5% fuel savings was itemized. Figure 23 shows a proposed timeline for implementation of heat recovery systems (or bottoming cycles) in the heavy-duty sector (60).

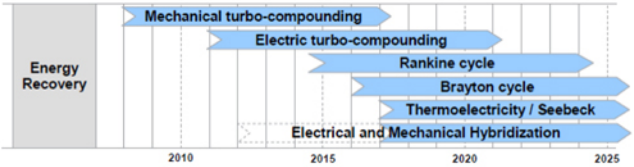


Figure 23. Estimate of implementation timeline for waster heat recovery system for heavy-duty engines. (60)

Combustion research is shifting from diesel- to gasoline-fueled engines with high levels of EGR and premixed combustion, similar to the HEDGE concept summarized in the light-duty section. Reitz, et al. (61), ran a 2.4 liter single-cylinder engine up to 11 bar BMEP at 1300 RPM using 80% multiport injected gasoline and 20% diesel to ignite the charge. They reported 53% indicated thermal efficiency (ITE, no friction or pumping losses) compared to 44% for the diesel baseline. Almost all the indicated fuel savings (~20%) came from reduced thermal losses to the cooling water and exhaust. The NOx emission was nominally 20 mg/kW-hr, and PM emission was 8 mg/kW-hr. Johansson adapted a 12 liter 6-cylinder HD engine to burn gasoline, and reported a brake thermal efficiency (BTE; all engine losses) of 48% at 18 bar IMEP and 1300 RPM (62). This represents perhaps a 10-15% fuel consumption reduction. However, NOx and PM emissions were much higher than reported by Reitz.

HD HYBRIDIZATION

Compared with light duty applications, heavy-duty hybridizaton is just beginning. It is mainly focused on urban vocational applications, but can save much fuel. For example, as shown in Figure 24, a medium duty utility truck can save 8 to 27% fuel depending on drive cycle (63). When used for stationary work, 80% of fuel is saved. Similarly, a medium duty box truck can save 24 to 32% of fuel, and a PHEV urban bus can save from 35 to 65% of fuel. For local courier delivery trucks, about 30% fuel is saved using a hydraulic hybrid design (64). These values compare with 10% savings for long haul applications, including idle reductions, and 5% savings when traveling (Figure 22).

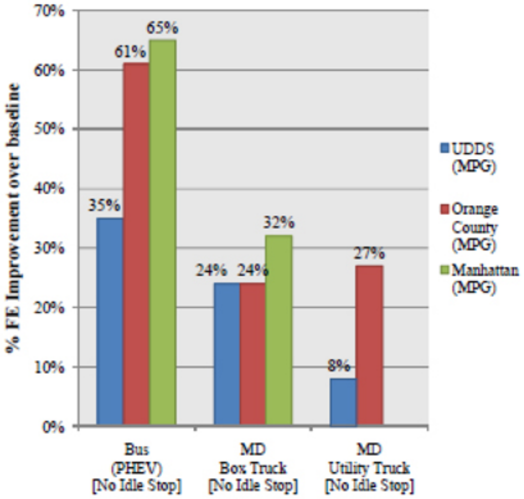


Figure 24. Fuel savings for various types of hybrid heavy duty trucks in different use patterns (63).

Historically, the economics of the systems restricted their use to heavily subsidized applications. However, this is changing. For example, in the courier truck application the additional $7000 for the hydraulic hybrid system has a two-year payback period at fuel prices of about $0.80 per liter ($3/gallon). For electric hybrid applications, the $16,000 incremental cost (65) of the system might be recovered in four years. As such, some projections show 40,000 hybrid trucks being sold in the US by 2015 (65), with 20% of them being hydraulic hybrids.

Hybrid configurations are even beginning to show in the nonroad construction sector. Caterpillar introduced the D7E diesel electric hybrid bulldozer, which reduces fuel consumption by 20% (66). The $100,000 incremental cost on the $600,000 machine has a payback period of 2.5 years (67), largely because it is 10% more productive.

HD VEHICLE CONCLUSIONS

The HD truck sector emits about 6% of the GHGs in the US, Europe, and Japan. In the US, about 70% of this comes from the long haul sector. Contrary to the LD sector, wherein most of the fuel savings comes from engine improvements, in this segment, 65% of the opportunity is in the vehicle (e.g., aerodynamic design) and operations. Looking at the whole long haul truck, 8 to 18% of fuel savings can come from wider use of technologies that are already on some trucks. In 2030, 18% of the segment's fleet-wide fuel can be saved by utilizing technologies that have a three year payback period. Considering only the engine, research engines are delivering 14% lower fuel consumption using largely incremental advancements in current engine technology. An additional 10% reduction might be gained by increasing emission control system deNOx efficiency from 80 to 97%. Waste heat recovery systems (bottoming cycles) have demonstrated 6 to 7% fuel savings in preliminary tests. Further out, HD engine research is migrating towards gasoline engines with high amounts (40-50%) of EGR. Steady state BTE values of 48% at 18 bar IMEP and 1300 RPM have been reported, for a roughly 15% fuel savings and a 25% CO_2 reduction. Hybrid HD trucks are emerging in the vocational market, with payback periods of 2 to 4 years becoming possible.

