TECHNOLOGIES TO IMPROVE LIGHT-DUTY VEHICLE FUEL ECONOMY

DRAFT REPORT

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1 INTRODUCTION

EEA periodically updates the list of technologies and their attributes to account for continuing developments in technology, largely by holding meetings with the staff of the world's largest auto-manufacturers and the largest "Tier 1" suppliers. This documentation of technology characteristics is based on new data obtained by EEA from technology suppliers and auto-manufacturers in late-2005 on conventional technologies, and in 2004 on hybrid and diesel technologies

An overview of the analysis methodology is provided in Section 2 to permit comparisons of results from studies using different methodologies. Technologies have been grouped into several broad areas for the discussion in this report. Section 3 reviews the costs and benefits of spark-ignition engine improvement technologies, while section 4 reviews improvements in vehicle body and accessory related improvements, including weight reduction. Section 5 reviews potential transmission and driveline related improvements. Section 6 documents the costs and benefits of hybrid technologies updated from the findings documented in an EEA study completed in 2004, using publicly available data, while Section 7 documents diesel technologies.

2 METHODOLOGY

2.1 OVERVIEW

The analysis presented in this report relies on a technology evaluation methodology developed by EEA over the last 20 years./1 As part of this methodological development, EEA have reviewed reports or participated in studies that have included comprehensive analysis of technologies to improve fuel economy for light-duty vehicles.

It is important to present the methodology so that agreements and disagreements with the results from other studies are placed in the proper context. The consideration of future technology potential requires the assessment of each technology's "cost," and its benefits to the customer and to society. The term cost is one that can have many different meanings and needs to be carefully considered in the context of technology analysis. Benefits to the consumer and society can be measured in several dimensions, which can range from fuel savings, to improved vehicle drivability, to better utilization of space.

2.2 TECHNOLOGY COST AND PRICE ESTIMATES

The term 'technology cost' has created a considerable degree of confusion, as some observers have linked it to manufacturing costs, others to the retail price of the technology. In this analysis, the term 'price' has a very specific meaning, and relates to the incremental retail price effect due to technology adoption on a new car. This effect is measured as an average across new cars and is referred to the retail price equivalent (RPE) effect. The actual price effect on an individual car or light truck model may be higher or lower than the estimated RPE, but these price variations represent cross subsidies between consumers. For example, marketing strategies may require certain models to be priced lower than other technologically similar models to efficiently compete in the marketplace, but average price increment is the focus of this analysis.

The underlying concept behind the use of RPE is that in a highly competitive industry, economic theory states that manufacturers can only earn a ‘normal’ return on capital unless they possess proprietary technology or production methods. Most of the technologies considered in this report cannot be considered as proprietary. This also holds for production methods, although different companies can be more or less efficient in production. In a competitive marketplace, all manufacturers must price their product so that the average producer earns a normal rate of return on capital; more efficient producers can gain market share by pricing lower than average at the expense of less efficient producers. I have used a methodology that is based on a manufacturer's “expected” rate of return on capital which may be higher than the “normal” rate of return, (if sales volume goals are attained) due to the market not being perfectly competitive. The calculated price impact using this method may overstate the actual price impact in very competitive segments, but may understate the impact in segments with limited competition. It is also not directly applicable to luxury car manufacturers, where fixed costs are amortized over a much smaller sales volume.

It is important to note that the entire cost of a technology need not be allocated to fuel economy improvement if the technology affects other vehicle attributes. For example, fuel injection is used to provide emission reductions, with improved drivability and improved fuel economy. Attribution of costs is necessary for those technologies that are adopted primarily in response to other forces (e.g., emission standards) but also have fuel economy benefits. Technologies that affect horsepower and performance will, therefore, use an adjusted RPE that values the performance gain according to the market value for performance. For example, the RPE of four-valve engine is determined as an increment to a two-valve engine of equal performance, which translates into a comparison with a larger displacement two-valve engine.

2.2.1 Methodology to Derive RPE from Costs

In a competitive market, the average retail price of a technology bears a relationship to the cost of manufacturing. The term "cost" itself is not specific, as there are different types of costs. For the purposes of this analysis, the RPE evaluation utilizes an approach that includes the variable cost per unit of the component or technology, and the allocation of the fixed costs associated with facilities, tooling, engineering and launch expenses.[/2] The methodology has been utilized widely by U.S. Federal regulatory agencies.

The methodology utilizes a three-tier structure to the allocation of costs. A specific component, such as an electric motor or a turbocharger, is first manufactured by a supplier company, or by a division of the manufacturer that is an in-house supplier (e.g., Allison supplying transmissions to Chevrolet). The supplier part 'cost' to the manufacturer has both variable and fixed components; the variable cost is associated with materials, direct labor and manufacturing overhead. The supplier or divisional overhead is associated with corporate and administration costs, and the pre-tax profit is calculated as a percent of variable costs. Tooling Expense and Facilities Expense are based on amortization of investments undertaken prior to production, and includes the return on capital. Since in-house and external suppliers are treated identically in the cost calculation, RPE is not affected by the sourcing decision, which is consistent with the idea of a competitive marketplace for subassemblies. For many technologies in this analysis, the cost to the auto-manufacturer has been obtained from suppliers and is the starting point for our cost computation.

The second cost tier is associated with vehicle assembly, where all of the “components” are brought together. (For example, the stamping plant producing body sheet metal parts can be treated as a “supplier” for costing). Again, manufacturer overhead and manufacturer pre-tax profit are applied to components supplied to an assembly plant, plus assembly labor and manufacturing overhead. Fixed costs include the amortization of Tooling, Facilities and Engineering, and include return on capital. Note that the profit margins utilized refer to gross margins, and are not the net profit margins.

The final tier leads to the retail price equivalent, and involves the markups associated with transportation, dealer inventory and marketing costs, and dealer profits. Sales taxes are not included, but dealer and manufacturer margins are based on pre-tax profits.

This methodology does not lead to a fixed ratio or “multiplier” between cost and RPE, but is sensitive to the actual capital spending required at each stage as well as assumptions regarding the following variables:

- fixed cost spending distribution over time;
- return on capital;
- annual production capacity;
- amortization period.

Based on analysis of plant capacity by model, we have selected a plant capacity of 200,000 units per year as a "representative average" for automotive body related technologies. A typical model lifecycle is eight years, but there is a "facelift" at the midpoint in a model's product cycle so that the appropriate period for amortization of engineering expenses related to the exterior design is four years. Engine and drivetrain components usually have a longer lifecycle than vehicle platforms, ranging from 10 to 12 years. In general, there are no major changes to the engine block and heads over this period so that cost recovery over a ten-year period is appropriate. However, engines and transmissions can be modified and upgraded with add-on components such as variable valve timing during this period between complete redesign. Typical production capacity is 500,000 units per year for engines and transmission plants/designs. Calculations to derive unit costs assume operation at 85 percent capacity.

It should be noted that the purpose of this analysis is not to derive the total cost but the incremental cost of a technology relative to the existing baseline technology. The analysis therefore does not utilize the total variable cost or the total investment in a new technology, but the difference in variable costs and investment between a technology and the one it supersedes. In this context, the choice is not between continuing production of an existing technology whose investment costs may have been fully amortized versus a new technology, but between a new model with baseline technology versus a new model with new technology. This is a crucial difference that potentially accounts for the large differences between some public estimates of technology RPE and estimates presented here.

2.3 ESTIMATING TECHNOLOGY BENEFITS

A wide variety of technologies are available to improve fuel economy of automobiles. Auto-manufacturers can obviously choose any subset of the technologies discussed for adoption into their vehicles, and the number of combinatorial possibilities is large. The purpose of this analysis, however, is not to explore issues regarding which particular combination is most cost-effective or optimal from the market viewpoint, but to develop estimates for fuel economy improvement for vehicles adopting several of the technologies that can be combined into a single high technology vehicle.

A second and equally important issue is that manufacturers have the flexibility to vary the size, comfort, safety and performance features of any vehicle within fairly wide ranges. Even with this size specification, however, manufacturers have the option of varying body rigidity, interior volume (within limits), safety and luxury options, and acceleration performance. In the last decade, all of these have increased significantly for almost every market class of car and light truck. However, the forecasts in this report have been derived for a constant vehicle interior room and constant acceleration performance scenario. This is identical to the constraints used by most analyses, so that the estimates of technology benefits are comparable. Future changes to performance, size and weight can be accounted for explicitly using this method.

The analysis of individual technology benefits relies on three specific sources of information. First, the trade press, engineering journals and technical papers presented at engineering society meetings provide detailed information on the types of technologies available to improve fuel economy and the performance, when applied to current vehicles. Second, most of the technologies considered in this report have been introduced in at least a few vehicles sold in the marketplace, and actual test data on fuel economy can be used. Third, the world's largest auto-manufacturers have research and development staff with detailed knowledge of the attributes of each technology, and their inputs in an unconstrained situation can be used to estimate the benefits of technologies. EEA has typically used all three methods to the extent possible to provide robust estimates of technology fuel economy improvement potential.

When several technologies are combined in the same vehicle, the estimate of the combined effect of all of the technologies requires the ability to estimate the synergistic effects of the technologies acting together on factors affecting fuel economy. There are both positive and negative synergies, and in general, technologies with large negative synergies are not used together in the same vehicle for obvious reasons. EEA uses three different techniques to estimate these effects. First, there are several models being sold today in the world that feature many of the technology combinations of interest. Actual data from fuel economy tests of these vehicles provide the most defensible estimate of synergy effects.

Second, EEA uses an engineering model to estimate synergy effects. The engineering model used by EEA follows the work by GM Research Laboratory scientists Sovran and Bohn./3 This type of model used by EEA is known as a "lumped" parameter model and it allows the tracking of the various components of energy use and energy loss. The model ensures that the basic laws of energy are not violated and that benefits are not double counted. For example, the model has an explicit estimate of pumping loss associated with a baseline vehicle. As technologies reducing pumping loss are added to the baseline vehicle, pumping losses are progressively reduced with each successive technology having a smaller effect, and pumping loss is never reduced to zero.

Third, EEA examines results from other studies which use computer simulation models like ADVISOR or PSAT that solve the equations described by Sovran and Bohn, on a second-by-second basis. While this type of model has the potential to provide more accurate results, the main drawback is that it requires <u>a large number of inputs</u> to be specified. For example, modeling the benefits of a five-speed automatic transmission relative to a four-speed transmission requires not only the specification of all gear ratios but all the shift points as well as a detailed transmission efficiency map at all speeds and loads. Since the shift points need to be optimized for each engine and vehicle combination, it is not clear how an arbitrary specification of shift points for the model will deliver accurate results. Hence, the detailed model is superior only if all inputs are available from hard data; if many "guesses" have to be incorporated, it is not clear how accurate the results are. In contrast, EEA results are checked on the basis of actual vehicle comparisons, e.g., with a sample of vehicles having five-speed automatics.

REFERENCES FOR SECTION 2

1. EEA, *Automotive Technologies to Improve Fuel Economy to 2015*, prepared for the U.S. Congress Office of Technology Assessment, June 1995.

2. EEA, Documentation of Fuel Economy, Performance and Price Impact of Automotive Technology, prepared for Martin Marietta Energy Systems, July 1994.

3. Sovran, G. and Bohn, M., Formulae for Tractive Energy Requirements for Vehicles Driving the EPA Schedule, SAE Paper 810184, 1981.

3 SPARK IGNITION ENGINE TECHNOLOGIES

3.1 OVERVIEW

Improvements to spark ignition engine efficiency have the potential to improve the fuel economy by up to 25 percent. Engine efficiency can be improved by:

- increasing the thermodynamic cycle efficiency,
- reducing pumping and throttling loss during normal driving, and
- reducing internal friction losses from moving parts.

Many engine technologies can simultaneously affect two or all three of the above parameters, and combinations of multiple technologies can have substantial overlap in their fuel economy impacts. In the discussion that follows, all RPE and fuel economy benefits are referenced to a conventional 4-valve engine with fixed valve lift and timing.

