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Chapter 11:

Overview of Light-Duty Vehicle Fuel Economy Technology To 2025 and Policy Implications

by K.G. Duleep

The transport sector is a major contributor to greenhouse gas (GHG) emissions in the United States (U.S.), but the traditional methods of control, such as carbon taxes, do not apply to the sector, especially to the personal transport sector. This is because consumers are relatively insensitive to fuel prices and require very large increases in fuel price to change their buying preferences significantly. More direct methods using command-and-control regulations have been successful in the past, and the corporate average fuel economy (CAFE) regulations were widely viewed as a success in bringing more fuel efficient vehicles into the marketplace. As a result, fuel economy has become a focus of legislative activity in response to concerns about GHG-related emissions and high fuel prices. In 2008, the administration of U.S. President Barack Obama announced a plan to improve fuel economy (FE) by 40 percent over the next decade relative to the standards set for vehicles in that year, which implied a fuel economy standard for the combined car and light truck fleet of about 35 miles per gallon (mpg). More recently, the U.S. Environmental Protection Agency (EPA) and Department of Transportation (DOT) jointly announced standards approximately equivalent to 35.5 mpg for model year (MY) 2016 motor vehicles (NHTSA 2009).

Typically, FE standards are set by cost benefit analyses that equate the cost of technological improvements to vehicles to the benefits realized from fuel consumption reduction and allied benefits of reduced GHG emissions and improved energy security. Hence, good information on technology attributes to improve FE is essential to the regulatory process. Technology continues to develop at a rapid pace and periodic analyses are required to maintain an up-to-date list of technologies and their costs and benefits. ICF has provided the Department of Energy (DOE) with such periodic analyses based on interviews with the technical staff of major automotive manufacturers and Tier I suppliers of new technology around the world.

This chapter summarizes recent analyses of new developments in technologies to improve the FE of light duty vehicles (LDVs), including cars and light trucks, which will be available in the 2010 to 2025 time frame. Two specific points are relevant in the discussion. First, all technology benefits are referenced to the U.S. official test procedure for FE. Second, technology “cost” is defined as the cost to the consumer and more correctly referred to as “retail price equivalent” (RPE). This value represents the fully burdened cost with normal profit margins if a technology is produced at high volumes and the benefits of learning and scale are accounted for. Initial costs of introducing a technology at low production volume can be 40 to 80 percent higher than the RPE values referenced in this chapter.

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Engine Technology

While the popular press focuses much of its attention on battery and hybrid electric vehicles, manufacturer product plans show that improvements to the existing engine and drivetrain will continue to be a major focus of effort over the next decade. Both suppliers and automakers have shown new technologies capable of substantial improvements to vehicle FE, while continuing to use the basic spark ignition cycle.

In the conventional spark ignition engine, most driving conditions use only 5 to 15 percent of the maximum power capability of the engine, but maximum power is required under certain infrequently occurring situations, such as during hard accelerations or mountain climbing with full loads. As a result, the engine is usually operating at a highly throttled condition, and throttling loss and mechanical friction each use 17 to 20 percent of the energy generated by fuel combustion. The energy generated by fuel combustion is itself subject to the thermodynamic limitations of the Otto cycle. Hypothetically, reducing throttling loss and mechanical friction loss to zero would improve the fuel economy by as much as 40 percent, but this is not possible in real life.

Manufacturers are looking into two major types of technologies to reduce these losses. First, throttling loss can be avoided by being able to vary valve lift and timing. Variable valve timing (VVT) changes the times when the intake and exhaust valves open and close by camshaft phasing, and is already in widespread use. Variable valve lift (VVL) is used only by some automakers, notably BMW and Honda. BMW started its combined VVL and VVT system, called Valvetronic, on its higher end models, but now the technology is available on most engines. BMW has claimed that the system achieves a FE improvement of about 12 percent, but this includes the benefit of dual cam phasers and reduced friction (Kreuter *et al.* 2003). Subtracting these benefits, the VVL system is expected to yield about 8 percent FE improvement in high performance cars but only 6 to 7 percent improvement in average performance vehicles. This comparison is relative to a port fuel injected (PFI) engine with fixed valve timing and compression ratio. In addition, friction losses can be reduced by 10 to 15 percent, which can yield a 22 to 33 percent improvement in fuel economy.

A similar approach is used on larger engines where both exhaust and intake valves are disabled on some cylinders so that four of eight cylinders in a V8 engine run at a much higher load with reduced throttling loss (Albertson *et al.* 2003). The system is used in many General Motors (GM) and Chrysler V8 engines, but its use in six or four cylinder engines is more problematic, due to noise and vibration when running on two or three cylinders. Hence, VVLT and friction reduction may be the preferred approach for smaller engines in the future.

