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Chapter 10:

The Case for Diesel Cars To Reduce Greenhouse Gas Emissions

by Johannes-Joerg Rueger

Governments worldwide are adopting rules, laws, and incentives aimed at reducing greenhouse gas (GHG) emissions and petroleum fuel consumption of vehicles. All of them also have aggressive rules to reduce conventional pollutants. Europe has the most aggressive GHG rules, while California has the most aggressive rules for local conventional pollution.

While these goals are challenging for the auto industry, many technologies are available to help attain them. However, these goals can often conflict since some of the technologies to achieve the largest GHG reductions may slow reductions in tailpipe criteria emissions. Thus, the state of California's continuing focus on reduction of criteria emissions may make it more difficult for automotive engineers to craft maximum reductions in GHG emissions, in particular emissions of carbon dioxide (CO_2).

In addition, California is planning to take into account well-to-wheel GHG emissions for fuels in order to account for the full spectrum of the impact of the use of different fuels, while at the same time reducing the carbon intensity of these fuels. These regulations have been codified in the Low Carbon Fuel Standard, adopted by the California Air Resources Board and expected to be implemented beginning in 2011 (CARB 2009b). This adds another layer of complexity for the auto industry by requiring it to adapt to new liquid fuels, while also seeking to meet increasingly stringent GHG and criteria emission regulations.

While the regulations aim at reducing tailpipe emissions based on defined test cycles, it is important to keep an eye on the real-world behavior of the different technologies as well, as illustrated in Figures 10-1 and 10-2.

One concern is that some of the test cycles do not always reflect the real world attributes of the various technologies. A Bosch test lab simulation compared conventional gasoline and diesel vehicles and a full Prius-style hybrid electric vehicle (HEV) version of otherwise identical cars. The base car was a 1,700 kilogram (kg) Mercedes E-Class. For this simulation, the hybrid version was assumed to be equipped with a 110 kilowatt (kW) internal combustion engine, a 31 kW electric motor, a lithium-ion battery pack and a 6-speed automatic transmission. The tests found that the HEV had 10 percent better fuel economy than the diesel in a city driving cycle, while the diesel outperformed the HEV by 23 percent on the highway cycle.

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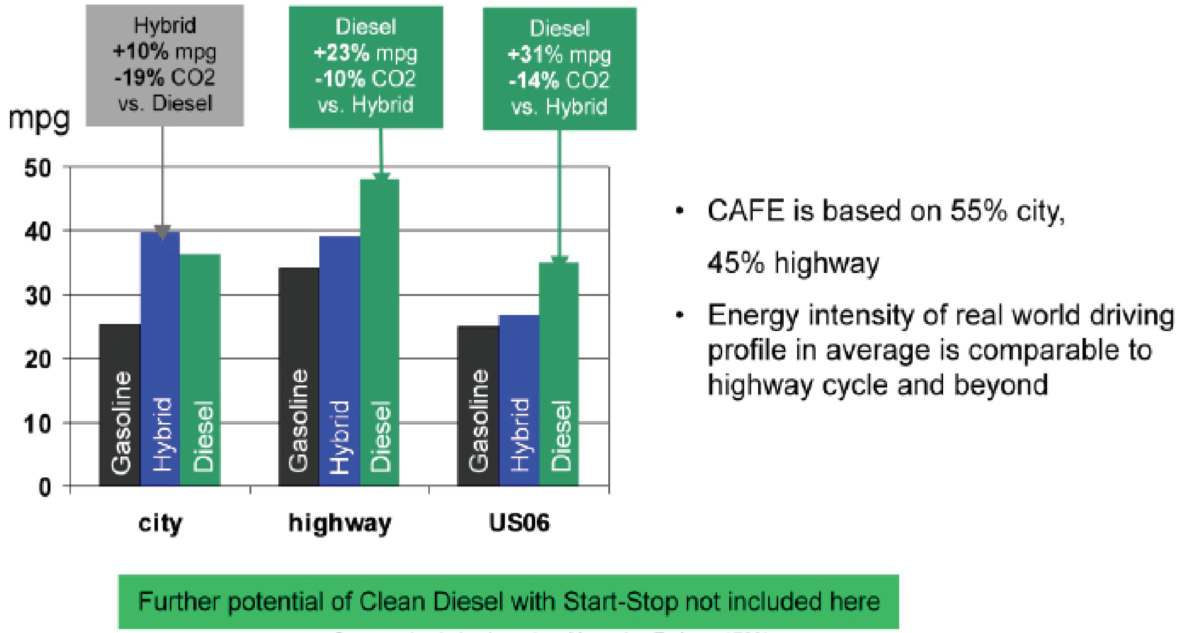
Figure 10-1: Driving tests favor clean diesel