In a broad sense, all of the available technologies to improve engines have been conceptually identified and understood for quite some time, but cost, mechanical, and (especially) high-speed computerized control design breakthroughs have made more varied applications possible. A relatively large number of improvements have been recently introduced in some vehicles or are in the pre-production stage of development.

Engine layout and base configuration affect the types of improvements possible and their costs and benefits. The OHV or ”pushrod” design is not used in passenger car engines except by GM and Daimler-Chrysler, although Ford, Daimler-Chrysler and GM engines of this type are used in several light truck models. All OHV engines available now use 2 valves per cylinder. The alternative single or double overhead cam (SOHC/DOHC) design is common and the vast majority of light trucks and passenger cars use engines of this design. Almost all of these engines use the 4-valve-per-cylinder head, with only a few SOHC V-8 engines offering the 2-valve cylinder head in model year 2006. Typically a 4-valve head provides a 10 to 15 percent benefit in maximum power and a 5 to 7 percent benefit in peak torque relative to a 2 valve head based on production engine specific output data. This can be translated to a 3 to 5 percent fuel economy benefit by downsizing the engine and adjusting the axle ratio to provide equivalent performance.

3.2 VARIABLE VALVE TIMING AND LIFT

Technology Description

Historically most spark ignition engines use fixed valve timing and lift. That is, neither valve timing nor lift changes with speed or load and operating parameters are generally set at levels that reflect a compromise between low speed torque and high speed horsepower. It has long been recognized that closing the intake valve early at light loads would significantly reduce pumping losses. Pumping losses, associated with throttling the airflow to achieve the proper part-load combustion charge in spark ignition engines, have a significant impact on the total efficiency of the engine. Reducing pumping losses increases fuel economy, since less engine power is lost in the intake process. Moreover, speed and load dependent (i.e., variable) valve timing and lift can enhance both low speed torque and high speed horsepower, without compromising either.

Variable Valve Timing (VVT) is also known as cam phasing. A single phaser installed on either the exhaust or intake camshaft can vary valve opening time relative to piston position. Some engine designs feature linked intake and exhaust cams varied by one phaser./1 Yet others utilize dual cam phasers for independent exhaust/intake valve actuation. In all cases, valve opening duration and valve lift is fixed by the cam profile. VVT is very common now and were used by all Toyota models sold in 2006, as an example.

Variable Valve Lift (VVL) technologies can be configured to make continuous variations in lift or make discrete valve height lift increments.[/2] These technologies can also be introduced either separately or in combinations, providing, in addition to reduced pumping losses, improved power output that permits engine downsizing and substantial fuel economy improvement. Honda's "intelligent" i-VTEC system is well known and combines variable timing control for the intake camshaft with a two or three step change in valve lift and duration. [/3] The system has been successfully expanded into the company's mainstream models.

BMW is the only manufacturer that currently (2007) offers continuous VVL-type system in the US market. Their system, called "Valvetronic" is designed to adjust the intake valve lift continuously and enables the conventional throttle unit elimination. Other manufacturers, such as Honda, Nissan and Toyota, are expected to roll out similar systems in the near future.

Analysis

The FE improvement potential and associated costs for variable valve timing and lift were assembled from the study of actual vehicles with these technologies, with cost data obtained from suppliers.

The latest information from suppliers and auto-manufacturers is that an oil pressure-based cam phaser, including controller and engine assembly, costs $35 ± 2. This is consistent with an RPE of $52 ± 2 for a single cam phaser. DOHC engines need two cam phasers, but cost savings is typically achieved by external EGR elimination (with a cost saving of $15 to 19) for the net cost of $53 ± 4. This translates to an RPE of $80 ± 4. For V block OHC/DOHC engines, costs are twice as high due to the need for separate phasers for each head but FE benefits are the same.

There is good agreement among auto-manufacturers, available studies and actual data on the fuel economy benefits of VVT mechanisms. For SOHC and OHV engines, the FE benefit of VVT is estimated to be 1.6 ± 0.3 percent, assuming the same timing change for intake and exhaust. For DOHC engines, intake only VVT has the same cost and FE benefit of 1.5 ± 0.3 percent. For DOHC engines with both intake and exhaust control, the FE benefit is estimated at 2.4 ± 0.3 percent. For all engines, VVT will provide 3 to 5 % improvement in low (1200 to 1500 RPM) speed torque and the fuel economy estimates listed assume transmission shift points are re-calibrated to take advantage of this benefit.

For the analysis purposes, we have considered the intake-only VVL system, such as the two lobe camshaft with a switching rocker arm system or a two step hydraulic lifter for OHV engines. Our information from suppliers suggests that the step lifter system for OHV engines costs around $90 for a V6 ($15 extra per lifter) with an additional $15 for the oil supply gallery and controls. Total cost with assembly is estimated at $125 for a SOHC V-6 (RPE $205). OHC systems or DOHC (with rocker arm) systems are estimated by auto-manufacturers to be more expensive due to its mechanical complexity with 4 valves, and we estimate total cost of $150 for a V6 and an RPE of $245. RPE values for 4 and 8 cylinder engines were scaled from this analysis.

According to a detailed study by Delphi engineers, the two-step VVL is most effective with cam phasers.[/4] The stand-alone VVL system is expected to return about 3 to 4 percent FE benefit with no low RPM torque improvement. The two-step VVL, in combination with dual cam phasers, can improve torque curve by 5 to 6 % across the RPM range. If the engine is downsized (by 5%) for constant performance, the FE benefit is expected to be in the range of 6 to 7 percent. Delphi engineers estimate is at 7.5% but auto-manufacturers believed that this was too optimistic for most engines.

Fully variable valve lift and timing (intake port throttling) has already been implemented by BMW, also other engine developers have shown prototype designs. One design by FEV-Mahle was estimated to cost $240 (RPE $400) incremental for an I-6. Suppliers indicate that this may be reasonable for the BMW design, but a V-6 implementation would cost about 15% more implying an RPE of about $460.The BMW engine is claimed to achieve FE improvement of about 11 percent but this includes the benefit of dual cam phasers. Subtracting the VVT benefits, the system is expected to yield the benefit of about 8.2%. However, other manufacturers recommended lower values since the BMW model on which the estimate was based had a relatively high power-to-weight ratio and BMW may have included the benefits of other improvements. Hence a 7.5 percent benefit is utilized as an average across non-luxury vehicle manufacturer estimates.

3.3 CYLINDER DEACTIVATION

Technology Description

In the early 1980s, General Motors produced the V8-6-4 Cadillac engine. The base V8 engine would operate in three distinct modes, during which 4, 6, or 8-cylinders were active depending upon engine speed and load. The engine was not well received by consumers because the transition between the various modes was not smooth. Additionally, reliability was insufficient for mass application.

Since that time, advanced electronic controls have significantly improved the technology performance and several manufacturers have re-introduced cylinder deactivation in mass-produced V8 and even V6 engines. Mercedes launched its S class 5.0 DOHC engines in 1999 with Lotus-supplied deactivation. GM is now using the Delphi-supplied pushrod-and-lifter “Displacement on Demand” system on V8 engines and has announced its introduction on the Vortec V6. DaimlerChrysler, which calls its system “Multi-Displacement,” offers cylinder deactivation on some US versions of its V8 Hemi engine. [/5] Honda has introduced the “Variable Cylinder Management” system on a V6 engine platform.

The new generation cylinder deactivation essentially turns a V8 or V6 into a 4 or 3 cylinder engine at light loads exhibiting the improved fuel efficiency of an engine that is of lower displacement due to reduced pumping losses. Cylinder deactivation/reactivation software and power train and exhaust system modifications have been improved to the point where the mode transition is virtually transparent to the driver. Some systems, particularly on smaller V6 engines, use noise-cancellation electronics and active engine mounts to smooth out harmonics generated by mode switching. As far as 4-cylinder engine is concerned, cylinder deactivation would impose significant loss in smoothness even with the current technology advancements and will likely be unacceptable to customers. Hence, cylinder de-activation is considered for use only with six and eight cylinder engines.

GM's implementation of cylinder deactivation is made relatively simple by virtue of their OHV engine architecture. Their "Displacement On Demand" system utilizes a series of computer controlled solenoids to selectively unlock specific valve lifters as needed. This has the effect of preventing the lift of the camshaft from being translated into lift at the valve, thereby deactivating the associated cylinders. By closing both the intake and exhaust valves simultaneously, a volume of air is trapped in the cylinder. Since no fuel is injected, this trapped air simply acts as a spring to help reduce the amount of work the engine has to perform. Since fewer cylinders are drawing air into the engine, the "pumping losses" of the engine are also reduced, thus improving fuel efficiency. [/6]

Daimler-Chrysler's Hemi V8 Multi-Displacement mechanical implementation is similar to GM's.[/7] The system also incorporates a decoupling mechanism in the valve lifter, which is actuated by oil pressure controlled by electro-hydraulic solenoid valves. One valve is used for each deactivating cylinder.

For overhead cam engines, such as those made by Honda, deactivation is accomplished by lifting cam followers away from the overhead shaft. Honda's V6 system deactivates the rear cylinder bank, effectively turning the transverse-mounted V6 arrangement into a three cylinder engine.

Earlier, many manufacturers considered cylinder deactivation as available technology only for larger displacement V8 engines. The technology was considered feasible for V6 engines, as long as the loss in transitional smoothness is handled by alternative means. The recent Honda and GM introduction of the V6 cylinder de-activation indicates that the problem was solved by using means such as Active Engine Mounts, as well as Active Noise Control, designed to create an opposite phase sound to increased engine vibrations.

Analysis

The data on test fuel economy from model year 2005 engines with cylinder deactivation systems, when compared to the same base engines without deactivation, show the fuel economy benefit of 7 to 8 percent (FTP cycle), with Honda's V6 lower due to comparison against base engine with VTEC. However, in all cases the benefit includes the benefit from low rolling resistance tires and the net FE benefit of cylinder cut-out alone is estimate to be between 6.0 and 6.5 percent. The Honda V-6 with cylinder deactivation when compared to an equivalent engine with fixed valve lift and timing implies an FE benefit of as much as 11.7 percent, suggesting that the dis-synergy with other pumping loss reduction technology has been overestimated.

Based on supplier input, cylinder deactivation cost for OHV engines is estimated at about \$15 per cylinder plus an additional \$15 in control system costs. Total cost for a V8 2-valve engine is \$135 (RPE of \$215), using these estimates.

Due to tighter packaging and mechanical complexity, cost for OHC V6 is estimated to be about \$150 (RPE \$250). The commercialized V6 cylinder deactivation technology by Honda comes equipped with active engine mounts, as well as the active noise cancellation technology.[/8] Manufacturer estimates suggest that engine mounts will add about \$60 and active noise cancellation could add \$80 in additional costs (net total cost of about \$290, or RPE \$430). However, it appears that future systems would be refined to the point where these active mounts could be replaced by more cost effective solutions, especially to reduce active noise cancellation technology costs. In the future, manufacturer comments on our estimates suggest that the RPE for a V6 could be reduced to \$300.

3.4 CAMLESS VALVE ACTUATION

Technology Description

Camless valve actuation expands upon the concept of variable valve timing and lift by completely eliminating the camshaft and mechanical valve actuation mechanism from the cylinder head. In place of the camshaft mechanism, the valve is actuated and controlled through either electrical or hydraulic actuators, and this can occur over a wide range of engine operating conditions.[/9]

Fully camless valve actuation would open new possibilities to achieve optimum valve lift and timing for maximum performance and optimized fuel economy. These engines would not need intake air throttling and can deactivate any number of cylinders as opportunity exists. While the technology has achieved various demonstration-level successes, the commercial applications are yet to be realized, although recent advances in computerized electromagnetic actuators offer renewed optimism.[/10]

Valeo, a major French automotive systems supplier, has made numerous announcements that the technology (SVA) could be on the market as early as 2009. Valeo is using the electromagnetic actuation design with each valve operated and controlled individually. The technology will be configured in two different packages. The first one is called "full camless" and is designed to actuate valves on both the intake and exhaust side of the engine. The second one is called "half camless" as it activates the inlet valves only.