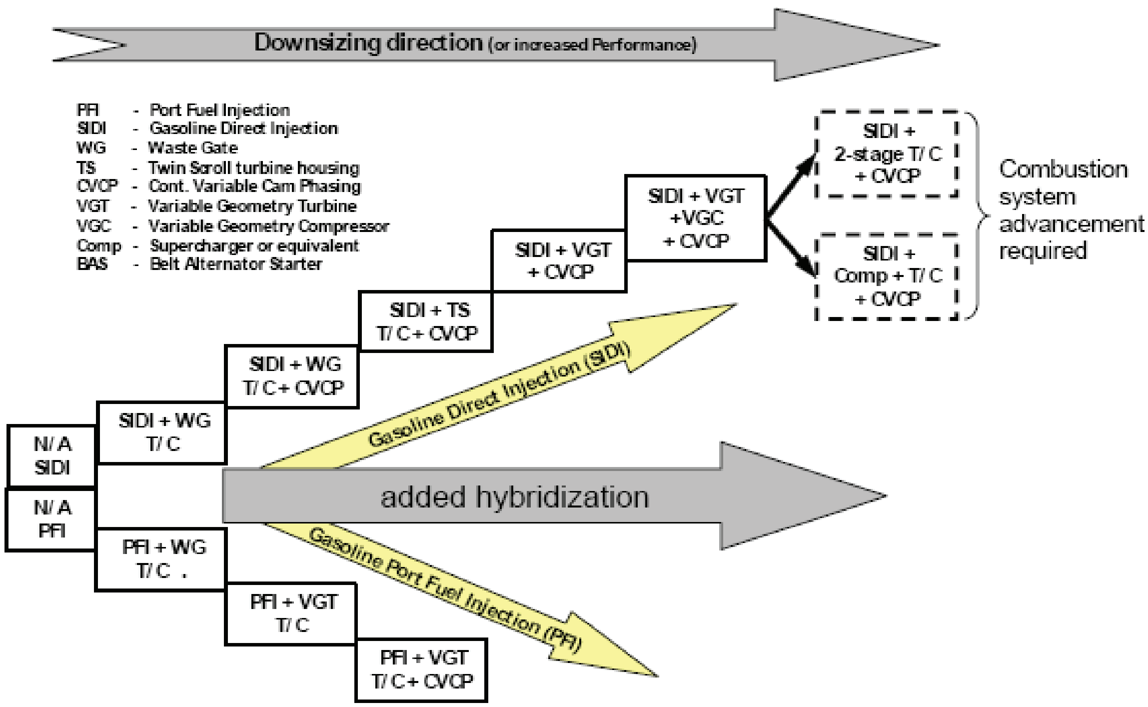
While VVL and VVT technologies have been around for some time, new attention has focused on using small turbocharged gasoline engines to replace larger engines. Turbocharged gasoline engines were introduced over 30 years ago to tepid market response since the small engines performed poorly at low speeds. A new technology, direct injection, is changing the performance map to make these engines more competitive.

Direct injection spark ignition (DISI) engines can be differentiated into the stoichiometric homogeneous combustion and lean stratified mixture combustion types. The stoichiometric DISI process forms a homogenous mixture by injecting fuel into the cylinder during the intake stroke and controls the fuel/air ratio in the same way as conventional PFI engines. These types of engines typically achieve fuel consumption improvements, among other effects, due to intake air cooling caused by fuel vaporization directly in the cylinder and the resulting opportunity to increase compression ratio, thereby increasing the thermodynamic efficiency of the cycle. The emissions are controlled by a conventional 3-way catalyst, and FE gains of 3.0 to 3.5 percent can be realized with a compression ratio increase of two points.

The latest generation lean-burn DISI systems control air/fuel mixture stratification in the cylinder by the spray formation of a centrally mounted injector, and therefore, are called spray guided. The air/fuel mixture formation takes place independently of gas flow and piston movement, and lean burn can increase the fuel economy of gasoline engines by 10 to 12 percent (Bosch). Stratified lean combustion has high costs due to the complexity of aftertreatment catalysts to meet stringent U.S. emissions standards. In the U.S. market, shifting spray-guided operation toward stoichiometric combustion over some parts of the driving cycle may offer a solution to the emissions issues.

Most auto manufacturers agree that DISI combined with turbocharging and VVT offers an attractive path for the future. Figure 11-1 provides a pictorial illustration of the downsized, or enhanced performance, and turbocharged engine pathways from GM's perspective (Grebe and Larsson 2007). The company has demonstrated that turbocharging and downsizing can be executed in numerous configurations and can be used for both PFI and DISI engines. The package with the most promising fuel economy improvement potential is DISI with variable geometry turbocharging and VVT. GM further argues that all downsizing and DISI turbo packages would work well with hybridization, since the turbo lag issue can be minimized with the electric motor power assist.