Note: Simulation based on Mercedes E-class, 1,700 kg combustion, 110 kw electrical, 31 kWh lithium ion battery, 6-speed automatic tramsmission

But in the US06 test cycle, which is used by the United States (U.S.) Environmental Protection Agency (EPA) to show emissions and fuel economy at high speeds and with rapid acceleration simulating typical freeway driving, the diesel had 31 percent higher fuel economy than the HEV. These results are even more impressive as they were calculated without applying additional technology like start/stop, which is standard with the HEV, to the diesel vehicle. As noted in the comparative miles per gallon (mpg) and carbon dioxide (CO_2) numbers, the CO_2 reductions are not equivalent to the fuel economy gains of diesel compared to gasoline hybrids because of the difference in the carbon content of the fuels.

Similarly, a test by *Popular Mechanics* magazine, echoing a similar one in the European magazine *Auto Motor und Sport* illustrated in Figure 10-2, examined the measured real world highway fuel consumption of a 2009 Toyota Prius and a 2009 VW Jetta TDI and found the Jetta superior, achieving an overall fuel economy of 45.4 mpg compared to 44.8 mpg by the Prius. The Prius surpassed the diesel fuel economy on city roads, but the magazine concluded that:

> When it comes down to which of these two popular efficient cars is more fun and more comfortable to drive every day, it's an easy pick: We like the Jetta TDI, and the fuel economy numbers in the real world for VW's new player make it … a legit Prius fighter. (Stewart 2008)

The two cars are both five-passenger models. The Prius has a larger interior volume, 96 compared to 91 cubic feet, but a smaller cargo area, 14.4 versus 16 cubic feet. Similarly, the Prius has a longer wheelbase, 106.3 inches compared to 101.5 inches for the Jetta, but is shorter overall, narrower and slightly taller. The Prius weighs 350 pounds less than the Jetta with an automatic transmission and a little less than 300 pounds less compared to the Jetta with a manual transmission. Performance numbers from the manufacturers indicate the Prius accelerates zero to 60 miles per hour (mph) in about 10 seconds, while the Jetta accomplished the same feat in 8.2 seconds with a manual transmission and 8.5 seconds with an automatic.

What is clear from this and other observations of real world fuel economy is that there are multiple technology pathways to achieve improved fuel economy and lower CO_2 emissions, keeping in mind that the two are not

Figure 10-2: Real-world driving favors clean diesel

In a real world test by automotive magazine editors the fuel consumption and CO_2 Emissions of the Prius were compared to a similar-size VW Jetta. Auto Motor und Sport magazine averaged 35.1 mpg in the Prius and 40.6 mpg in the Jetta with similar CO_2 numbers

CO_2: 155 g/km 154 g/km

interchangeable. Because of diesel's higher carbon content, CO_2 reductions are not as dramatic as fuel consumption reductions. For instance, while a typical diesel vehicle has approximately 35 percent better fuel economy than a comparable gasoline vehicle, it would have about 25 percent lower CO_2 emissions, as is seen in Figure 10-1. The key is the ability to match automotive technologies to the needs of the customer.