Valeo's current plan is to commercialize the half-camless SVA, which would achieve around 80% of the benefits of a fully camless engine, at half the cost (described in the press to be about $400). The company claims that the half-camless engine would improve fuel consumption by about 12% (implying 14% fuel economy gain) and provide 15 to 20% 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 total efficiency gain can reach 17% (20% fuel economy). These figures were derived under laboratory test conditions, although Valeo did confirm this data on a test vehicle equipped with 2L I4 under European NEDC cycle conditions. The vehicle tests showed that when a transmission is optimized for the camless engine operation, the benefit can reach 19% (23% fuel economy).

Analysis

Camless valve actuation should be theoretically better than the BMW "Valvetronic" system in its ability to improve fuel economy but the energy loss in the electro-magnetic actuators counteracts some of the additional benefit over a cam-actuated system.[/11] It is not yet clear whether the actuators will have the claimed efficiency in production and the cost of a mass-produced system is still quite speculative.

The benefits of camless valve actuation depend to some degree on future research on combustion. At the very minimum, it can provide the same benefits as the continuous valve lift control mechanical system and can selectively cut-out cylinders as a function of load and speed. More sophisticated strategies could disable one or both intake valves, and even switch operating principles to say, Miller cycles or HCCI combustion. Of course, the actuation loss must be compared to the camshaft loss in conventional valve drives to obtain system benefits under any strategy. The basic strategy of intake valve throttling plus cylinder cut-out could provide 13 to 15 percent FE benefit according to FEV, a respected European engine research firm.[/12] Initial experiments suggest that HCCI combustion could approach the diesel-like efficiency.

A cost estimate from Eaton for an electro-hydraulic system at high volume production for a 4 cylinder engine is about $900 (RPE $1,600). Low volume initial introduction would likely add as much as $1,250 (RPE 2,250) cost premium. However, electro-hydraulic systems are not likely to be the first choice, and electro-magnetic systems could be in production earlier, which has some cost implications. TRW has a working system whose initial cost per actuator is estimated at $30, so that costs for an intake only system on a four cylinder engine will be $240 plus a controller cost of $60 to 75. This estimate is similar to Valeo's information. The cost figures translate to a retail price of about $400 to

600 for a four cylinder half-camless engine. Longer term costs at high volume could decline by 30% resulting in RPE values of about $300 to 400.

3.5 STOICHIOMETRIC AND LEAN BURN GASOLINE DIRECT INJECTION

The stoichiometric and lean burn gasoline direct injection engines are treated together in this report because of the commonalties in components used for both technologies. One of the primary benefits of the Gasoline Direct Injection (GDI) technology is that it facilitates lean burn. However, due to emissions and performance concerns, most current GDI engines operate at stoichiometric mode, while development continues toward more fuel efficient second generation lean-burn solutions.

Technology Description

A lean burn engine is designed to operate at a very lean (i.e., excess air) air-fuel ratio during light load conditions. Most modern gasoline engines are designed to run at a stoichiometric (i.e., just enough air for complete combustion) air-fuel ratio (about 14.7:1) to promote high efficiency three-way (i.e., simultaneous oxidation and reduction) catalyst operation, which is required to meet stringent emission standards. Lean burn engines mix more air with the fuel when full power is not needed, resulting in better fuel economy. The air-fuel ratio in conventional lean burn engines can be as high as 20:1, but emissions performance is compromised. When full power is needed, such as during acceleration or hill climbing, a lean burn engine reverts to a stoichiometric, or richer, air-fuel ratio.

The first generation lean burn GDI engines, also known as Direct Injection Stratified Charge (DISC) engines, are able to run at ultra-lean air-fuel ratios (up to 40:1) by using special injectors and in-cylinder airflow to produce a “stratified” charge in the combustion chamber. Tailored intake airflow combined with a “reverse tumble” flow pattern within the cylinder (promoted by specially shaped piston crowns), creates a layered effect (i.e., a stratified charge) of air and fuel in the cylinder. The mixture is rich in the immediate vicinity of the spark plug but progressively leaner with distance from the spark plug. This charge "shaping" facilitates ignition of the air-fuel mixture at *very* lean *overall* air-fuel ratios. The advanced air and fuel control features of GDI engines allow them to be operated at either stoichiometric (high load conditions) or lean burn (light load conditions) as required. This type of GDI system is referred to as "wall-guided" and Mitsubishi pioneered the approach. [/13] Any lean-burn engine will have problems meeting NO_x emission standards since conventional three-way catalysts, which are very efficient at reducing NO_x at stoichiometric air-fuel ratios, do not effectively reduce NO_x at lean-air fuel ratios. Lean burn is insufficient to meet Tier II emission standards without enhanced NOx after-treatment. The NO_x adsorber system capable of reducing NO_x from lean burn engines is still considered very expensive.

The first generation GDI technology advancements and market penetration should be examined from Japanese and European perspective because the engines were not marketed in the US. The first generation lean burn GDI has never reached predicted light duty gasoline share of as much as 25 percent by 2003 in Europe, largely due to customer dissatisfaction with real world fuel economy. Most current GDI engine production programs in Europe have moved away from stratified charge mode toward stoichiometric operation. The Volkswagen Group is marketing their FSI (Fuel Stratified Injection) technology in the US, although the engines are designed to operate at stoichiometric mode. Stoichiometric GDI eliminates the NO_x emissions issue and most developers have reported its engine-out emissions superior to that of conventional port injection engines.

The stratified lean burn development toward second generation models, however, continues, driven by significant fuel economy improvement potential. [/14] The current GDI development is moving toward increased injection pressures, multi-injection capability, and injector nozzle advancements so that the charge stratification is spray guided rather than wall –guided as in the first generation systems.[/15] Bosch, Siemens, Delphi and Denso are positioning themselves to supply the technology. [/16/17/18]

Analysis

Stoichiometric GDI is available in a number of European and US models. Analysis of the actual certification data from Europe shows that GDI provides 3.5 ± 0.5 percent increase in fuel economy at constant displacement combined with a 5 percent increase in torque and horsepower, which is not easily recovered as fuel economy. The fuel economy benefit is based on the ability to increase compression ratio by 1.5 to 2 points from a 9.5 to 10.0 CR base, and also from the reduction in cold start enrichment and acceleration enrichment requirements. Based on data provide by Bosch and Siemens, the cost of stoichiometric GDI systems is lower than anticipated due to the low cost of the injectors. New stoichiometric systems use "side injectors" that cost about $10 per injector more than the port injector. The high pressure pump and rail add about $50 for a six cylinder engine over the low pressure pump and fuel rail used in conventional engines while additional controls and injector drivers add another $10. Total system cost is estimated by EEA at $100 for a 4-cylinder engine, $120 for a 6-cylinder engine and $150 for an 8-cylinder engine. The resulting RPE values are $150, $200 and $250 respectively. All three manufacturers who examined the cost estimates stated that these numbers were reasonable.

Lean-burn systems cannot use the simpler side injector but must use a centrally mounted injector for spray guided systems. Because of the spray shape control requirements, Bosch believes that only the high performance piezo-actuated injectors can be used. These injectors will add about $40 per injector in cost relative to a port injector. In addition, the cylinder head requires modification to accommodate the central injector placement, with relatively high fixed cost. Finally, the system requires the use of a NOx adsorber which will add another $180 to 240 to total system costs (since the three way catalyst has to be retained for NOx reduction at high loads when the engine is operating at stoichiometric air-fuel ratio). Hence total system variable cost for a V-6 engine is as follows:

- Six piezo-actuated injectors: $240
- High pressure pump and rail: $35

– System controls	$15
– NOx adsorber	$210
– **Total variable cost**	**$500**

The fuel economy benefit was estimated by Bosch at 12 ± 1 percent. BMW has reported that their spray guided DISI can provide as much as 25% fuel economy gain while still providing about 5% power gain for natural aspirated downsized engines (comparison against 4-valve PFI). However, the requirement to redesign the head and uncertainty about the NOx adsorber costs and performance under in-use conditions make this an unlikely technology in the near term mass penetration for the US but possible in the post-2012 time frame.

3.6 TURBOCHARGING/SUPERCHARGING

Technology Description

Internal combustion engines reject 25 to 50 percent of the fuel energy into the exhaust. A turbocharger recovers some of this wasted energy, thereby increasing the power rating of the engine. The turbocharger consists of a turbine placed in the exhaust path, which drives a compressor in the intake manifold, compressing incoming air to the engine. The higher pressure of the intake manifold results in more air being forced into the engine, which therefore generates more power. A supercharger performs similar intake air compression but uses engine power rather than an exhaust turbine to drive the compressor. Current state-of-the-art turbochargers incorporate a variable geometry (VGT) feature that provides quicker boost at all speeds to maintain performance from downsized engines, especially at lower speeds where turbo lag can otherwise result in sluggish performance.

FE benefits due to turbo charging/supercharging result from the fact that engines can be downsized without sacrificing performance. However, actual performance and fuel economy impacts are dependent on how the turbocharger is “matched” to the engine. If the turbocharger is sized to provide intake boost at low RPM with some sacrifice in top-end power, fuel economy benefits over the EPA test cycle can be attained relative to a larger normally aspirated engine of the same power rating. High performance designs that maximize power from a given engine size may have poor low speed performance and very different fuel economy impacts.[/19]

In addition, the presence of the turbine in the exhaust stream adds to the thermal inertia of the system, so that catalyst warm-up is delayed. This has led to some emissions concerns at the very stringent Tier 2 standards, but the problems appear to have been solved through the use of close-coupled start catalysts and insulated exhaust manifolds.

Analysis

The fuel economy improvement data from actual vehicles over the last 10 years for turbo charging are relatively consistent on an equal torque basis, with an estimate of 7.0 ± 1.5 percent. The cost data are very variable and appear to be related to the issue of the credit for engine downsizing. New data from suppliers show the following costs for an engine in the 3L V-6 size range:

- conventional turbocharger at $180 ± 10
- intercooler at $ 65 ± 10
- engine upgrades for a 6-cylinder at $60 ± 5
- additional controls and sensors at $25 ± 3
- intake and exhaust modifications at $30 ± 5

The turbocharger and intercooler package total cost is about $360 ± 16 for a V-6, implying an RPE in the $560 to 600 range, while the RPE for a 4-cylinder engine is about $100 lower. A variable geometry turbo would add another $50 to 60 to total cost, or $80 to 100 to RPE. Hence a $800 RPE credit for downsizing from an 8-cylinder engine to a 6-cylinder engine will result in a negative cost of about $200 to a conventional turbo package, or about half that with a VGT. However, emissions concerns with a port fuel injection and turbocharger package suggest that most manufacturers will pursue the GDI/turbocharger combination discussed below. The engine can be downsized by about

35 percent, but the compression ratio must be reduced, so that the net fuel economy benefit is 7 ± 0.5 percent. If the engine size is not reduced, peak horsepower and peak torque increase by 40 ± 5 percent, but there is some fuel economy reduction.

A factor not considered by earlier studies is the combination of the turbocharger and GDI system. The combination is quite attractive because the compression ratio can be maintained at relatively high levels, and the turbocharger matching at low engine RPM can be improved, so that low end torque and turbo response lag are less of an issue. [/20] Bosch data shows that the engine can be downsized by 30 to 35 percent with no loss of acceleration performance. The fuel economy benefit with this level of downsizing is in the 12 to 14 percent range and the RPE of the turbocharger, intercooler and GDI package is estimated at $600 to 650. However, if a 4-cylinder engine replaces a 6-cylinder engine (3L V6 being replaced by a 2L 4-cylinder Turbo/GDI engine), then the cost can approach break even due to the engine cost savings. This strategy is being used in Europe to meet the aggressive fuel economy requirements mandated by the EU. Manufacturers commented that the strategy was reasonable for Europe, but they were unsure of customer acceptance of this strategy of reducing cylinder count in the US due to the prestige associated with a V-8 or V-6 option. In addition, this strategy is less applicable to cargo carrying light trucks, which may require very high levels of low speed torque for good launch feel.