Figure 11-1: Pathways for future turbocharged engine evolution

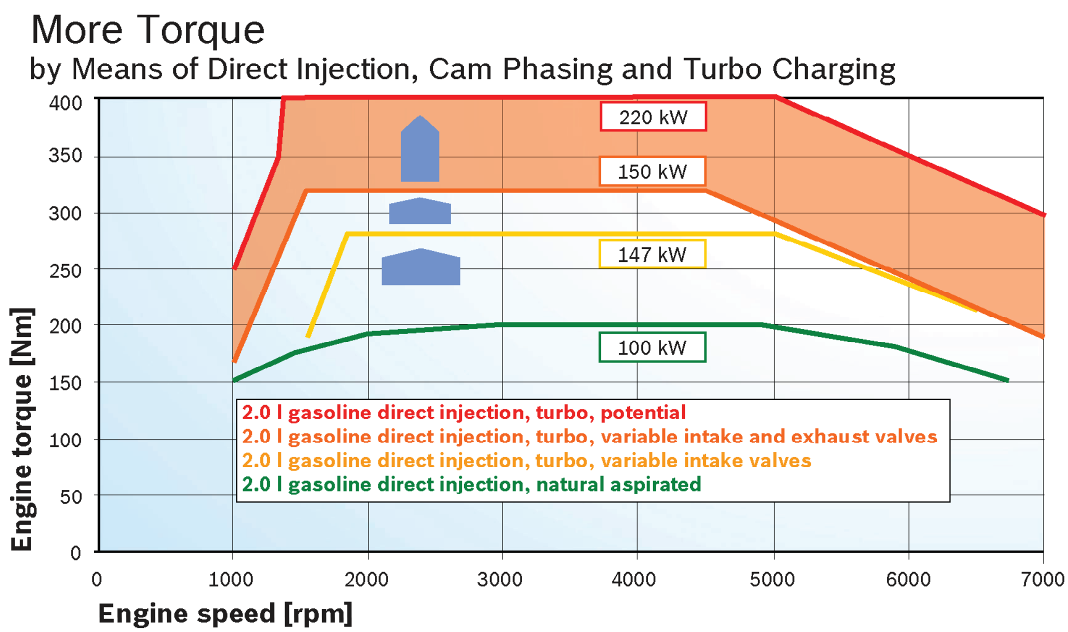


The ability to downsize the engine by one-third makes the turbo DI package particularly appealing from a cost viewpoint. A typical 3.5 liter V-6 can be replaced by a 2.4 liter 4-cylinder turbo DI engine, with the cost reduction from the engine downsizing offsetting much of the cost of the DI system and the turbocharger package. Similarly, a 5.2 liter, V8 engine can be replaced by a 3.5 liter V6 turbo DI engine with similar savings. The U.S., with its high concentration of V8 and V6 engines, is a good market for this strategy. The smaller engine also has lower levels of mechanical friction due to the reduced cylinder count. This strategy can provide roughly a 13 percent improvement in FE with the level of downsizing implied. The strategy is more difficult to execute starting from a smaller cylinder engine because of the noise and vibration issues with 3-cylinder and 2-cylinder engines, but this may become acceptable eventually.

Additional developments are likely to occur in the post-2016 period with the use of technologies such as twin sequential turbochargers and advanced combustion control with piezo-injectors for direct injection. As shown in Figure 11-2, current concepts (the orange line) have 1.5 times the output of naturally aspirated engines (the green line), while future concepts (the red line) can have 2.2 times the output, implying the potential to downsize engines by more than 50 percent with no loss in peak performance (Bosch).

Additional improvements in the post-2015 time frame are being shown in prototype form by automakers and suppliers. Engine developers have long been interested in camless valve actuation (CVA), since it promises as much as 20 percent improved FE over an engine with conventional mechanically operated valves. There is less assembly complexity, engine friction, and weight with camless design because mechanical camshafts and related parts are eliminated.

Figure 11-2: Engine and motronic system concepts

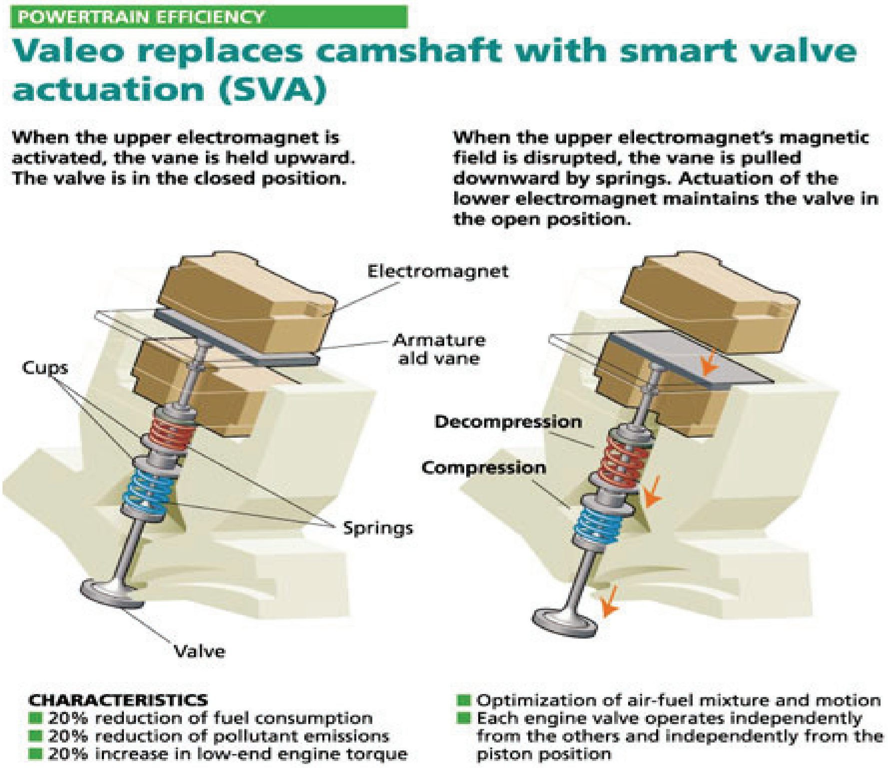


Camless valves could eliminate the conventional throttle and, as a result, reduce pumping losses. An example of such a system has been shown by a French supplier, Valeo. In Valeo's electromagnetic camless engine design, shown schematically in Figure 11-3, each valve is operated individually by an actuator that is placed on the upper surface of the cylinder head, directly above the valve guides (Durrieu *et al.* 2007). The individual actuators are linked to an engine-mounted valve control unit (VCU) that performs the power drive function. Each actuator is linked to an engine-mounted valve control unit (VCU) that performs the power drive function.