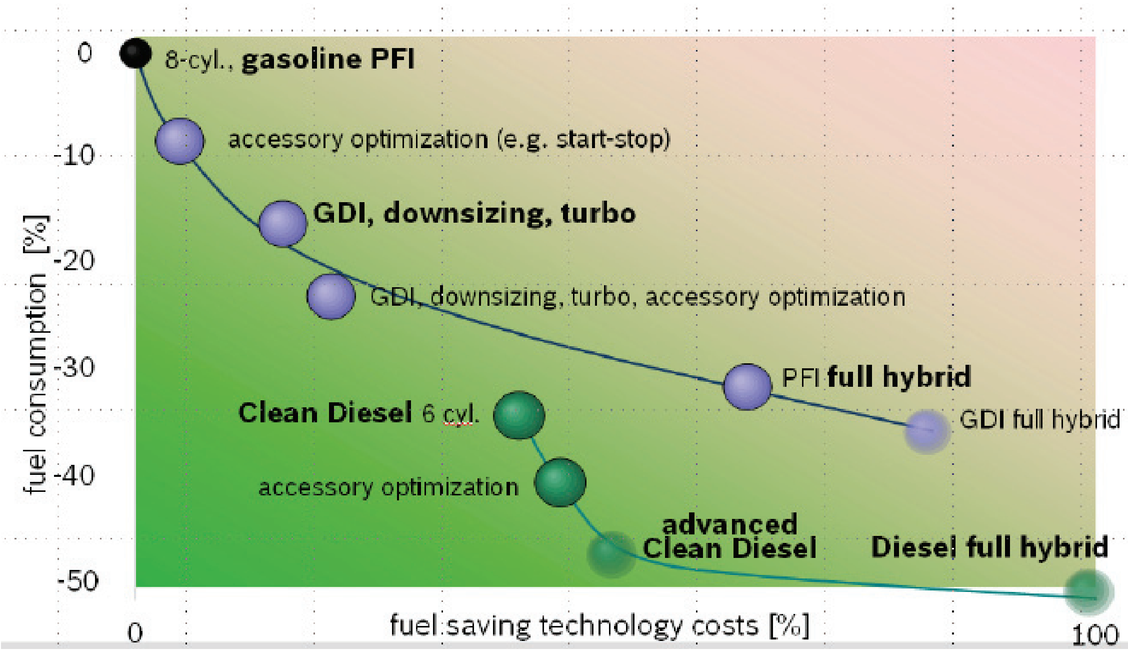
Technology Today

While the automotive sales market in the United States is in flux, having shrunk substantially in size during 2008 and 2009 and shifted in model mix toward smaller vehicles, it still retains a broad spectrum of vehicles ranging from small, highly fuel efficient models to ones that offer lower fuel economy, but feature capabilities such as towing or hauling capacity deemed essential for a significant segment of the consumer market. What is clear is that consumers appear to prefer a variety of different size vehicles with different performance characteristics as opposed to ones solely focused on fuel efficiency. While all sizes of vehicles can be made more fuel efficient, the laws of physics dictate that larger, heavier vehicles will inherently be less fuel efficient than smaller, lighter ones.

The first technology path toward reduced greenhouse gas emissions for the auto industry, as shown in Figure 10-3, is to bring improvements to the basic gasoline engine by adding technologies such as start/stop, which automatically shuts down and restarts the internal combustion engine to reduce the amount of time the engine spends idling, and other accessory optimization technologies including high efficiency generators, friction reduction, thermal management, and electrified accessories. Eventually, industry could shift to gasoline direct injection in combination with downsizing and turbocharging. These technologies promise GHG reductions between 5 and 20 percent at relatively low costs based on Bosch engineers' estimates, which are comparable to those found by K.G. Duleep of ICF International and those of the committee of the National Research Council that assessed technologies for the improvement of fuel economy in 2008. Estimates on the fuel consumption and CO_2 reduction vary in different studies because of a variety of factors. Sometimes different components are employed in similar technologies by different companies. Other studies may reflect that the reported numbers may be obtained from real-world testing, laboratory testing, or simply computer simulation, all of which can yield different results, even when discussing the same components.

Additional hybridization offers a significant CO_2 reduction potential, but is associated with a far less attractive cost/benefit ratio. Hybridization has achieved significant market recognition since the launch of the Toyota Prius. As an alternative, today's modern clean diesel shows a large CO_2 reduction and has significant additional future potential with the aforementioned accessory optimization technologies and downsizing. Hybridization is an option for this technology, too.

Figure 10-3: Fuel economy and technology costs in today's landscape



Acronyms used: PFI = port fuel-injected engine, the typical current gasoline engine; GDI = gasoline direct injection

A Gasoline Vehicle Example

To examine what can be accomplished to move automotive vehicles toward California's environmental goals with current technology, consider a basic 8-cylinder port fuel-injected (PFI) gasoline engine, which is standard technology in many larger U.S. passenger cars, light duty trucks, and sport utility vehicles (SUVs). The same principles also apply to other configurations of PFI engines, including 6- and 4-cylinder configurations. With accessory optimization using start/stop systems, high efficiency generators, friction reduction, thermal management, and electrified accessories, a fuel economy improvement of 10 to 15 percent can be achieved with relatively low cost, while reducing CO_2, criteria emissions, and fuel consumption with no change in the performance characteristics of the base engine.

