

Review of CO₂ Emissions and Technologies in the Road Transportation Sector

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ABSTRACT

The topic of CO₂ 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% CO₂ reductions from 1990 levels by 2050. Regulators are beginning to respond by requiring ~25% reductions in CO₂ 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% CO₂ 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 CO₂ 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. CO₂ savings shows a general linear relationship with cost. Diesel hybrids offer the greatest CO₂ reduction potential. Plug in hybrids can lead to heavy electrification of the fleet for energy diversity and greenhouse gas reductions, but their CO₂ 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 CO₂ 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% CO₂ 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 CO₂ 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), NO_x, 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 CO₂ 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 CO₂ 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 CO₂ targets for 2050 and beyond, which will likely drive CO₂ regulations into other vehicle and equipment segments. As such, it is reasonable that it could be more difficult to meet emerging CO₂ regulations than emerging criteria pollutant regulations.

There are numerous technologies being considered to reduce CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions regulation, or “equivalent” CO₂

regulation, which encompasses most climate change agents. The third subsection will summarize fuel economy or CO₂ 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 CO₂) 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).

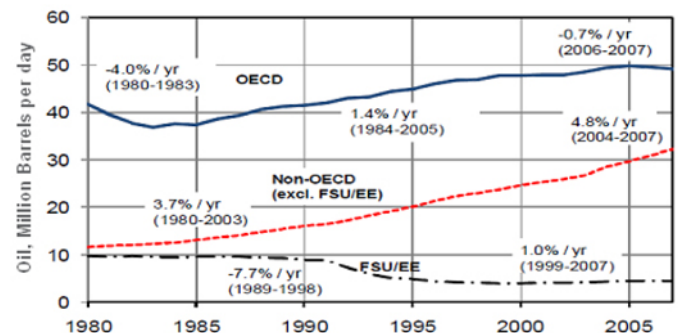


Figure 1. Non-OECD countries' oil consumption has been growing ~3X faster than OECD countries.

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%

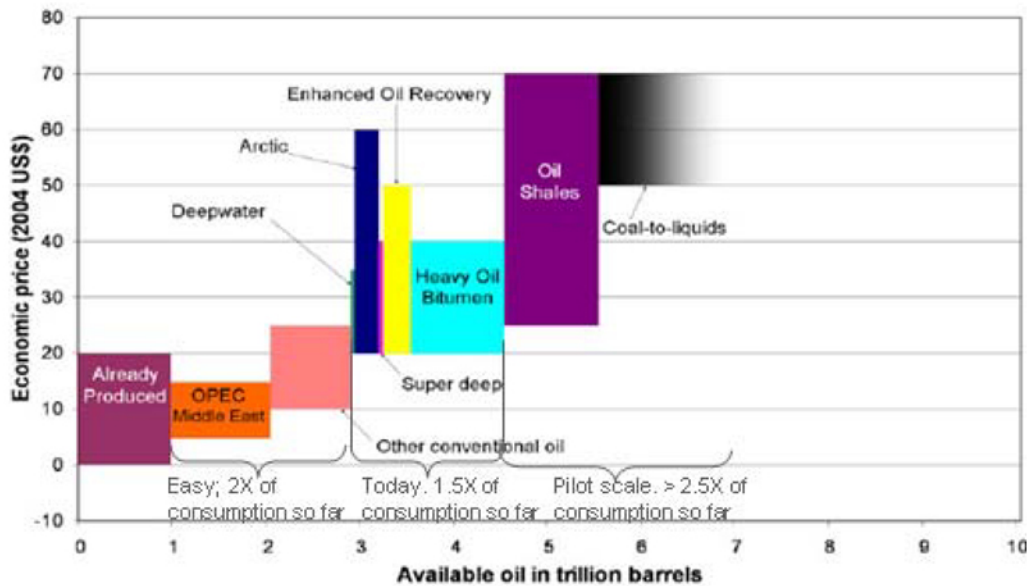


Figure 2. Estimates of probable oil reserves as a function of price (4). Notes were added by author. At EIA consumption estimates for 2030 of 44 billion barrels per year, these reserves would last >100 years.

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), CO₂ emissions from the burning of fossil fuels would appear to drive vehicle fuel consumption and CO₂ 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 CO₂ and the impact on CO₂ concentrations in the air (5). The Panel's analyses show that the 450 ppm goal for CO₂ 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% CO₂ 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 CO₂ 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 (CO₂ normalized to GDP) versus 2005 levels, by 2020. All these proposals are nonbinding and will be negotiated in subsequent meetings. However, the pledges suggest CO₂ 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 CO₂, 14% from methane; and 8% from N₂O. About 57% of the CO come from fossil fuels, while most of the CO₂ 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

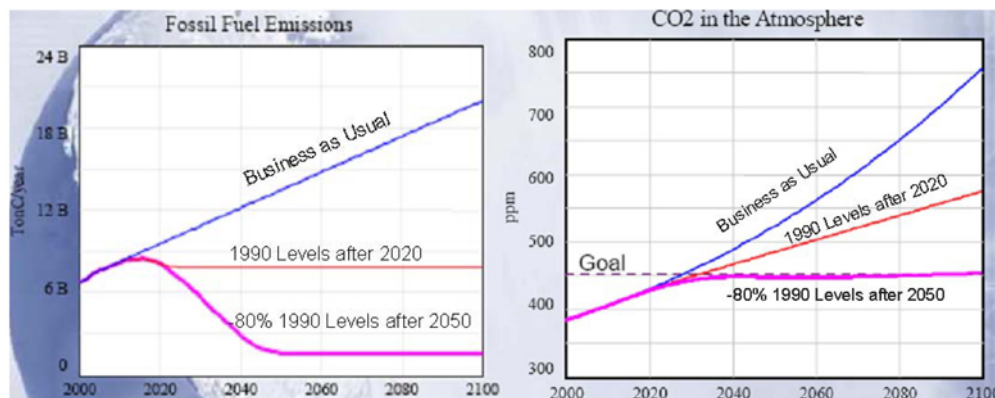


Figure 3. The UN IPCC models show that 80% reductions in anthropogenic CO₂ are needed to stabilize CO₂ levels to 450 ppm in the atmosphere (5).