Valeo is developing two different systems, each one including actuators, the VCU, the wiring rail, and the electronic control unit (ECU) with the specific strategies dedicated to these new concepts. The first one is called full camless, since it manages the valves on both the intake and exhaust side of the engine. The second one is called half camless because it manages the inlet valves only. Valeo claims that the half camless engine would improve fuel consumption by about 12 percent, implying a 14 percent FE improvement, and provide 15 to 20 percent more low end torque than a conventional gasoline fixed valve timing engine. When cylinder deactivation benefit is included, implying that the exhaust valves must have a separate deactivation mechanism, the FE gain can be as high as 20 percent.

Another exciting development is a new form of combustion called homogenous charge compression ignition (HCCI). This type of combustion permits ultra-lean mixtures to be used without combustion stability problems and is sometimes described as bridging the gap between diesel-type droplet compression ignition and homogenous mixture spark ignition. Its appeal lies in the potential to attain diesel-like efficiency with very low emissions, but combustion control has proved difficult. Recent announcements by several automakers suggest that commercialization by 2020 is a good possibility (Yun *et al.* 2009**)**. It is quite possible that direct injection of fuel and camless valve control will be enabling technologies to achieve the

Figure 11-3: Valeo electromagnetic CVA design



desired level of combustion control. HCCI in combination with these technologies and friction reduction could ultimately provide a total gain of up to 28 percent in FE by 2025.

Table 11-1 provides a summary of mid-term and longer term engine improvement prospects in percent changes to fuel economy as well as the RPE in 2009 U.S. dollars for a four cylinder engine. As can be seen by the data in the table, the mid-term technologies offer gains that typically cost less than $40 per percent improvement in FE, but the longer term improvements are likely to be more expensive at $50 to $60 per percent improvement.

Table 11-1: Mid-term and longer term engine improvement prospects

Technology	*Near Term FE Benefit*	*RPE (2009 $)*	*Long Term FE Benefit*	*RPE (2009 $)*
Variable Valve Timing	1.5 to 2%	50 to 100	2 to 2.5 %	80 to 100
Variable Valve Lift	5 to 6%	150 to 250	6 to 7%	150 to 200
Camless Valves	11 to 13 %	400 to 500	15 to 17%	600 to 700
Direct Injection (DI)	2.5 to 3%	180 to 230	3 to 4%	160 to 200
DI – Turbo/ Downsize	11 to 15%	100* to 600	13 to 17%	100* to 600
DI Lean Burn	-	-	12 to 15%	900 to 1200
HCCI	-	-	18 to 20%	~1500
Friction Reduction	1.5 to 2%	20 to 40	3 to 4%	40 to 60

* with reduced cylinder count

Driveline Technology

While the engine improvements described above will be a major contributor to near-term fuel economy improvement, there is substantial scope for improvements in all other aspects of the vehicle that contribute to energy losses.

Transmission improvements include both the addition of more gears and the reduction of internal losses within the transmission. Adding more gears allows improved matching of engine operation to the vehicle power demand. While the majority of transmissions in the 2000 time frame were four-speed units, there is a major changeover to six-speed units that has already started. Technology breakthroughs in transmission design have allowed packaging a 6-speed transmission in the same general package size as a 4-speed unit with relatively low marginal cost, while providing a 4.0 to 4.5 percent gain in fuel economy, and the 6-speed unit is expected to be standard equipment in a majority of vehicles by 2012 (Schener 2003). Seven- and eight-speed units have appeared in luxury cars, but their marginal benefit over a 6-speed unit is small—in the range of 1.0 to 1.5 percent—so the 6-speed unit is likely to be the transmission of choice in mass market vehicles for the next decade (Konda *et al.* 2007).

The continuously variable transmission (CVT) is the logical extension to the increasing number of gears, but it has more internal losses than conventional gear-based automatic transmissions, so many manufacturers have not opted to deploy the technology. Others, notably the Japanese manufacturers, are more optimistic about the prospects for the CVT, especially in small cars, so increased penetration in the subcompact and compact segments appears likely (Vaughan 2007).

A notable competitor is the new double clutch transmission (DCT), which is the equivalent of having two manual transmissions in parallel. The manual transmission offers much lower internal losses relative to an automatic, largely due to the elimination of the fluid torque converter, but a problem results from torque interruption, due to clutch disengagement when the gears are shifted. The 6-speed DCT solves this problem by having one of the two parallel units engaged at all times, and is 33 to 44 percent more fuel efficient than the six-speed automatic (Matthes 2003). DCT units have become more popular in Europe, where the manual transmission enjoys high levels of market penetration.

Reductions in other driveline losses, such as axle friction and brake drag, are also likely through design improvements and better axle lubricants. The net benefits from these actions are small at 0.5 to 1.0 percent improvement in FE.

Weight, Drag, and Rolling Resistance

A reduction in power required to move a vehicle can be achieved by reducing the inertial and frictional components resisting motion. Smaller vehicles have better fuel economy because they have less weight, lower aerodynamic drag, and lower tire rolling resistance, but these reductions can also be achieved with improved technology.