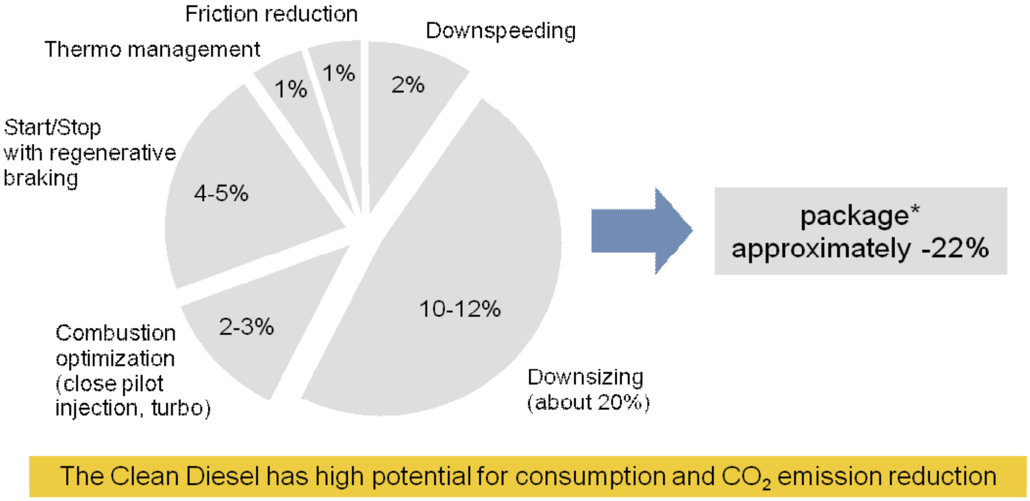
The next stage of reductions, collectively contributing another 5 percent efficiency gains, could be obtained through the use of gasoline direct injection (GDI) technology and turbocharging, which will allow for the downsizing of the engine. In some cases, this might mean an 8-cylinder engine could be downsized to a 6-cylinder engine or a 6-cylinder model downsized to a 4-cylinder version, keeping the original performance, but adding efficiency. This stage would produce an approximate 15 percent reduction in fuel consumption compared to the base engine at a cost more than double that of accessory optimization.

A next step would be full accessory optimization with new GDI technology, which would boost efficiency to more than 20 percent compared to the original engine, but also raise costs. A further level of efficiency could be gained through applying a full hybrid electric drivetrain to the basic PFI engine. This would result in about 30 percent efficiency improvement compared to the original engine, but with a far less favorable cost/benefit ratio compared to the GDI technology. Finally, a full hybrid electric system could be applied to a GDI engine, resulting in a gain of about 5 percent compared to the PFI hybrid, but again with significant incremental costs.

A Diesel Vehicle Example

A similar scenario can be explored with today's clean diesel technology. Figure 10-4 describes the technological options to reduce CO_2 emissions from advanced diesel vehicles. One difference between gasoline and diesel vehicles is that a 6-cylinder diesel engine could be used to compare to the 8-cylinder gasoline PFI engine since they would have similar torque, horsepower, and acceleration characteristics. The diesel engine would start with an average of 30 percent less fuel consumption compared to the 8-cylinder gasoline engine, but at a cost incrementally more than a fully optimized GDI engine. Accessory optimization could be applied to the diesel to gain an approximately 5 percent improvement in fuel consumption at relatively low cost.