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 CO₂ 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 CO₂ 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 CO₂ regulations. California emerged first with automobile regulations in 2004, dropping emissions from about 240 g CO₂ (equivalent - includes all GHG normalized to CO₂) 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 CO₂ (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 CO₂ 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 CO₂ mandates in March 2009 at 130 g CO₂/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 CO₂/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 CO₂ standards around the world on a normalized basis - CO₂ 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 CO₂ regulations. The US is about 30% higher than Europe or Japan. The US CO₂ 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 CO₂ 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.

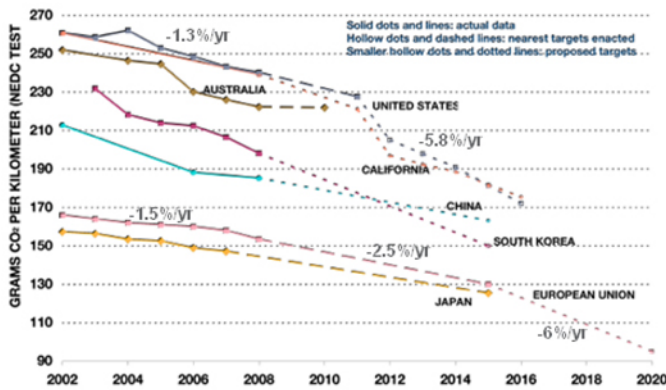


Figure 4. Historic CO₂ emissions (solid lines), and enacted (dashed lines) or CO₂ regulations (dotted line) for various countries with fuel consumption or CO₂ regulations (13). Data were normalized to CO₂ emissions on the NEDC test. Percent improvements per year were added.

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, CO₂ 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 CO₂ 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 CO₂ 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 cowlings 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 cowlings 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 CO₂ (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 CO₂ (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 NO_x, hydrocarbon, particulates, and CO, have been commercialized for more than 30 years, it is reasonable that meeting the future CO₂ emissions standards will be more challenging than future criteria pollutant standards.

BIOFUELS

One of the cornerstones to decreasing transportation CO₂ 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 CO₂ 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 CO₂ 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

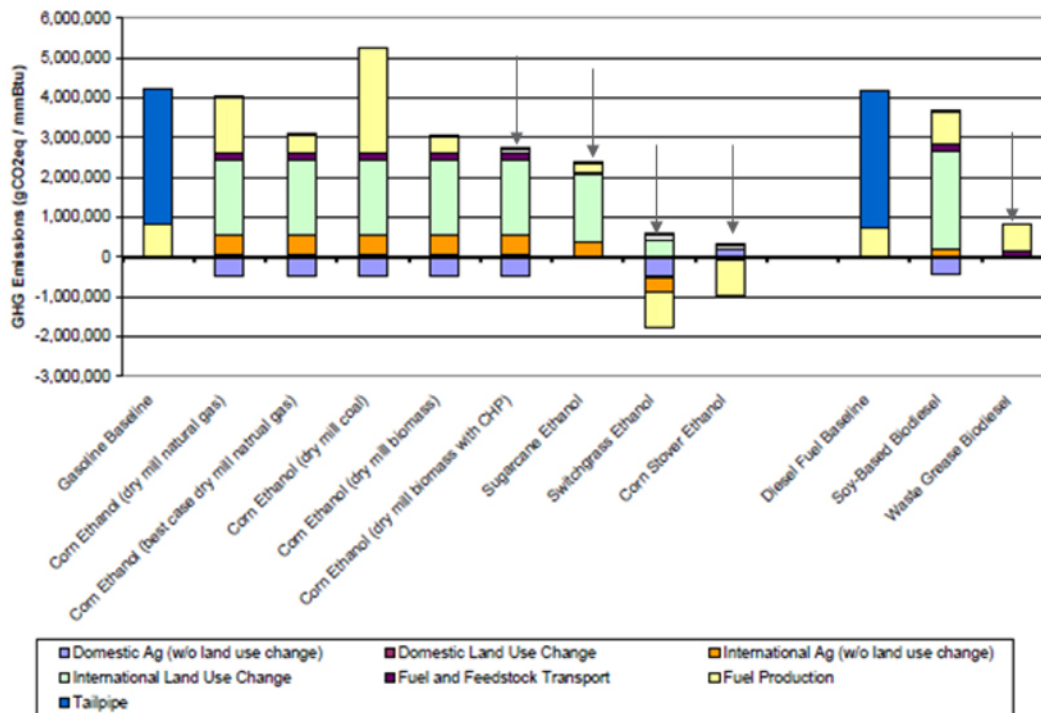


Figure 6. CO₂ life cycle analyses for various biofuels over a 100 year time horizon at a 2% discount rate (19). Using these analyses, the identified fuels meet the cellulosic (>50% reduction) or advanced biofuel (>60%) requirements of EISA.

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 $\geq 50\%$ reduction of GHG emissions from baseline*	21
Cellulosic Fuels – Includes cellulosic ethanol, biobutanol, green diesel, green gasoline All must achieve $\geq 60\%$ 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