Weight can be reduced without size reduction through the use of alternative materials, improved packaging, and weight conscious design. Although the industry has, over the last 25 years, shown very lightweight prototype vehicle bodies using aluminum or composite materials, very few concepts have actually made it into production. This is because of the high cost of alternatives relative to steel, and the need to develop new production processes to handle such materials. In addition, steel continues to improve, and new ultra-high strength steels have closed the gap in weight reduction potential so that marginal costs of alternatives per unit weight saving have increased.

Manufacturers expect that with intensive use of high strength and ultra-high strength steel and advanced design techniques most vehicles can have 5 to 10 percent weight reduction at relatively low costs of less than $1 per pound saved (EEA 2007). Aluminum has already achieved high penetration in the market for castings, such as engine blocks and transmission cases, and in applications, such as suspension members, where weight reduction brings additional benefits in ride and handling. Advanced composite materials are widely used in interior components, such as the dashboard, seats, trim, and in selected engine components like intake manifolds and valve covers, but have seen only limited use in exterior components or in load bearing structures. ICF does not anticipate weight reduction beyond the 5 to 10 percent forecast for most vehicles, although some vehicles like luxury cars may showcase more high-cost approaches with alternative materials.

Aerodynamic drag reduction can be achieved through design and styling changes, but, contrary to popular belief, does not require all vehicles to look like sports cars. Low-speed aerodynamic drag reduction requires attention to details like the airflow around the bumper and hood of the car and the wheel arches and controlling flow separation towards the rear of the vehicle. There are limits to drag reduction as measured by the drag coefficient, which is a non-dimensional measure of drag force. Car bodies may be limited to a coefficient of 0.22 to 0.24 without seriously impacting desirable attributes. This represents a 20 to 25 percent reduction from the current average levels of 0.30 to 0.32, although some models such as the Mercedes S-class are already at 0.25. Trucks are limited to even higher levels due to their boxy shape and higher ground clearance, but the percentage reductions possible from current levels are believed to be similar to that for cars (*Automotive Engineering* 2008).

Rolling friction is measured by the tire rolling resistance coefficient (RRC), which is also a non-dimensional measure of tire energy loss. The rolling resistance can be improved by changes to tire tread and shoulder design and changing the materials used in the tire belts and traction surfaces. The tire size and sidewall height also affect the rolling resistance of the tire, with larger diameter tires and shorter sidewalls reducing the rolling resistance (NAS 2006). The RRC for typical family cars is in the 0.007 to 0.009 range, but performance tires with high speed ratings and off-road tires have higher RRC values. While tires with RRC values as low as 0.005 are commercially available, such as the ones used in the GM EV1 battery electric vehicle a decade ago, the main issue has always been the tradeoff with other tire parameters that are desired by the customer. Tires are selected for vehicles based on a complex set of properties of which rolling resistance is one. The properties also include wear, noise, ride comfort, traction, and wet and dry braking. For a given tire size, the properties are interrelated and improving one results in some other property becoming worse.

Technological improvements to tires can simultaneously increase all desirable properties at some increase in cost. Tire manufacturers indicate that evolutionary design improvements and material technology improvements will continue to drive down average RRC by 5 to 7 percent per decade. Market trends to larger diameter tires with low aspect ratios may assist in lowering RRC further, especially if the trends towards higher speed ratings and better traction performance slow in the future.

The FE effect of these changes depends on whether the vehicle is re-optimized for constant performance. For example, reducing weight by 10 percent will improve FE by 4.0 to 4.5 percent, if nothing else is changed. If the engine size is reduced so that the vehicle still has similar performance, the benefit can be 6.0 to 6.5 percent. In the long run, the engine and drivetrain will be re-optimized for the new weight, drag, and rolling resistance to obtain maximum FE benefits.

Vehicle Electrification and Hybrid Technology

Accessories use 8 to 10 percent of engine output on the federal test procedure (FTP), but several technologies are available to reduce this demand. In the past, accessories were generally designed for low cost and good durability, and efficiency was only a secondary concern. For example, the typical claw-pole alternator is used in vehicles because of its low cost and good durability, but it has an efficiency of about 60 percent in converting shaft power to electrical power compared to other alternator types that can provide up to 90 percent efficiency.

Power steering pumps are somewhat different in that they operate continuously, but are needed infrequently. Electrical, as opposed to hydraulic, systems can save relatively large quantities of energy by eliminating continuous operation that wastes energy. Water and oil pumps also operate continuously independent of cooling or lubrication requirements, and moving to an electric drivetrain can save energy by providing the service on demand. Increasing the level of electrification can be part of a strategy to employ and store electricity onboard the vehicle to improve efficiency.

Engine stop/start technology, the first step in the hybridization process, is used to shut the engine off during idle and deceleration, which can provide a 3 to 4 percent FE gain (Bosch). While this seems to be a simple process, it is not easy to implement, especially in vehicles with air conditioning and automatic transmissions. The frequent restarts require a significantly upgraded starter, and the stress on the electrical system requires that the battery be upgraded to withstand frequent high current demand. The automatic transmission needs to be shifted to neutral and torque converter fluid pressure maintained to permit quick launch at restart, while a hill-holder clutch is required to prevent the vehicle slipping backwards with the engine off. Maintaining air conditioner operation with the engine stopped is difficult due to large power demand, but ingenious solutions like storing cold coolant can overcome short engine stoppage periods. As a result, such systems are more popular in Europe, where neither the automatic transmission nor air-conditioning has high market penetration.