Figure 10-4: CO_2 potential of advanced clean diesel compared to current diesel



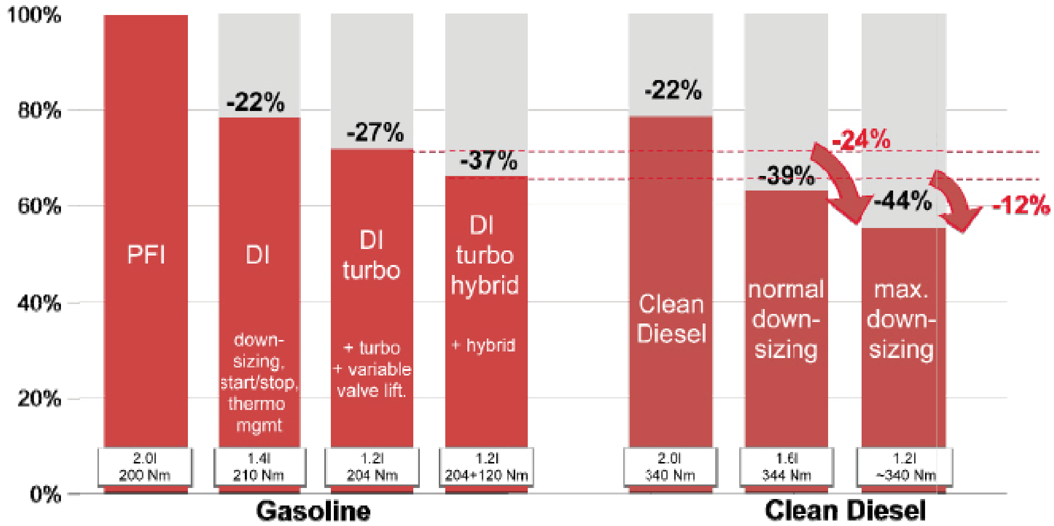
* Package is Optimized conventional combustion system. All data is approximate from Bosch internal investigation

A next step would be to move to advanced clean diesel technology, including start/stop with regenerative braking, combustion optimization, friction reduction, thermal management, additional downsizing, and downspeeding through the application of a longer gear ratio. This would reduce fuel consumption, compared to the base gasoline engine, by almost 50 percent. A further step for diesel vehicles would be to develop a full hybrid electric drivetrain that would deliver more than 50 percent improvement in fuel consumption, but would be the most expensive variant on this technology landscape. More details about the impact of technology changes on CO_2 reduction are detailed in Figure 10-5.

Dieselization

It is well documented that a modern, clean diesel engine offers 20 to 25 percent CO_2 reduction compared to a similar gasoline engine (Stewart 2008; see also Figure 10-6). At the same time as modern diesels have increased efficiency, they also have drastically reduced criteria pollutants, including particulate matter, hydrocarbons, and nitrogen oxides. These advances have resulted in recent launches of new clean diesel

Figure 10-5: CO_2 reductions in diesel and gasoline concepts



Note: Additional clean diesel mild hybrid potential is about 10 percent

vehicles in the United States, all of them meeting EPA Tier 2 Bin 5 and low emission vehicle (LEV) emission limits for all 50 states, the same emission level that most gasoline vehicles achieve. This is a technology available immediately and offers significant further improvement potential, making it an even more attractive choice for the consumer in the future.

The European Experience

After the signing of the Kyoto Treaty in 1997 (Global Warming Glossary 2008), the European Union (EU) took a different route than the United States to reduce CO_2 from the transportation sector. While the United States continued to focus primarily on the reduction of criteria pollutants, Europe shifted its attention to CO_2 reduction as well. Clean diesel technology has been playing a major role in this strategy supported by the early introduction of low sulfur diesel fuel and a structured fuel taxation system that favored diesel in most countries. The generally high fuel prices motivated many EU consumers to focus on fuel efficiency as a key purchase requirement for their vehicles. The European Union also had less stringent criteria pollutant standards than the United States.