BMW has shown that when the lean burn DI is combined with turbocharging, up to 22% fuel economy improvement and simultaneous power boost of as much as 50% is possible even with downsized engines. Other manufacturers, such as Renault and Audi, have reported similar or even higher fuel economy gains, when the expected next generation DI plus turbo technology and downsizing benefits are fully optimized for efficiency.

Supercharging provides less benefit in fuel economy relative to a turbocharger since the power to drive the supercharger is supplied from the engine output shaft. Its main advantage is the ability to provide instant boost at low engine RPM, but its power absorption results in a fuel economy penalty relative to the turbocharger, so that the net fuel economy improvement with a 30 to 35 percent reduction in displacement is about 5 ± 0.3 percent. Costs are about $50 lower than the basic turbocharged system. Supercharged systems have been available for over two decades in the US market, but their popularity has been limited to small high-performance market niches. The advantages of the supercharger are relatively small compared to a turbocharger-GDI combination even in the area of low RPM torque, and we anticipate that the latter technology will be dominant in the future.

3.7 VARIABLE COMPRESSION RATIO

Technology Description

Engine efficiency increases with cylinder compression ratio. The compression ratio of a cylinder is the ratio of the cylinder volume at the end of the intake stroke to the cylinder volume at the end of the compression stroke and reflects the degree to which the air-fuel mixture is compressed in the engine. The greater the compression, the more work performed. In gasoline engines, compression ratio is set as high as possible without encountering knock. Knock, caused by the spontaneous combustion of gasoline, is a function of the octane rating of the gasoline and can be very damaging to the structural integrity of the engine.

In standard technology engines, the compression ratio is fixed across all operating conditions based on cylinder geometry. However, the tendency of engines to experience knock varies with operating conditions. For example, at light loads, higher compression ratios can be tolerated without knock, but since the geometry of a standard engine cannot be varied it is not possible to optimize compression ratio for specific operating conditions. In addition, turbocharged or supercharged engines have reduced compression ratios (between 8 and 9) to avoid knock at high intake pressures. These factors result in fuel economy penalty (relative to higher compression ratio engines) at part load.

Some developers have announced engine designs that can vary cylinder geometry by changing the distance from the crankshaft centerline to the cylinder head. The technology was demonstrated by Saab, FEV and others. /21/22 Under this approach, compression ratio can be varied across a range as wide as 8 to 14. This allows the use of a small supercharged engine that operates at high compression ratio under low load, low boost conditions. Fuel economy benefits account for both the variable compression ratio effect across loads, and the ability to use a smaller engine to achieve identical performance. Another approach to achieve the variable compression ratio was announced by the US EPA. The agency has developed the concept that uses "piston within piston" mechanism to achieve two compression ratios by the effectively changing piston crown geometry.

Analysis

To date, the different variable compression ratio technologies have not advanced beyond the prototype stage. Considerable uncertainty exists regarding both the costs and benefits of this technology and its synergy with other technologies. Saab has been one of the leaders in developing this technology and claimed a fuel economy benefit of 30 to 35 percent, comparing a downsized and supercharged 1.6L engine with VCR to a conventional 3L V-6 engine, both engines rated at about 220 HP and 305 N-m of torque. EPA has worked with FEV on this technology and claimed a 15 percent improvement in fuel economy. Others such as VW suggest that the benefit is only on the order of 4 to 6 percent, although the specific reasons for the low estimate are not detailed, nor is the comparison baseline which may be a supercharged conventional engine. While Saab has not quoted any specific cost numbers, FEV analysis for EPA shows a $430 manufacturing cost for a V-8 while EPA estimates $330 cost for a V-6. However, the technology is still in the research stage and unlikely to be commercialized before 2015, if ever.

3.8 ENGINE FRICTION REDUCTION

Technology Description

The reduction of engine friction is an ongoing effort with continuing evolutionary improvements. The level of friction in an engine is measured in normalized terms as friction mean effective pressure (FMEP). A typical advanced OHV or OHC engine has a brake mean effective pressure at wide-open throttle of about 930 kPa and an FMEP of about 170 kPa. Major components that contribute to friction are, in order of importance, pistons and piston rings, valve train components, crankshaft and crankshaft seals, and the oil pump. Considerable work has gone into the design of these components to reduce friction and significant friction reduction technology is usually incorporated into modern engine designs.

A major opportunity in the valve train friction reduction is the use of roller cam followers. Industry testing has shown that the breakaway and sustaining torque necessary to rotate a camshaft is halved when roller lifters are substituted for conventional flat lifters. Roller cam followers are in widespread use on current OHV engines, but its use is less widespread with SOHC engines, and roller cam followers are not easily applied to DOHC engines. Various additional technologies are available to reduce engine friction. Among these are:

- low mass pistons and valves
- reduced piston ring tension
- reduced valve spring tension
- surface coatings on the cylinder wall and piston skirt
- improved bore/piston diameter tolerances in manufacturing
- offset crankshaft for inline engines
- higher efficiency gear drive oil pumps

Several technologies for reducing engine friction that are distinct from roller cam followers have been widely employed over the last decade or so. For example, lightweight pistons and rings with reduced tension were widely utilized in the late 1980s and early 1990s. Second generation friction reduction technologies such as lightweight valves, lower tension rings, improved bore/piston fit tolerances, and improved designs for the piston skirt and ring shape have also penetrated a considerable portion of the US fleet by 2000.

Over the last 20 years, auto-manufacturers have delivered total friction reduction of around 8 to 10 percent per decade, which is also the design lifecycle of most engines. About 20 to 25 percent reduction in FMEP is possible with further technology development at relatively low costs for engines that were redesigned in the 1996-2005 time frame, exclusive of the effect of roller cams. These technologies include dimpled pistons and piston rings (through shot peening), offset crankshafts for inline engines, piston coatings, and plasma metal sprays on cylinder bores. /23/24

Analysis

Recognizing that friction reduction is an ongoing process EEA has reported fuel economy and cost figures separated into four incremental technology sets, designated as Engine Friction Reduction I (EFR I) through Engine Friction Reduction IV. Roller cams are treated as a separate technology. These technology sets treat FMEP reduction in incremental steps equal to 7.5 percent age point reductions. The total available friction reduction (as FMEP) is 42.5 percent if roller cam follower technology is considered, or 32.5 percent if only the lumped as Engine Friction Reduction I through Engine Friction Reduction IV technologies are considered. This translates to 22.5 percent friction reduction for most engines except those that have not been redesigned since the early 1990s. Table 3-1 summarizes these technology definitions.

Table 3-1 EEA Engine Friction Reduction Technology Definitions

Technology	*Definition**
EFR I	10.0 percent reduction in FMEP
EFR II	17.5 percent reduction in FMEP
EFR III	25.0 percent reduction in FMEP
EFR IV	32.5 percent reduction in FMEP
Roller Cams	10.0 percent reduction in FMEP

> *Baseline FMEP is represented by an engine of early 1990s design vintage. By model year 2000, many engines have already been redesigned to Friction Reduction I levels and some to EFR II levels..

Table 3-2 summarizes the FE improvement potential and costs for EEA defined engine friction reduction technology in evolutionary steps. The cost range can be associated with 4 to 8 cylinder engines as a broad average. The estimate is that a 10 percent internal friction reduction translates to a 2 ± 0.2 percent FE improvement.

Table 3-2 Engine Friction Reduction FE Improvement Potential and Costs

Study		F/E Benefit (%)	RPE ($)
	EFR I	2.0 ±0.2	20 to 30
	EFR II	3.4 ± 0.2	50 to 75
	EFR III	4.8 ± 0.25	90 to 135
	EFR IV	6.1 ± 0.25	145 to 210
	Roller Cam	2.0 ± 0.2	16 to 32

3.9 IMPROVED LUBRICATING OIL

Technology Description

Lubricating oil actually serves several functions within an engine, including friction reduction, engine cooling, limiting wear on moving parts of the engine, and protecting against corrosion. However, it is primarily the effect of lubricating oil on engine friction that impacts fuel economy. The lubricating oil reduces friction in two ways: (1)The oil separates opposing metal surfaces to prevent contact (hydrodynamic lubrication) and (2) friction-modifying additives in lubricating oil alter metal surfaces so friction forces aren't as great when metal-to-metal contact does occur (boundary lubrication).

Two-thirds of the friction losses within an engine are estimated to occur during hydrodynamic lubrication and one-third during boundary lubrication or mixed hydrodynamic/boundary lubrication. New energy-conserving motor oils are designed to reduce friction losses from both types of lubrication by tailoring the viscosity characteristics of the base oil and the chemistry of the friction-modifying additives.

Engine lubricating oils are characterized into grades such 5W-20 or 10W-30. The first part of the grade (e.g., “5W” or “10W”) refers to the oil viscosity when cold (“W” signifies winter grade). The lower the number, the more fluid the oil at low temperatures. Oil fluidity affects engine starting ability, with more fluid oils making cold starts easier. The second part (e.g., “20” or “30”) refers to the oil viscosity when hot. The higher the number, the more viscous (less fluid) the oil at high temperatures. A second method of classifying oils is based on mineral versus synthetic composition. While synthetic oils offer more durability, the viscosity rating is one primary factor affecting fuel economy.[/25] Friction modifying compounds are the second major factor affecting fuel economy. Additional fuel economy related specifications for oils have been developed by ILSAC that has a GF-3 rating for fuel efficient oils, to account for all properties of oils.

Analysis

A number of papers from research staff at the auto-manufacturers have been published on this topic. Korcek and Nakada, research scientists at Ford, provided data on the benefits of 5W-20 and 0W-20 oils over 5W-30 oils in a 1995 paper. [/26] Data in the paper suggest that a fuel economy benefit of one to two percent is possible, although the range shown is large due to differences in friction modifiers between the different oil formulations. A more direct comparison of two commercially available oils with popular vehicles is found in the paper by Tseregounis and McMillan.[/27] The paper indicates that 5W-20 engine oils demonstrate 1.0-2.2 percent (average 1.5 percent) FE gains on the FTP over the 5W-30 oils with several GM vehicles.

Most concerns with lower viscosity oils are associated with their effect on engine wear. Tanaka et al.[/28] from Honda addressed these concerns. They studied the impact of using a 0W-20 oil enhanced with a relatively common molybdenum based friction modifier. In their study, they compare the 0W-20 oil to a standard 5W-30 oil, with the same additive blends, both for fuel economy benefit and engine durability. They conducted tests on a Honda engine and a Honda vehicle, and found an impact of 1.5 percent on FE with no significant difference on engine durability. Hoshino[/29] et al. (Ref. 4), researchers from

Toyota, found that the fuel economy of in-use engines can be improved by 1.5 percent on average using SAE 5W-20 oils containing friction modifying additives, when compared with the fuel economy achieved with conventional SAE 5W-30 oil without these additives. They also found that, in new engines, the fuel economy can be improved with the same SAE 5W-20 oil by 3.5 percent. An improvement of more than 1.5 percent was retained to 10,000 kilometres (relative to conventional SAE 5W-30 GF-2 oil). These tests were done on a Toyota vehicle with a 2.2L, 4 cylinder, DOHC engine using the FTP test.

Although a 1.5 percent FE benefit from the use of 5W-20 GF-3 oils appears defensible EEA has used a 1 percent benefit as a realizable average for using this oil relative to a 5W-30 or 10W-30. Costs are based on actual observed prices and are based on a discounted lifetime RPE assuming the oil costs $0.25/quart more than 10W-30 and the oil change requires 5 quarts replaced 24 times over a vehicle's lifetime.