The belt alternator starter (BAS) is the next step up the hybridization ladder. Here, the alternator also operates in reverse as a motor to restart the engine using the accessory belt drive. The alternator is more powerful than a starter motor, thereby permitting smoother restarts. It also allows capture of some braking energy (Itagaki *et al.* 2002). GM has introduced this system in several models, but market response has been tepid since its FE benefit is less than 8 percent. The availability of more electrical energy does permit the easier electrification of accessories discussed above.

Increasing electrical machine power output from the 3 to 4 kW of the BAS system to 10 to 15 kW or higher gives rise to the hybrid electric technology now employed in most hybrid electric vehicles (HEVs) marketed in the US. The Honda IMA system is one such design. It uses a single electric motor sandwiched between the engine and transmission (Hanada *et al.* 2005). The motor provides the start/stop function and also assists the engine during periods of high power demand, while recovering more braking energy. Operating solely with electricity is challenging, however, since the electric motor must also restart the engine when more power is demanded.

More sophisticated systems using two electric motors that provide all of the functions, including low to mid-speed electric drive, are represented by the Toyota hybrid synergy drive system and the GM two-mode hybrid design that typically feature electric motors with a combined output of over 60 kW (Nitz *et al.* 2006). The RPE of the Toyota system is estimated at $4,500 for a mid-size car in high volume production, while the Honda system is about half this price. However, the hybrid system includes a significant downsizing of the engine and the system can provide an additional 28 to 30 percent FE benefit for the Honda system and a 40 to 44 percent benefit for the Toyota system in comparison to a conventional vehicle of equal size and performance, with additional benefits from accessory electrification.

The Toyota Prius, for example, achieves almost 60 percent improvement in FE over a Corolla of equal performance, but it has numerous other technology improvements over and above hybridization. Some have argued that the IMA system provides a better cost-benefit than the 2-motor type system since it provides about 70 percent of the benefits for half the cost, but others believe that the drivability and feel of the IMA system is inferior to that of the 2-motor system.

The benefits of hybridization relative to conventional vehicle technology will not be degraded by 2020. Although some of the technology improvements for conventional vehicles are not applicable to HEVs, such as the improvements to transmissions or throttling at the intake valve, most others are. In addition, the electrical system efficiency will increase in the future, and increased battery capacity with reduced internal resistance will permit more of the operating modes to be all-electric. As a result, incremental FE benefits may actually increase in the short term, but stay at current levels even in the long term (Oba *et al.* 2004).

While the hybrid electric systems have demonstrated significant benefits in fuel economy, their high cost has limited market appeal to date. The Toyota system costs over $100 per percent improvement in FE, which is more than twice that of conventional technology improvements. Cost reduction of 25 to 30 percent per design cycle of seven to eight years appears possible and likely for both the Honda and Toyota type HEVs, which would make them cost competitive with conventional vehicles in the 2020 to 2025 time frame.

Plug-in Hybrids and Electric Vehicles

Plug-in hybrid electric vehicles (PHEVs) have received much attention over the last few years, and this technology is seen as one step on the path towards U.S. energy independence. Pure battery electric vehicles (BEV) have also enjoyed a renaissance, with several manufacturers announcing their intent to introduce a BEV model by 2012. Both these vehicle types have been made possible largely because of the development of the lithium ion battery, which now appears to be on the verge of commercial introduction as an automotive power and energy storage device.

The lithium ion battery actually refers to a number of different chemistries. In such batteries, the anode is typically made of graphite, while the cathode can be lithium alloyed with manganese, iron phosphate, nickel-cobalt, or other alloys. Each particular chemistry offers a different trade-off between energy density, safety, durability, and cost, but so far, no consensus has emerged on an optimum chemistry for automotive applications. Batteries maximizing energy storage or balancing power versus energy capacity currently have a cost of about $700 to $750 per kilowatt hour (kWh) of energy storage capability if manufactured in volume. This cost refers to the cost of individual battery cells, not the retail price. Individual cells are combined into a battery that features thermal and electrical management of the cells and ensures safety from both internal short circuits and external forces, such as a crash. The RPE of an entire battery is currently over $1,300 per kWh. Battery manufacturers seem confident of reducing cell costs to under $500 per kWh by 2015 and aim to cut costs by another 30 percent by 2020, which would reduce the battery RPE to about $600 per kWh.

A second major area of uncertainty in automotive use is battery life. There is little experience with lithium ion batteries under on-road conditions, and manufacturers appear confident of only an average seven-year life. By 2020, battery manufacturers hope to extend the life to 12 years or more to match the typical lifetime of a conventional car, but this is also not assured.

Converting a 2-motor, Prius-type HEV into a PHEV requires a considerable expansion of the energy storage capability. The current Prius model stores only a maximum of 1.3 kWh of energy, but the system does not allow extended all-electric operation. If the Prius were to have an all- electric range of 20 miles, it would require about 5 kWh of usable energy. Since battery life deteriorates by discharging toward empty or charging to 100 percent of capacity, five kWh of usable energy requires a battery of about 7.5 to 8.0 kWh capacity, which adds about $10,000 to the HEV retail price. In addition, cabin heating and ventilation systems must be redesigned to accommodate all-electric operation, which adds another $1,500 in RPE. Turning on the heat or air conditioning also has a large effect on all-electric range. The RPE increment could be reduced to about $5,000 by 2020. Such high RPE increments have been a matter of great concern to automakers. The energy efficiency of the PHEV would be similar to that of an HEV when the batteries are low, but it would be much more energy efficient as a BEV.