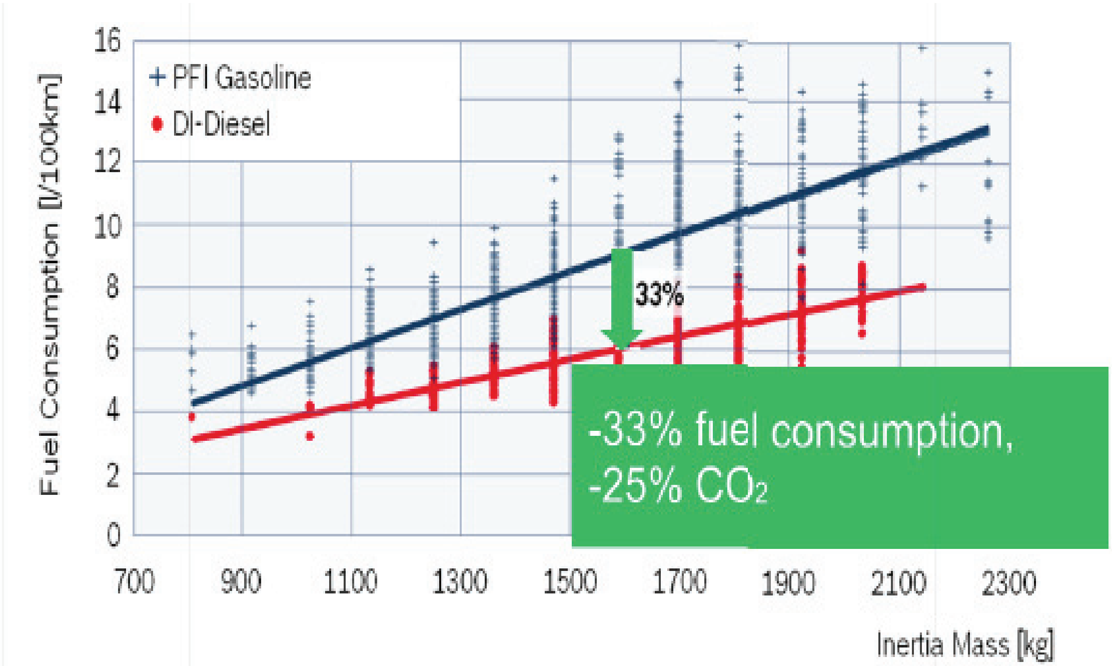
In 1997, automakers employed the newly developed common rail fuel injection system, enabling improved combustion systems and resulting in reduced criteria and CO_2 emissions, higher fuel economy, and increased engine power. Since then, the common rail system has continued to be developed, enabling automakers to offer vehicles that continued to improve performance and reduce GHG and criteria emissions.

The new vehicle market in Europe shifted rapidly to diesel vehicles in the latter half of the 1990s and first half of the last decade, reaching 50 percent of the market in the European Union by 2008 (*Green Car Congress* 2009). This change in basic engines resulted in the reduction of petroleum use and CO_2 reductions in new vehicles. The European Environmental Agency reported that from 1995 to 2004 the GHG emission rates of new passenger cars dropped 12 percent, although overall sector emissions increased due to higher vehicle miles traveled, a larger consumer vehicle fleet, and other factors (EEA 2006).

Zero Emission Vehicles and Life Cycle Emissions

Regulatory and industry attention has recently focused on zero emission vehicles (ZEVs), which eliminate GHG emissions at the vehicle level. A variety of ZEVs are in demonstration or pre-commercialization

Figure 10-6: The CO_2 reduction potential of diesel vehicles today



Note: Additional clean diesel mild hybrid potential is about 10 percent

phases, presenting regulators and early adopters with concrete examples of the potential of the technology. However, these vehicles are by far not yet cost competitive with traditional gasoline or diesel vehicles on the market.