3.10 SUMMARY FOR CONVENTIONAL ENGINE TECHNOLOGIES

Based on the information discussed in subsequent sections, Table 3-3 summarizes engine technology fuel economy and performance benefits. The baseline for the benefit estimates is a 4-Valve engine with fixed timing and lift unless specifically indicated otherwise. As a total, the turbocharged DI engine with aggressive engine downsizing or camless valve actuation provide similar FE benefits of around 14 to 15 percent that could be realized by 2016. In addition, engine friction reduction and the use of fuel efficient oils could add 3.8 to 5.2 percent FE improvement for a total of 18 to 20 percent from the engine alone.

Table 3-4 summarizes expected RPE increases for various engine technologies. The RPE values depend on the engine configuration and the number of cylinders, and the table summarizes data for most common configurations of engines, coupled with technology applicability.

Table 3-3 Engine Technology Benefits Summary

(all benefits are in percent relative to port fuel injected engine with fixed valve timing and 9.7 CR)

SYSTEM	CONSTANT ENGINE SIZE		CONSTANT LOW SPEED TORQUE * AXLE RATIO	
	FE BENEFIT [%]	TORQUE INC. [%]	FE BENEFIT [%]	ENGINE SIZE [%]
INTAKE CAM PHASER DOHC	1.4 ± 0.3	3.5 ± 0.5	1.5 ± 0.3	0
SINGLE CAM PHASER (SCP) - SOHC/OHV	1.6 ±0.3	3.5 ± 0.5	1.6 ±0.3	0
DUAL CAM PHASER – DOHC	2.2 ± 0.4	5.0 ± 0.5	2.2 ± 0.4	0
TWO STEP VVL	3.5 ± 0.5	0	3.5 ± 0.5	0
TWO STEP VVL + SCP	5.0 ± 0.6	6.0 ± 0.5	6.4 ± 0.6	-6 ± 0.5
TWO STEP VVL + DCP	6.4 ± 0.6	7.0 ± 0.5	8.0 ± 0.6	-7 ± 0.5
THREE STEP VVL + DCP	6.7 ± 0.6	7.0 ± 0.5	8.2 ± 0.6	-7 ± 0.5
CONTNUOUS VVLT	8.0 ± 1.0	10.0 ± 0.5	10.0 ± 1.2	-10 ± 0.5
CYLINDER CUT OUT	6.6 ± 1.0	0	6.6 ± 1.0	0
CYLINDER CUT + TWOSTEP VVL +SCP	10.0 ± 1.2	6.0 ± 0.5	11.2 ± 1.3	-6 ± 0.5
CAMLESS VALVE ACTUATION (em)	13.6 ± 1.5	12.0 ± 2	16.0 ± 2.0	-12 ± 2
DIRECT INJECTION (DI)	3.5 ± 0.5	5.0 ± 0.5	3.5 ± 0.5	0
DI +DCP	5.5 ± 0.6	10.0 ± 1.0	7.5 ± 0.8	-10.0 ± 1.0
TURBOCHARGING	-1.0 ± 0.3	37.0 ± 3.0	7.0 ± 1.3	-32.0 ± 2.0
DI + DCP + VNT (TURBO)	4.2 ± 1.0	40.0 ± 3.0	14.3 ± 1.2	-35.0 ± 2.0 (fewer cyl.)
ROLLER CAM FOLLOWERS	2.0 ± 0.2	0	2.0 ± 0.2	0
Engine Friction Red. I (1995+ design vintage)	2.0 ± 0.2	0	2.0 ± 0.2	0
Engine Friction Red. II (2001+ design vintage)	1.5 ± 0.1	0	1.5 ± 0.1	0
Engine Friction Red. III	1.5± 0.1	0	1.5 ± 0.1	0
Engine Friction Red. IV	1.5 ± 0.1	0	1.5 ± 0.1	0
Improved Lube Oil (5W-20)	1 ± 0.1	0	1 ± 0.1	0

Notes – all benefit estimates assume shift point optimization to suit changes to the torque curve.

Turbo-charged DI engine benefit in constant performance case assumes engine downsized from eight to six or six to four cylinders.

Table 3-4 Updated RPE Values for Spark Ignition Engine Technologies

Technology	**RPE ($)**			
	4-cyl	**I-6**	**V-6**	**V-8**
DOHC Variable Valve Timing (Intake)	52 ± 2	52 ± 2	104 ± 4	104 ± 4
Variable Valve Timing (Intake +Exhaust) SOHC	52 ± 2	52 ± 2	104 ± 4	104 ± 4
Variable Valve Timing (Intake +Exhaust) DOHC	80 ± 4	80 ± 4	184 ± 6	184 ± 6
Variable Valve Lift – Discrete (OHV-2v)	88 ± 6	130 ± 10	130 ±10	157 ± 13
Variable Valve Lift – Discrete (OHC-4v)	150 ± 8	200 ± 12	210 ±12	270 ± 15
Variable Valve Lift and Timing – Intake Continuous (DOHC)	330 ± 16	400 ± 20	460 ± 20	600 ± 25
Cylinder Deactivation	Na	170 ± 8 (+140)*	170 ± 8 (+140)*	215 ± 10
Camless Valve Actuation (short term ~ 2012) (long term > 2015)	 500 ± 40 400 ± 30	 700 ± 60 500 ±50	 700 ± 60 500 ± 50	 900±80 630 ± 60
Stoichiometric Gasoline Direct Injection	150 ± 5	200 ± 7	200 ± 7	250 ± 10
Turbocharging (with engine downsized)	500 ± 20 Na	560 ± 20 -500 credit	580 ± 30 -500 credit	660 ± 30 -500 credit
Engine Friction Reduction I	20 ± 2	25 ± 2	25 ± 2	30 ± 3
Engine Friction Reduction II	30 ± 3	38 ± 3	38 ± 3	45 ± 4
Engine Friction Reduction III	40 ± 4	50 ± 5	50 ± 5	60 ± 6
Engine Friction Reduction IV	55 ± 5	78 ± 7	78 ± 7	80 ± 8
Improved Lubricating Oil	16 ± 2	20 ± 3	20 ± 3	24 ± 4

* costs for noise/NVH control

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4 BODY AND ACCESSORY TECHNOLOGIES

4.1 WEIGHT REDUCTION TECHNOLOGIES

Technology Description

A principal determinant of vehicle fuel economy performance is vehicle weight. Lower vehicle weight reduces the forces required to accelerate the vehicle and maintain steady speeds, which in turn improves fuel economy. The principle vehicle weight reduction methods are:

- material substitution
- improved packaging
- downsizing
- unit body construction

Material substitution involves the use of advanced materials for vehicle systems, including high strength low alloy (HSLA) steel, aluminum, magnesium alloys, and plastics, in place of traditional carbon steel. This frequently involves the redesign of parts to optimize for strength with the new material or even redesign of the entire vehicle to optimize the new structure. [/1/2]

Packaging reflects the ratio of interior volume to exterior size and total weight. Improved packaging is estimated to be a zero variable cost technology. Although design costs are incurred, variable costs are potentially negative. Improved packaging is possible in all cars to some degree.

Downsizing reduces vehicle weight since it takes less material to make a smaller car. This process, however, does not conserve interior room and results in a loss of consumer utility.

Unit body construction refers to the elimination of the conventional chassis/body structure. A unit body utilizes the body panels themselves as stressed members to carry the structural load. By the year 2000, the majority of cars were manufactured with unit bodies. As far as trucks and SUVs are concerned, the current product trend have moved strongly toward unit body construction for compact and mid-size vehicles, or so–called crossover vehicles, while the full size trucks have retained the chassis/body configuration.

Analysis

There are some zero or low cost opportunities such as improved packaging and conversion to unit body architecture that are applicable to some specific models in the fleet. However, material substitution is the most widely applicable technology and the estimates of weight reduction are based on this potential. Weight reduction from material substitution has been broadly classified by material and vehicle part type. Broadly speaking, high strength low alloy (HSLA) steels, plastic composites, cast aluminum, forged aluminum and aluminum sheet are the materials most likely to be used in mainstream vehicles. Other materials, like magnesium and carbon fiber, are more likely to be used in very specific limited applications. Each of these alternative materials have specific advantages in different parts of the vehicle,

The issues surrounding material substitution are part specific and this analysis is a simple aggregation of definitive studies for a range of material/ part combinations. At one end of the spectrum, an aluminum intensive vehicle that uses all aluminum body-in-white, cast aluminum engine block/heads and transmission casing, forged aluminum suspension components and forged aluminum wheels, as well as light-weight composites for interior parts have been found by Ford and Audi to reduce total vehicle weight by 25 to 28 percent relative to a conventional steel vehicle with a cast iron engine, of about model year 2000 vintage. For a mid-size unibody SUV, this translates to total weight reduction of 900 to 1000 lbs. This figure includes the effect of secondary weight reductions associated with downsizing the engine, brakes, tires, etc as overall vehicle weight is reduced. Of course, any real vehicle will contain a mix of materials, and it should be noted that many vehicles already feature all aluminum engines, so that the net potential will be smaller in these cases.

In the absence of a vehicle model specific and material specific approach for the more generic study in this report, we have broadly classified weight reduction opportunities in terms of costs associated with 5 percent weight reduction increments. Data for these estimates were drawn from studies conducted for the Ultra Light Steel Body, the Auto/Steel Partnership, the Ford P2000 aluminum intensive unibody SUV project, and the Audi space frame A2., etc. The resulting estimates are shown in Table 4-1:

Table 4-1 Weight Reduction and Cost Estimates for Various Material Choices

(Based on EEA analysis prior to 2007 study)*

Weight Reduction	**Materials**	**Typical components**	**Average cost/lb. saved**
8 percent	Advanced steel	Frame, body-in-white	$0.30 ± 0.05
10 percent	HSLA, SMC, RIM	Body-in-white, closures, interior	$0.50 ± 0.10
15 percent	Above + Aluminum castings	Above + engine block, housings, wheels	$0.75 ± 0.15
20 percent	Above + Aluminum forgings, load bearing composites	Suspension, driveshaft, seats, bumpers	$1.10 ± 0.20

*-In 2007 EEA completed a comprehensive review of light duty vehicle weight reduction potential, as reported in the literature. The updated cost figures are currently being reviewed by the DOE/DOT.

The costs are expressed in dollars per pound saved and are a composite of part based cost data collected. Note that the marginal costs are much higher than the average costs so that the last 5 percent has a marginal cost of $2.15 per pound saved. The retail price equivalents are built from these material and processing costs (as opposed to finished sub-assemblies) and are approximately a factor of 2.1 higher than basic material costs.

The fuel economy benefit of weight reduction is well understood from theoretical and actual data. If the weight reduction is not accompanied by engine size reduction and re-optimization of the drive-train, the effect of a 10 percent weight reduction (at constant size and drag) is a 4.9 ± 0.2 percent improvement in fuel economy. If the system is re-optimized to maintain constant performance, the benefit is 6.4 ± 0.2 percent.

4.2 ROLLING RESISTANCE REDUCTION

Technology Description

Rolling resistance is a measure of the force required to move the tire forward. When multiplied by the radius of the tire, this force gives the resistive torque that must be overcome by the engine when the vehicle is in motion. The force to go forward is directly proportional to the load supported by the tire, and the ratio of the force to the load supported is called the Rolling Resistance Coefficient (C_R). The higher this coefficient, the more fuel is required to move the vehicle a specific distance. For passenger cars, the observed relationship is that a 6 to 8 percent reduction in rolling resistance produces a 1 percent increase in fuel economy. The C_R of a tire can be improved by tire tread and shoulder design, and materials employed in the tire belt and traction surfaces. [/3]

While tires with C_R values as low as 0.005 are commercially available (such as the ones used in the GM EV1 electric vehicle), 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. However, technological improvements to tires can simultaneously increase all desirable properties at some increase in cost.