The two-motor PHEV operates in electric-only mode up to moderate speeds and acceleration rates. The engine is turned on during periods of high power demand or at freeway speeds. GM has developed another type of PHEV termed an extended range electric vehicle (EREV), which is similar to a BEV with a small battery and an onboard engine/generator combination to recharge the battery. The GM EREV has a 16 kWh battery and a claimed 40 mile all-electric range, and is capable of electric operation at all speeds and loads. Costs of such a vehicle are even higher than the PHEV. ICF estimates an RPE increment of $23,000 for a compact car assuming normal overhead and profit margins, or about $18,500 more than an HEV.

The pure BEV with a 100-mile range is technically possible, but still an expensive proposition. To achieve a 100-mile range in a compact car a battery capacity of about 24 kWh is required, and the 100-mile range is possible only without turning on the heating and air conditioning systems. On a cold rainy day, use of the defroster and heat and headlights along with reduced battery capacity may cut actual range to 50 miles.

The pure BEV battery is a little cheaper per kWh compared to a PHEV battery, but, even so, the RPE increase is quite large. With normal profit margins, a 100-mile range compact BEV would have an RPE of about $30,000 more than a conventional car, but this could decrease to about $20,000 by 2015, if planned cost reductions are achieved and volume production occurs. Recent comments by manufacturers about the 2012 models suggest that they will be pricing BEVs at expected 2015 levels rather than actual 2012 costs and lose money initially to ramp up sales volume quickly.

The BEV would have an energy efficiency of about 0.25 to 0.28 kWh per mile when calculated from the plug to the wheels. For larger vehicles, energy efficiency scales approximately inversely with vehicle weight. Typically, recharging at home with a 110 Volt outlet will take 8 hours or more, but this time can be halved when charging through a 230 Volt outlet. Specialized recharging equipment is now available to recharge the batteries in 0.5 hours or less, but the effect of such fast recharging on battery life is not clear.

Diesel Engines

The diesel engine is not new, but many new technological improvements to this engine could offer significant increases in FE. Diesel engines provide a 33 percent increase in FE at similar performance levels to gasoline engines (Scmidt 2006), and proponents point to its 50 percent penetration of the European market as a proven path to fuel efficiency. The diesel car in Europe has been helped both by the high absolute price of fuel and the lower cost of diesel fuel relative to gasoline, conditions that do not exist in the United States. In addition, more stringent emissions standards in the United States impose high aftertreatment costs, and the RPE of a four-cylinder diesel engine suitable for compact cars is around $2,300, while a V6 diesel engine has an RPE of about $3,300. This makes the diesel very similar in terms of cost and cost effectiveness to the IMA hybrid electric drivetrain.

The diesel engine has two issues to contend with in the U.S. that are not faced by the IMA hybrid or other gasoline-fueled hybrid electric drivetrains. First, the GHG reduction is much smaller than that for an IMA hybrid due to the fact that diesel has 12 percent more carbon content than gasoline per gallon. Second, diesels have struggled to meet the current California emissions standard and have only recently demonstrated compliance with existing regulations. Meanwhile, California has announced its intention to further tighten emission standards. The continuing uncertainty about future emissions compliance and cost, and the emergence of GHG emission standards as a constraint have affected manufacturer interest. Only the German car manufacturers offering diesel engine options now include them in U.S. product plans for the future. Diesels may yet emerge in larger trucks where the low-end torque and the durability of the engine are valued, but the prospect of high market penetration in the United States as in Europe seems unlikely now.

Forecast and Policy Implications of Technology

Table 11-2 provides a summary of the improvements possible to 2016 and 2025 from the technologies discussed when applied in a midsize car, starting from a 2008 baseline. These levels can be considered as the maximum that can be done in that time frame, since every make and model would have to be redesigned to include all available technology. The table shows that improvements to conventional technology can provide a gain of 33 percent by 2016 and up to 50 percent by 2025, and going beyond these levels will require increasing levels of hybridization. In reality, even these levels will require moderate increases in hybridization, since the pace of technological change is also a limiting factor, and not all products can include all technology by 2016.

Table 11-2: Midsize car technology improvements possible by 2016 or 2025

Technology	*Near Term FE Benefit*	*RPE 2009$*	*Long Term FE Benefit*	*RPE 2009$*
Engines	14 to17 %	200* to 800	25 to 28%	$1,100* to $1,700
Transmissions	5 to 7%	200 to 350	6 to 8%	$240 to $400
Weight, Drag & RRC Reduction	5 to 6 %	180 to 250	10 to 12%	$400 to $500
Electric Accessory Power	2 to 3 %	70 to 100	3 to 4%	$100 to $130
Idle Stop	3 to 4%	300 to 400	2 to 3%	$200 to $300
Total Conventional	**33 ± 3%**	**1,200*± 100**	**50 ± 3%**	**$2,300* ± 150**
IMA Hybrid*	28 to 30%	$2,300 ± 100	30 to 33%	$1,600 ± 100
Two Motor Hybrid*	40 to 45%	$4,500 ± 200	44 to 48%	$3,100 ± 200
Diesel Engine* (mpg)	32 to 35%	$1,800 ± 100	32 to 35 %	$1,800 ± 100

* includes credit for engine cylinder count reduction. Baseline is a 2008 midsize car with a 3L V-6 and 5-speed automatic. All values are increments to baseline.