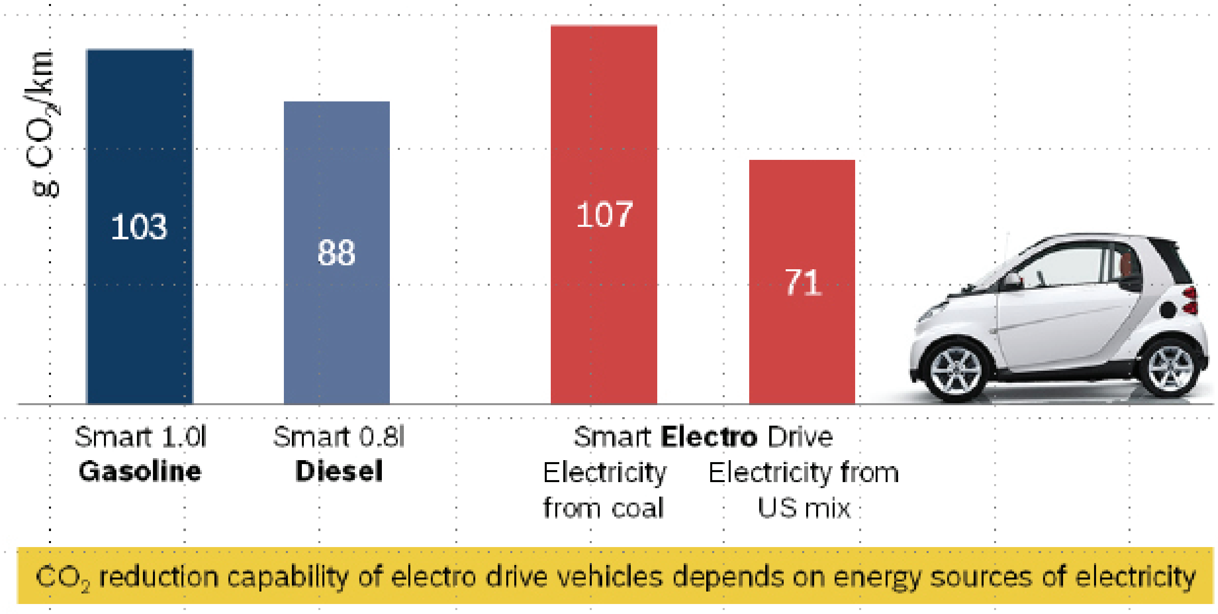
Another shift during recent years has been to take a broader view of these vehicles' emissions, encompassing the well-to-wheel emissions of the energy used as fuel rather than merely focusing on the emissions directly from a vehicle tailpipe. The impact of this approach can be seen from a comparison of the European versions of the Smart Fortwo car in gasoline and diesel engine modes and in a battery electric configuration, as shown in Figure 10-7. The full well-to-wheel GHG emissions of the gasoline Smart were calculated to be 103 grams of CO_2 per kilometer (km). Well-to-wheel emissions from the diesel car were found to be 88 grams of CO_2 per km. The well-to-wheel emissions from the battery electric Smart were even higher, 107 grams of CO_2 per km, when coal was the source for electricity generation, although they dropped to 71 grams of CO_2 per km if the average mix of the U.S. electricity generation was applied, and would be even lower based on California's electricity mix (ADAC 2008).

The conclusion from this exercise is that the energy source for electricity generation determines in large part the potential CO_2 reduction of a battery electric vehicle, while emissions from traditional gasoline and diesel vehicles are relatively fixed. Therefore, the expectations of CO_2 reduction from the deployment of electric vehicles must be analyzed along with the expected source of electricity to power the vehicles. California's Low Carbon Fuel Standard is a step toward establishing values for these upstream impacts. Another issue to note is that the CO_2 reduction gained shifting from one technology to another, whether it is gasoline to gasoline-electric hybrid or gasoline to diesel, will vary depending on the vehicle platform and powertrain.

Policy Conclusions

The examples cited in this chapter suggest that policies that promote a technology without considering elements such as the full well-to-wheel impact of emissions or real-world driving results can potentially fall short of their goal to reduce GHG emissions. Due to this and because of different driving needs

Figure 10-7: Zero emission is different from no emissions



Source: ADAC *Motorwelt* November 2008

of consumers, it is important to use all available technologies that contribute to GHG reduction now. Furthermore, a new technology can take a decade or more to reach market maturity and mass production, which is usually considered to be more than 100,000 vehicles.

The Toyota Prius HEV is a good example of this phenomenon. It was initially introduced in Japan in 1997, and brought to the U.S. in 2000 and to selected other countries shortly thereafter. It was not until the 2004 model year, however, that its annual sales passed the 100,000 unit mark on a worldwide basis. Sales in the U.S., its largest market, reached the 100,000 mark in 2005. Worldwide sales hit more than 280,000 in 2007, a decade after the vehicle's introduction.

Another factor to be considered is the behavior changes required by new technology. The Prius did not require significant changes for consumers in terms of refueling or driving habits to obtain its higher level of fuel economy. Behavioral changes will be required for many of the newer technologies expected to be introduced commercially during the coming decade, particularly electric vehicles. This presents a challenge to industry and should be taken into consideration by policymakers and regulators.

Automotive engineers are making rapid progress in developing and commercializing technologies to reduce GHG emissions. Further development and commercialization of diesel technology is one of the near-term opportunities. In the future, advanced gasoline and diesel technologies, possibly integrated into homogeneous charge compression ignition engines, allied with hybrid electric drivetrains, show even greater potential to reduce GHG emissions. These new technologies will take time to develop and will increase the cost of vehicles, thereby limiting their market penetration.

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