The 1990s saw the introduction of tires utilizing a variety of new technologies that can reduce rolling resistance. Different tire companies are following different paths in pursuit of lower rolling resistance; the materials reformulation being implemented include the incorporation of silica mixed into SBR polymers. Goodyear has recently developed a line of tires that replaces carbon black and silica with a corn-based filler. [/4]

The shape of the tread and the design of the shoulder and sidewall, as well as the bead, are all areas that offer potential improvements in tire C_R. The type of material in the belts and cords can also have an impact. Aramid fibers have been used to replace steel cords and polyamide mono-filaments have recently been introduced as a replacement for polyester multi-filaments. These new materials can also reduce the C_R, and they can reduce tire weight, which provides secondary fuel economy benefits. Lessening the tread depth and making the tires less wide are all options that will offer fuel economy benefits, although these factors affect other desirable attributes such as durability and cornering ability.[/5/6] The large increase in demand for horsepower and luxury features in the 1990s led to significant <u>increases</u> in these other desirable attributes while rolling resistance essentially stayed constant.

The rolling resistance of tires are also a function of tire size, speed rating, aspect ratio and width. Until the recent study by the National Academy of Sciences on tires, there was inadequate data to develop statistically meaningful relationships between tire specification and rolling resistance. New data has shown that tire rolling resistance decreases with increasing diameter, decreasing aspect ratio and decreasing width.
The actual C_R levels of current OEM tires are not well documented, and the issue is further complicated as there are several methods for determining a tire's C_R. Anecdotal evidence from experts indicates that most normal (i.e., not performance oriented) tires have C_R values of between 0.006 to 0.009, as measured by the SAE J1269 method.[1] Performance tires used in luxury and sports cars, and often in high performance versions

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[1] The Society for Automotive Engineers (SAE) has defined a test procedure for measuring the RRC of a tire at 50 mph in the J1269 method. The newer J2452 method evaluates RRC over a range of speeds.

of family sedans, use tires which have C_R values of (SAE) 0.009 to 0.012. Light truck tires for compact van applications have C_R values of 0.007 to 0.009 while four-wheel drive trucks and SUVs feature tires with C_R values of 0.008 to 0.012. The large overlap is due to the diameter differences between tires in different applications.

Analysis

The historical data obtained form auto-manufacturers show that for a specific tire type, rolling resistance decreased sharply in the 1992 to 2000 time frame by about 15%, but the average annual rate of decrease since 2000 is only about 0.6 to 0.8 percent per year due to continuing technology improvements.[/7] If this rate continues to 2016, the total expected decrease is about 6 to 7 percent due to technology improvements. Under a regime of standards, it appears possible to reduce RRC by an additional 7 to 8 percent in the next 10 years by moving to larger diameter tires (which is happening to some extent due to styling) and to lower aspect ratio tires, without moving to wider tires or higher speed ratings. The net combined decrease will be on the order of 14 ± 1 percent. The recent NAS study confirms that each 10 percent decrease in RRC increases fuel economy by 1.5 ± 0.3 percent, so that the 14 percent decrease corresponds to a FE benefit of 2.0 percent. RPE values are expected to be around $5 per tire for the size and aspect ratio changes, and about $3 per tire for the technology improvement relative to OEM costs although consumer aftermarket costs are likely to be twice this value.

4.3 DRAG REDUCTION

Technology Description

The reduction of aerodynamic drag has the effect of reducing the load on the engine and hence improving fuel economy. Aerodynamic drag is a resistance force acting on a moving vehicle's surface areas caused by wind intensity and direction. It is a function of a vehicle's frontal area and body shape. The drag coefficient (C_D) is a measure of the streamlining of the body. The higher the coefficient, the greater the drag and the larger the car's frontal area, the greater the drag. Drag related power requirements are a cubic function of a car's speed through the air. Drag has a minimal effect at low speeds but a strong impact at high speeds, so that a reduction in drag affects highway fuel economy much more than city fuel economy. Twenty years ago, an average new U.S. car had a 0.48 C_D; in 2000 that figure was around 0.31, with the very best mass-produced vehicles achieving levels of 0.26. Pickup trucks and SUVs, with their boxy shape and high ground clearance, typically have drag coefficients that are 0.40 to 0.45, with vans typically having coefficients between 0.36 and 0.40. It is generally believed that each 10 percent reduction in drag is associated with about 2 percent increase in fuel economy, provided other changes are made to keep performance constant.[/8]

Aerodynamic drag cannot be reduced without affecting the styling characteristics of the vehicle. Since drag depends on body shape and frontal area, a change in drag characteristics can impact the vehicle's interior volume and its utility to the consumer. Streamlining of the vehicle's shape is subject to these limitations, as well as public acceptance of highly aerodynamic shapes. Prototypes have been manufactured with C_D levels in the 0.19-0.20 region, and their shapes do not appear to have radical compromises. For example, the 1993 Toyota AXV-V concept car offered reasonable back seat space and cargo room but achieved a C_D of 0.20. The car did have wheel skirts and an underbody cover, as well as being longer than a typical car. Removing the wheel skirts typically increases C_D by 0.015 to 0.02, which would leave the AXV-V with a C_D of 0.22. However, a complete underbody cover makes maintenance difficult, and providing cooling airflow to the engine, exhaust system and brakes is more problematic. This suggests that 0.22 is an optimistic estimate for C_D in 2020 for most cars. The underbody and wheel covers are expected to add 45 to 60 lbs. to curb weight, assuming they are manufactured from lightweight plastic or aluminum materials. This increased weight will decrease fuel economy by about 1.5 percent, and airflow requirements for the engine/brakes may impose other weight and cost penalties, so that reaching a level of 0.20 may not be useful. Auto manufacturers have generally agreed that a C_D level of 0.24 and 0.25 for cars is attainable without sacrificing consumer attributes.

The potential for C_D reduction in trucks is quite different. [/9] Pickup trucks with their open rectangular bed and higher ride height have relatively poor C_D; the best of today's two-wheel drive pickups have C_D values of 0.45. Four-wheel drive pickups are even worse, with large tires, exposed axles and driveshafts and higher ground clearance. Compact vans and SUVs can be more aerodynamic, but their short nose and box type body design restricts drag coefficients to higher values than cars. Manufacturers have argued that tapering the body and lowering their ground clearance would make them more like passenger cars and hence less appealing to consumers.

Analysis

Clearly the co-efficient of drag varies by body style and market intent. Based on conversations with auto-manufacturers, the following values are technically feasible in a 10 to 12 year time frame:

- Conventional sedan : 0.24 to 0.25
- Sports sedan/ coupe: 0.22 to 0.24
- Van/ Wagon : 0.32
- SUV (2WD/4WD) : 0.33/0.35
- Pickup truck (2WD/4WD): 0.37/0.40

These particular values correspond to approximately a 20 percent reduction in drag coefficient relative to the average vehicle in the category. It should be noted that a few 2005 models were approaching these values. For example, the Lexus LS sedan has a Cd of 0.26, while the Saturn Vue SUV has a Cd of 0.38. The fuel economy benefit for a 10 percent drag reduction is dependent on the absolute value of the drag co-efficient times frontal area, to some extent, Hence, it is lower for cars than for trucks and we estimate that cars with a Cd of about of 0.3 have a fuel economy sensitivity of 0.18 (i.e., a 1.8% increase in fuel economy for a 10 percent decrease in drag) while vans and wagons with a Cd of 0.36 have a sensitivity of 0.2 percent, while pickup trucks with a Cd of 0.45 will have a sensitivity of 0.22.

Cost estimates for drag reduction are largely associated with fixed costs of design and development, and improved assembly tolerances, as only a few external aids like spoilers are used. Based on an average of cost data gathered from auto-manufacturers, the unitized fixed cost per vehicle for a 10 percent drag reduction is about $20 ± 5, for an RPE of $28 ± 7. We have estimated from general manufacturer comments that the next 10 percent drag reduction will be more expensive and have somewhat arbitrarily increased the cost to $30 and the RPE to $42.

4.4 ACCESSORY IMPROVEMENTS

Technology Description

Engine driven accessories account for 8 to 10 percent of the fuel consumed over a typical driving cycle. The accessories examined in this report include: (1) the alternator, which provides electrical output for use in the engine, and lighting/comfort systems; and (2) the power steering pump which provides hydraulic pressure for steering assist and (3) the water and oil pump

In the past, the accessories were generally designed for low cost and good durability, but efficiency was a secondary concern. For example, the typical 'claw-pole" alternator has an efficiency of 55 to 60 percent in converting shaft power to electrical power, when compared to other alternator types that can provide 90± percent efficiency. It is used in vehicles because of its low cost and good durability. Power steering pumps are somewhat different in that they operate continuously but are needed infrequently. Electrical (instead of hydraulic) systems can save relatively large quantities of energy by eliminating this continuous operation that wastes energy. [/10] Water and oil pumps also operate continuously independent of cooling or lubrication demand, and moving to electric driven systems can save energy.

Analysis

The benefit of improved alternators on the test cycle is quite small since the alternator load is limited to engine operating requirements of about 600 to 900 watts. The smaller the engine, the greater the benefit since the alternator load is larger as a function of power delivered. Typically, for a four cylinder engine, using an alternator with an efficiency of 85 percent and including the use of "smart charging" of the battery, provides about 0.6 ± 0.2 percent improvement in fuel economy. The improvement is estimated by manufacturers to decline by about 0.1 percent for a six cylinder engine and 0.2 percent for a V-8. Supplier estimates of costs are about $10 to 12 more than the conventional alternator, equivalent to a RPE increase of $15 to 18.

Electric power steering with existing 14V systems is limited to on-road vehicles that are below 3500lb (Inertia Weight). Cost is estimated at $40 to $50 over hydraulic power steering (RPE of $65 ± 7) and FE benefit can be expected around 2 ± 0.2 percent, in vehicles with engines below 3L displacement. FE benefits on larger vehicles (engines above 3.0L displacement) are smaller, around 1.5 percent since the power steering pump uses a smaller fraction of total power, making it a less attractive proposition.

Electrically driven water pumps have received some attention recently since they offer some efficiency advantage and have the capability to reduce emissions during the engine warm-up phase after cold start. There are overall synergies with the use of an efficient alternator since more electrical power is available and the power is being produced more efficiently. Manufacturers have estimated that the total FE benefit for a V-6 engine was about 0.5 ± 0.1 percent at a cost of about $30 (RPE of about $50). Similar FE benefits were expected for other engine sizes, but costs for a 4 cylinder were estimated to be a little lower (due to smaller size electric motor and controller) and a little higher for V-8 engines. EEA has estimated costs to be lower/ higher by $5 for the two cases.

4.5 STOP-START SYSTEM

Technology Description

Stop-start systems operate by turning the engine off at idle and deceleration modes, and instantly restarting the engine when the accelerator is depressed. Such systems are not new, as VW marketed a system in Europe two decades ago. The initial systems were noisy and problematic, and fared poorly in the market. More study has shown that such systems need a much stronger battery and starter to withstand the repeated cycling in city driving conditions. In addition, cars equipped with automatic transmissions face special problems since the transmission must shift to neutral and the hydraulic pressure in the torque converter maintained with the engine off, while also maintaining "hill-holding" capability. Air conditioning units must also maintain some level of cooling capability while the engine is off.

New technology has recently enabled a re-launch of improved versions of this technology. Of course, all hybrid vehicles (described in Section 6 of this report) employ engine stop-start, and some of the developments in air conditioners and transmissions can flow down to this cheaper variant.

Analysis

Bosch has developed a new improved starter that pre-engages the flywheel when the engine is stopped so that the noisy engagement of the starter is eliminated. Together with an advanced VRLA battery and the control system that monitors state of charge and engine condition, the system represents a significant improvement over the original VW system. In conjunction with a manual transmission or automated manual transmission, the system cost is expected to be around Euro 100. Adding this to a vehicle with a conventional automatic upgraded with an electric hydraulic fluid pump and hill holder clutch, and using an air-conditioner with coolant storage is expected to double costs to Euro 200. Hence, the RPE of such a system will be \$350 and provide a fuel economy benefit of 4.5 ± 0.3 percent. Future improvements to transmissions may make some of these capabilities standard so that future RPE could drop to \$250. The system provides slightly less benefit in conjunction with a manual transmission.