Other analyses, such as the one by Kasseris and Heywood (2007) at MIT, have come to broadly similar conclusions, although there are differences in assumptions about individual technology improvements by 2030. They estimate that conventional technologies alone can increase fuel economy by 75 to 80 percent by 2035, partly because of a higher level of weight reduction and performance reduction assumed. Their analysis also points to a narrowing of the diesel benefit over gasoline engines by 2035, while they find incremental hybrid benefits to continue at current levels. The RPE for conventional technology estimated in a companion paper from Cheah *et al.* (2007) from MIT are similar to the ones in this chapter, at $2,650 for a midsized car compared to the ICF estimate of $2,300, although their estimate also includes costs for more aggressive weight reduction. Hybrid and diesel technology RPE are also quite similar, at about $2,500 and $1,700, respectively.

Economic considerations can determine how much and how far technology can be pushed, but the vehicle market presents some unique challenges. Even though vehicle life is about 14 years, manufacturers state that consumers do not purchase fuel saving technology unless the fuel saving offsets increases in vehicle first cost in about three years or less. On average a consumer drives about 40,000 miles in three years, and a midsize car with an on-road FE of 25 mpg will use 1,600 gallons of fuel. At $3 per gallon, fuel costs are $4,800. Hence, each 1 percent reduction in fuel consumption is worth about $48 to the consumer, and it appears that most of the conventional technology improvements to 2016 are within this cost/benefit ratio. Not coincidentally, the 2016 standards require about this level of improvement relative to 2008, so it does appear that the standards will be quite cost effective even from the consumer's perspective.

The two-motor type hybrid midsize vehicle will have an on-road FE of about 40 mpg and use $3,000 of fuel in three years for a saving of $1,800 relative to a conventional vehicle, but incremental vehicle costs are much higher. This explains the relatively low market penetration of HEVs to date. On a discounted lifetime net present value analysis with a 7 percent social discount rate, the HEV is cost effective as fuel savings are about $4,500, matching first cost increases. However, as conventional vehicles become more efficient, alternatives such as HEVs can be less cost effective, even if their costs are falling. For example, if the FE of the example conventional vehicles is improved by 40 percent to 35 mpg by 2020, fuel costs decrease to $3,400 and each additional percent reduction in fuel consumption is worth only $34 instead of $48, a reduction of 28.6 percent. If HEV costs decrease more than 30 percent over the next decade, as expected, its competitive position barely improves against the backdrop of improving conventional vehicles, making this level of cost reduction almost a requirement. Higher fuel costs and longer consumer valuations of fuel efficiency benefits will be required to change the market dynamics to expand HEV penetration without resorting to subsidies.

PHEV and BEV costs are so high in the near term that absent large subsidies, it is difficult to see any financial benefit to the consumer. The incremental price of a PHEV over an HEV in a compact car is about $10,000, and no amount of fuel saving can justify this amount to the consumer. Even with a subsidy of $5,000, the marginal benefit of the PHEV does not approach the increased price. The implication is that PHEV and BEV markets will be very small in the near term to 2015, and real market expansion must wait until 2020 or later, when battery costs have declined significantly and fuel prices could rise significantly. The BEV may succeed in niche markets, like urban commuter vehicles that are small with a range of about 50 miles, but previous attempts to sell these types of cars in the United States have not been successful.

Greenhouse Gas Reductions

In general, GHG emissions and fuel economy have an inverse relationship, so that the 40 percent increase in fuel economy planned for the 2016 period will result in a net reduction of GHG emissions by 28.6 percent, and reductions of approximately this magnitude from new light duty vehicles by 2016 seem assured with technology that is very cost effective to the consumer for the most part. GHG emissions from light duty vehicles will also be reduced by air conditioner improvements, and by the use of lower carbon content fuels.

The ICF analysis also points to difficulties in setting more aggressive GHG standards in the post-2016 time frame. Technologies become more expensive per 1 percent fuel savings, while lifetime absolute fuel savings become smaller as new cars become increasingly efficient. Hybrid electric technology appears to be cost effective on a lifecycle basis at $3 per gallon of fuel and could modestly improve its position to 2020 with anticipated cost reductions even with increasingly efficient cars.

Hybrid technology will likely be the focus of the next round of more stringent GHG standards for the 2016 to 2025 period, and could spur innovative ways of marketing or pricing HEVs to allow consumers to recognize lifecycle benefits instead of short-term benefits. Widespread use of hybrid technology with conventional technology improvements suggests GHG emissions from new light vehicles can ultimately be halved over the next two decades, while continuing to be cost effective to the consumer on a vehicle lifetime basis.

PHEV and BEV technology could allow further progress as economics improve, but it may be premature to judge these technologies. Over the next five to 10 years, understanding of battery costs and durability will improve, allowing better vehicle design decisions. This could help create cost-effective PHEV and BEV models as the next wave of technology improvements takes effect in the post-2025 period.

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