Black carbon reductions from vehicles can have a profound effect on GHG impact, accounting for upwards of ∼20% of CO_2 reductions proposed by the IPCC by 2050.

BLACK CARBON REDUCTIONS

As mentioned earlier, black carbon particles in the air retain heat and can cause warming. As it is a short-lived emission, staying in the atmosphere for weeks instead of hundreds of years like CO_2, early reductions can have immediate impacts. Black carbon is a significant fraction of the particles emitted by diesel engines without filters. Aside from the climate benefits, the health benefits alone justify PM reductions via the use of diesel particulate filters.

Figure 25 shows how worldwide vehicle black carbon emissions from on-road vehicles are projected to vary over time (68). About 60% of the emissions are from trucks. The base case assumes PM regulations that are currently planned. Emissions increase after about 2025 as the developing countries grow. The bars represent emissions if, by 2015, Euro VI HD and Euro 6 LD regulations are implemented in China, India, and Brazil; Euro IV HD and Euro 4 LD standards are implemented in Africa and the Middle East; and Euro 3 motorcycle regulations are implemented in Africa, the Middle East, and Latin America. By 2050, these advanced regulator initiatives remove 19 million tonnes of black carbon, or the equivalent of 38 billion tonnes of CO_2. This is ∼20% of the total CO_2 reductions the UN proposes between now and 2050.

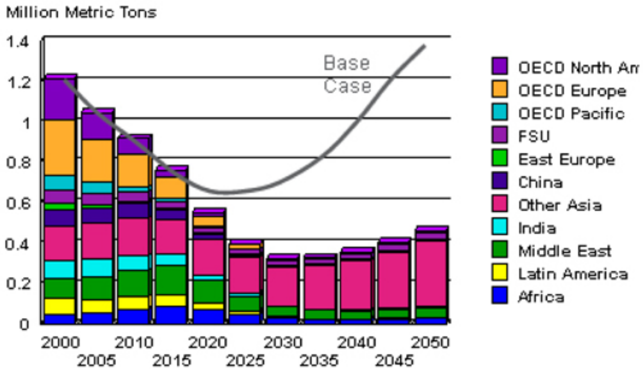


Figure 25. Black carbon reductions from on-road vehicles under current regulations (line) compared to those if developing countries adopt tighter PM standards by 2015. About 60% are for the HD sector. The difference represents about 20% of the total CO_2 reductions proposed by 2050 (68).

OVERALL SUMMARY/ CONCLUSIONS

Driven by scientific consensus of climate change impacts by anthropogenic sources and the desire to diversify energy sources, regulations governing vehicle emissions of CO_2 and fuel consumption are just now emerging in the light-duty sector, but are poised to be a long term trend and involve other vehicle sectors as well. Like criteria pollutant regulations, CO_2 regulations will force technologies on the vehicles that might not go commercial otherwise. This is a paradigm shift.

Many of the goals on emissions and fuel diversity are met with new fuels. As such, governments are implementing biofuel mandates. The US will be requiring that about 20% of the transportation fuels have >50% of the GHG emissions reductions (in neat form) versus conventional fuels by 2022. Europe will require 10% penetration of similarly effective fuels by 2020. Short term, the best approaches involve utilizing the cellulosic portion of plants or using waste products. The long term trend is towards integrating biofeedstocks into refinery operations to expand applications and reduce specific application issues.

For light duty vehicles, most of the potential savings comes from improvements in the powertrain. Some of the technologies are favored for light-load or city operation, like hybridization and engine downsizing, and some do better in high-load or highway operation, like diesel. Both the gasoline and diesel engines can improve, on the order of 20-30% from today's engines. These technologies are generally cost effective and will save the consumer money over the life of the vehicle. The greatest CO_2 saving comes for the diesel hybrid.

The HD truck sector, most of the energy saving opportunity is in the vehicle design and truck operations optimization. Although low fuel consumption in this segment is critical to a successful product today, 8 to 18% of fuel savings can come from wider use of technologies that are already on some trucks. Considering only the engine, research engines are delivering 14% lower fuel consumption using largely incremental advancements in current engine technology. Additional reductions can come from higher deNOx emission control efficiency and the use of bottoming cycles. HD engine research is migrating towards gasoline engines with high amounts (40-50%) of EGR. These engines might have 25% lower CO_2 emissions than today's best commercial diesel engines. Hybrid HD trucks are emerging in the vocational market, with payback periods of 2 to 4 years becoming possible.

Black carbon reductions from vehicles can have a significant effect on GHG impact, accounting for upwards of ~20% of CO_2 reductions proposed by the IPCC by 2050.

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