4.6 CONCLUSIONS FOR BODY AND ACCESSORY TECHNOLOGIES

The costs and benefits of body and accessory technologies are more strongly dependent on the vehicle type, and hence the FE improvement and RPE forecast are specific to vehicle type and weight. The conclusions of our analysis are provided in Table 4-2.

Table 4-2 Fuel Economy Improvement and RPE Values for Body and Accessory Technologies

Technology	FE Benefit (%)	Cost [$RPE]
Weight Reduction by 5%	3.2 ± 0.1	0.62 per pound
Weight Reduction by 10%	6.4 ± 0.2	1.10 per pound
Weight Reduction by 15%	9.5 ± 0.3	1.60 per pound
Rolling Resistance Reduction by 10%	1.5 ± 0.2	20 ± 2
Rolling Resistance Reduction by 20%	3.0 ± 0.4	52 ± 5
Drag Reduction by 10%	1.8 to 2.2*	28 ± 5
Drag Reduction by 20%	3.6 to 4.4*	70 ± 7
Alternator Improvements	0.5 ± 0.2	17 ± 1
Electric water pump	0.5 ± 0.2	50 ± 5 (V6)
Electric Power Steering	2.0 ± 0.2	80 ± 5
Engine Off at Idle (Auto. Transmission & AC)	4.5 ± 0.3	350 ± 30
Engine Off at idle (Manual transmission)	4.2 ± 0.3	180 ± 20

*varies by vehicle size

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5 TRANSMISSION TECHNOLOGIES

5.1 OVERVIEW

Technologies that affect the efficiency of the transmission and drivetrain offer opportunities for significant fuel economy improvement. The following transmission technologies are examined in the report:

- Five to eight-speed automatic transmission
- Continuously Variable Transmission (CVT)
- Automated manual transmission
- Early torque converter lock-up
- Aggressive shift logic

5.2 FIVE TO EIGHT-SPEED AUTOMATIC TRANSMISSIONS

Technology Description

In both automatic and manual transmissions, increasing the number of gears can provide a wider ratio spread between first and top gears, which allows the engine to operate closer to its efficient optimum at a wider variety of speeds, thereby facilitating an increase in fuel economy. Alternatively, the increased number of gears can be used to increase the number of steps with a constant ratio spread which improves drivability and reduces shift shock. In addition, the wider ratio spread can be used to improve performance in the first few gears while keeping the ratio of engine speed to car speed in top gear constant.

The Five-speed automatic is already a transmission of choice for many vehicles, especially ones equipped with more powerful engines. Six-speed automatic transmissions have been available for a few years in luxury cars and are transitioning into the mainstream market. [/1/2/3/4]

More recently, Mercedes and Lexus have unveiled seven-speed[/11] and eight-speed automatic transmissions in their "top end" luxury vehicles. Mercedes is marketing the 7-speed AT, 7G-Tronic, since 2004. The transmission was derived from a 5-speed AT design with the front single planetary gear set replaced by a Ravigneaux planetary gear set with add-on multi-disk brake.

The new transmission was first used by the Mercedes S-Class. Depending on the driving cycle, the fuel economy improvement was reported from 6.5 to 12.2%, when compared to 5-speed-equipped vehicle. In addition to wider gear spread advantage, DaimlerChrysler indicated that fuel economy was improved through improved lubricating fluid, reworked controller and shift schedule. The transmission was designed to enable gear skipping during rapid downshifting. The torque converter lockup was designed to be active in all forward gears.

Toyota/Aisin has developed a new 8-speed automatic transmission commercialized on the Lexus LS. The 8-speed was developed from Aisin's 6-speed AT which is based on a Leppelletier gear set. In order to obtain 8 forward speeds the Leppelletier set was connected to a Ravigneaux geartrain. The new transmission was designed to achieve fuel efficiency improvement through the extended fuel cut, higher top gear ratio, expansion of the neutral control operation range during idle and expanded lockup. The result of these improvements is that the 8-speed AT used on Lexus LS460 improved fuel economy by 6.5% (US combined) compared to 6-speed on older LS (comparison at constant 4.6L V8). Also acceleration performance was improved substantially.

Analysis

Since the five-speed transmissions have been available for over a decade, there are many vehicle models whose measured fuel economy can be used to estimate the benefits. However, the fuel economy benefits are usually in the 2 to 3 percent range, making it difficult to isolate the benefit from test data variability. Toyota makes both rear wheel drive and front wheel drive 5 speed units and has claimed a fuel economy benefit of 4 percent relative to a four speed unit in both cases.[/1/2] The 5-speed transmissions also have improvements to the torque converter, so that the net improvement in fuel economy from the wider ratio spread and increased number of gears is estimated to be in the 2.5 to 3 percent range relative to a 4-speed transmission. At the same time, acceleration performance is improved by 10 to 15 percent (reduction in 0 to 60 mph acceleration time). Many other analyses have also found fuel economy benefits in this range and we have selected an improvement of 2.5 ± 0.3 percent as representative. Many independent suppliers such as Aisin, ZF and Borg-Warner produce 5-speed units and information from them suggest a cost increment of $130 ± 15 relative to a 4-speed unit (about 200$RPE).

Six speed units have recently become very popular due to a technology breakthrough by a French engineer, Lepelletier. His invention has made it possible for the 6-speed unit to have fewer parts than the 5-speed, weighs less and have smaller internal losses. Data from transmission suppliers indicate that six speed units with the Lepelletier gear set are only $120 to $140 more than four-speed, virtually identical to the cost increase of a five speed. These costs indicate a $205 ± 15 RPE increase. Publications by transmission manufacturer ZF [/3], whose six-speed unit is used by several auto-manufacturers indicate a fuel economy benefit of 5 to 6 percent, but this figure includes benefits associated with a idle in neutral control. The new GM-Ford six speed[/4] is claimed to have a 4.5 percent fuel economy benefit which is consistent with the adjusted ZF estimate. In addition, acceleration performance is boosted simultaneously.

Mercedes has recently reported that lower-end fuel economy gain, 5-speed AT versus the 7G-Tronic, is about 6.5%, which is identical to Toyota's reported gain for the 8-speed versus 6-speed. Mercedes fuel economy gain does include other transmission improvements, such as improved lubricating oil, reworked controller and lockup schedule.

Lexus information indicates that the gear ratio spread increase with two additional gears contributes about 40% of the total fuel economy gain, or about 2.6% (0.4 x 6.5%). Other fuel economy gains for Toyota's design were associated with a new controller, which achieves additional fuel economy benefits at idling, a reworked torque converter and an expanded fuel-cut envelope.

Inputs from transmission suppliers suggest that additional costs for 7 and 8-speed are about $30 per additional gear over the 6-speed, which translates into an RPE of about $50 per additional gear.

5.3 AUTOMATED MANUAL TRANSMISSIONS

Technology Description

An automated manual transmission (AMT) is differentiated from the manual version on which it is based because it does not require clutch actuation or gear shifting by the driver. These functions instead occur by means of a hydraulic system or an electric motor, with the help of electronics. The mechanical connection between selector lever and transmission is eliminated and the transmission is controlled electronically via shift-by-wire. This offers more options when designing the gear selector than with conventional mechanical shifting systems. With the shifting implemented by algorithms in the transmission control unit, an AMT can execute gearshifts automatically and is considered a replacement for a conventional automatic transmission.

Compared to an automatic transmission, the advantages of the AMT include the ability of the manufacturer to use existing manual-transmission manufacturing facilities to achieve lower production costs as well as greater efficiency and lower weight. Improved fuel economy results from the elimination of automatic transmission torque converter losses and the programming of optimum shift points. An existing manual transmission can be modified into an AMT by "adding on" the components for automating the shift. However, the expense for automation can be considerable; a substantial amount of components are necessary to compensate for the omission of the clutch pedal and mechanical connection between the shift lever and transmission.

Due to the additional components, automation adds about 10 percent to the weight of a manual transmission, but this still equates to a weight reduction compared to a conventional automatic. Two disadvantages of a single clutch AMT are reduced shift comfort compared with conventional automatic transmissions, and an interruption of traction during shift actuation. The latter results in vehicle deceleration during shifting in full automatic mode. These disadvantages may be not be severe in replacing a manual transmission with an AMT, but are considered as unacceptable for replacing an automatic. In this context, the new double clutch system provides a level of shift quality comparable to modern automatics but is considerably more expensive than a single clutch system. [/5]

The AMT was first brought to market in 1996 in the BMW M3. Since then the technology have not expanded in the US, as anticipated, although it has seen higher penetration rates in Europe. The Volkswagen/Audi Group is one of the technology leaders in the US. Their AMT design, called "Direct Sequential Gearbox – DSG®", is available on many models and is a double clutch design with 350N-m input torque capacity.[/6]

VW has announced that a brand new transmission was developed for the DSG® AMT family, the 7-Speed AMT. The transmission has torque capacity of 250 N-m, so it will be used in compact models and perhaps lower power version of the Passat.

In addition to a higher gear ratio spread, the new transmission features a "dry" clutch design (hence the reduced torque capacity). The new clutch reduces internal losses substantially since the cooling oil drag is eliminated. Other reported design benefits include gear ratio change for better drive-off performance and cruising and decreased controller power consumption.

The new 7-speed AMT achieved substantial fuel efficiency improvement even compared to the already competitive 6-speed AMT. VW's data shows that, under NEDC cycle conditions, the 6-speed AT fuel consumption is 5 to 15% higher when compared to 6-speed manual transmission. The 6-speed AMT fuel consumption performance is basically the same as the manual transmission, although under certain conditions, the AMT can achieve 5% fuel consumption reduction but also up to 3% penalty can be realized. The new 7-speed AMT is claimed to have fuel consumption advantage across the board, 7 to 12% better than the 6-speed manual.

Cost estimates for the new transmission are not publicly available but the fact that its application is targeted for subcompacts in Europe, such as Polo, suggest that the costs must be competitive with the older 6-speed AMT. By eliminating the clutch cooling oil circuit, VW removed parts such as suction filter, oil cooler and pressure lines. Also the dry clutch design allowed decreased transmission oil requirements from 7 to 1.7L. The shift mechanism was simplified so that 7 speeds can be controlled with four actuators. The result of these modifications is that the 7-speed AMT weight decreased to 73kg (compared to 80kg for 6-speed AMT). Also transmission size was substantially reduced.

Analysis

The benefits of the six-speed double clutch AMT should be similar to that of the conventional 6-speed automatic with the additional benefit of torque converter loss elimination. Based on data from ZF, the six speed AMT fuel economy benefit is estimated to be 7 ± 1 percent benefit over conventional 4-speed automatic, with 2.5 percent of the benefit due to torque converter elimination. AMT system costs are stated to be competitive with conventional six speed unit for the model used by VW. Available cost data suggests the use of $130 ± 10 as a cost estimate and an RPE of $210 ± 15 for the double clutch AMT.

VW has shown that further AMT speed number increase can result in an additional fuel efficiency benefit of up to 10% (7-speed versus 6-speed AMT). While this large benefit is yet to be demonstrated under FTP conditions, EEA feels that AMT separation into discreet 6-speed AMT and 7-speed AMT technologies might be warranted. The discussion above indicates that 6-speed versus 7-speed automatic transmission fuel economy difference is about 1%. EEA expects that similar AMT speed number increase should deliver at least a similar benefit due to gear ratio spread increase. More precise fuel economy difference should be confirmed when these new transmission models are introduced in the US market.

5.4 CONTINUOUSLY VARIABLE TRANSMISSIONS

Technology Description

Most current transmissions feature a discrete number of gear ratios (usually 3 to 6) that determine the ratio of engine to vehicle speed. This results in some loss of flexibility in matching the engine speed/load condition to vehicle requirements. A Continuously Variable Transmission (CVT) offers an infinite choice of ratios between fixed limits, allowing optimization of engine operating conditions to maximize fuel economy. In a CVT, varying "gear" ratios are created by means of a variator, with axial repositioning of a conically shaped pair of discs between which a chain or belt transfers torque. [/7] Limitations on the belt stress result in the CVTs being limited in their torque transfer capacity. The trend toward greater performance in small cars and the development of higher-torque diesel engines have sharpened the design focus on overcoming the CVTs torque limitations.

Most first-generation designs used wet or magnetically actuated clutches for the startup element, though many newer designs use hydrodynamic torque converters. Other differences compared with earlier CVTs lie in the design of the oil pump, variator, and hydraulic control unit, as well as placement of shafts. Newer designs are more efficient and easier to package relative to first generation designs. [/8]

Although CVTs have been around for a number of years, their application tends to be in lower-horsepower vehicles and overall marketing results appear to be mixed. GM discontinued the CVT used on the Saturn programs,[/9] while Ford used it on the Ford Freestyle and Five Hundred models. Audi offered it on the A4 line.[/10] Nissan is the only manufacturer to offer a full CVT lineup for small, medium and large class passenger vehicles, including the Murano crossover SUV with 3.5L V6.

Analysis

CVT technology is now better understood for use in conjunction with larger engines, where the fuel economy gains are somewhat reduced from the gains with smaller engines. However, there continues to be a divergence of views on the actual fuel economy benefit with some manufacturers (notably Nissan and ZF) claiming benefits of about 9 to 10 percent, with others such as Ford claiming much smaller benefits of about 5 percent. Some of this divergence is potentially due to the differences in CVT design with respect to internal losses, and some due to calibration, drive "feel" and engine noise issues.

Based on EPA certification data, the fuel economy benefits are in the order of 7.5 ± 0.5 percent based on the transmission which was used on GM Saturn Vue with a 2.2L 4 cylinder engine. If the CVT is used with a wet clutch instead of a torque converter, the FE benefit increases to 10.5 ± 0.5 percent in small cars. One new model in MY2007, the Nissan Versa, is sold in trim levels with either CVT or 4-speed AT with otherwise identical specifications. The fuel economy benefit of 5% is realized compared to 4-speed AT, although the CVT-equipped model is slightly heavier. Based on this data, the 7.5 percent fuel economy figure fall in the middle of the figures reported.

Auto-manufacturers interviewed stated that costs for smaller CVT models for use with 4 cylinder engines was about $150 while it increased to almost $240 for CVT models capable of handling a 3.5L V-6. This translates into an RPE of about $240 for smaller CVT units for four cylinder engines (1.7 to 2.5L displacement) and an RPE of $ 380 for

CVT units capable of handling V-6 engines from 3L to 4L displacement. In addition, the layout of the CVT makes it better suited to FWD cars with transverse engine mounting.

5.5 ELECTRONIC TRANSMISSION CONTROL

Technology Description

Electronic Transmission Control (ETC) is part of an automatic transmission, which uses modern electronic control technologies to control the transmission. Electronic sensors monitor the speed of the vehicle, gear position selection and throttle opening, sending this information to the Electronic Control Unit (ECU). The ECU then controls the operation of the transmission shift points, and torque converter lock-up. These systems were first introduced in Toyota's A43DE transmission in 1982. Domestic manufacturers started introducing them in mid-1980s.

There are two fuel saving technologies, described below, that can be implemented by an ETC over and above shift point and lock-up optimization:[/11]

1. Aggressive Shift Logic (ASL) – Conventional shift logic is not optimal for fuel economy because the large power reserve maintained during accelerations results in significant throttling losses. To maximize fuel economy, the shift logic can be modified for earlier up-shifts. However, earlier up-shift result in some loss of drivability, and very early shifts are perceived negatively by consumers. With ASL, a greater throttle opening is required to maintain the same acceleration rate and throttling losses are reduced. The vehicle feels less responsive because the accelerator must be depressed further to achieve any particular acceleration rate. However, the benefits of ASL are limited by the fact that torque converter efficiency decreases as load on the engine is increased.
2. Early Torque Converter Lock-up – The benefits of ASL are limited by the loss in torque converter efficiency associated with accelerating the vehicle at higher engine load. Further increases in fuel economy can be achieved through implementing the Torque Converter Lock-up at an earlier stage.

Analysis

Both early lock-up and aggressive shift logic are not " technologies" in the sense of being a discrete improvement but are calibration related actions that have some negative drivability and noise, vibration and harshness (NVH) consequences. Hence the cost is associated with overcoming the NVH, while the benefits are estimated from simulation models. GM is known to have implemented aggressive shift logic on most of its mainstream models. All of the analyses available such as the one form the NAS and the estimate by AVL for NESCAF are reasonably consistent for early lockup and aggressive shift logic, and fuel economy values of 0.5 and 1.5 percent can be selected along with an RPE of \$5 and \$30 as a mean of the estimates for early lockup and aggressive shift logic, respectively. However, the benefit of aggressive shift logic is likely to have a lot of variability depending on the application, as will the cost.

5.6 CONCLUSIONS FOR SECTION 5

The FE benefits and the increase in RPE associated with the different transmission technologies are summarized in Table 5-1 below. It should be noted that all of the multi-gear transmission technologies offer simultaneous improvements in acceleration performance (in the order of 5 to 15 percent reduction in 0 to 60 mph acceleration time), improved shift quality and more relaxed cruising at highway speed relative to current four-speed transmissions. In contrast, early lock-up and aggressive shift logic result in modest increases in NVH and slightly worse drivability.

Table 5-1 Fuel Economy Improvement and RPE Values for Transmission Technologies

(all figures compared to Four Speed Automatic)

Technology	Performance	FE Benefit [%	$RPE Increase
Five Speed Automatic Transmissions	Improved	2.5 ± 0.3	200 ± 10
Six Speed Automatic Transmissions	Improved	4.5 ± 0.3	205 ± 15
Seven speed Automatic Transmissions	Improved	6.0 ± 0.4	255 ± 15
Eight speed Automatic Transmissions	Improved	7.0 ± 0.5	305 ± 20
Automated Manual Transmissions (6-speed)	Improved	7.0 ± 0.5	210 ± 15
Continuously Variable Transmissions (engines > 2.8L) (engines < 2.8L)	Some issues on feel and engine noise	6.0 ± 1 7.5 ± 1	380 ± 20 240 ± 15
Early Torque Converter Lockup	NVH issues	0.5 ± 0.1	5 ± 1
Aggressive Shift Logic	Slightly worse drivability	1.5 ± 0.5	30 ± 10

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6 HYBRID TECHNOLOGY

6.1 CLASSIFICATION

Electric hybrid vehicles combine electric motor power and an internal combustion engine power to provide one or more of the following functions:

- engine stop at idle and instant re-start
- engine power assist during acceleration
- energy recovery by regenerative braking
- power for accessory drives during engine stop
- launch and low speed drive by electric motor only

Aside from the first function, the other functions also have the dimensions of extent of electric power available and the time for which it is available.

Hybrid vehicle introduction examples show different types of hybrid powertrain implementation. The simplest system is a 42V belt-drive starter alternator system that GM introduced in model year 2006. Similar systems using 14V have also been announced for small cars in Europe and Japan. The second system is a crankshaft mounted “integrated” starter alternator system operating at 42V that both GM and Daimler-Chrysler have introduced in their pickup trucks models (now discontinued). Honda also features a physically similar system in their hybrid Civic and Accord models. The third system in the dual motor and electric CVT type system offered on the Prius, Ford Escape and many other models. A design variant of this system, called Two-Mode Hybrid, is one that GM plans to use starting with full size SUVs. The fourth system is a four-wheel drive system where one set of wheels is driven entirely by the electric motor. The fourth system is embodied in the Lexus RX400 hybrid introduced in mid-year 2005, and resembles the third type of system except for the four-wheel drive design. These systems are considered individually below and span the likely range of designs available through 2016. It is possible that the future designs will vary the electric motor-to-engine power ratio as well as the total power-to-weight ratio but could have physically similar layouts. /1

A key finding from the analysis of hybrid technology is that it makes little sense to adopt hybrid technology as an incremental improvement, and the best way to adopt it is to fully redesign the entire power train to maximize synergy opportunities.

6.2 BELT DRIVE ALTERNATOR-STARTER (BAS)

As the name implies, the BAS system replaces the existing alternator with a starter motor/alternator to provide idle shutoff for the engine. In addition, the system is capable of some regenerative braking and modest launch assist, depending on the power capability of the belt. While simple in concept, the actual implementation has proved to be more complex. For example, the BAS Saturn Vue requires complex power electronics with inverter and converter to generate DC voltage of up to 36V. The controller also needs to operate the transmission fluid pump, hill start assist and the engine water pump. The NiMH battery is used for additional power storage.

The starter-generator for a 14V system is capable of generating about 40 to 50 N-m of torque at low RPM. This torque must be multiplied by a factor of 2 or 3 for starting a 2 to 3L displacement engine, which requires a unique pulley set for the BAS drive. The high ratio of the pulley set implies that the BAS will operate at very high RPM when engine RPM is high, i.e. it could operate at speeds up to 18,000 RPM. The high RPM requirement and the starting torque requirement make the starter-generator much more expensive than a simple alternator. In addition to the pulley set, the belt itself must be upgraded to handle the extra power, which can be about 8HP for a 42V system.

The need for a separate battery even for a 14V BAS system is due to the fact that repeated start events cause high battery loads that stress the conventional battery, reducing its life. In addition, older batteries can suffer unacceptable voltage drop during start, which causes electronic control units to reset or malfunction. Toyota in Japan has employed a separate Lithium-ion battery for the start-stop function, while the conventional lead acid battery is retained for lights, ignition and comfort options. In addition, significant additional battery capacity is required to operate the air-conditioner even in a reduced power mode. It is expected that a minimum of 2kw power will be required, implying that a 2-minute stop period will discharge the battery by 70Wh. This would be a very significant reduction in charge (about 15%) for a conventional 12V battery, and restart may be poor if the initial state-of-charge of the battery was low. Hence, most systems capable of keeping the air-conditioner on during idle stop use additional batteries to meet the higher energy storage demand.

The fuel economy benefits are dictated to some extent by the engine off strategy. If the engine is stopped for most decelerations (during braking) and idle, FTP city fuel economy can be improved by up to 13 to15 percent. However, detection and ramping delays for deceleration fuel shut-off causes about half the opportunity to be lost. A serious problem for a system that frequently stops the engine is vibration when stopping caused by the sudden loss of engine “creep” torque. This can be reduced by driving the engine with the BAS unit to reach engine idle speed. Smooth acceleration from an engine restart condition is also difficult due to the initial torque spike on restart and the BAS can reduce this by increasing engine RPM to near idle speed before ignition. These factors reduce the fuel economy potential of the system, so that a high value of city fuel economy benefit in drivable systems is about 10 percent. In addition, many engines already employ deceleration fuel shut-off to varying degrees and the actual city fuel economy improvement is typically limited to 5 to 8 percent. On the highway cycle, there is only three seconds of idle but about 60 seconds under braking conditions so that a fuel economy gain of about one percent is possible theoretically but only zero to 0.5 percent is realized in actual vehicles. Very modest amounts of braking energy can be recovered to contribute to 0.5 percent improvement in city fuel economy, while improvement to the alternator efficiency can contribute up to 0.5 percent benefit under both city and highway driving conditions. Hence the net benefits are around 7 to 9 percent under city driving and zero to 1 percent under highway driving for an EPA 55/45 combined fuel economy benefit of about 5 percent.

The use of a 42V system permits a larger BAS system with a peak power of about 6kw. In general, the system performs the same functions as the 14V system although the start is quicker. Depending on battery size and power rating, higher levels of braking energy recovery are possible, and the BSA can provide modest launch assist. These factors can increase 55/45 fuel economy benefits by one to 1.5 percent over the 12V system. In addition, the availability of 4kw of power can facilitate adoption of electric power steering and electric water pump to provide an extra 2.5 to 3 percent benefit in fuel economy. Hence, the net benefit of the system can be around 8 percent. This level can be attained in smaller vehicles with an enhanced 14V system.

Based on supplier inputs, we compute the current cost of a 42V BAS system with a purpose designed VRLA battery at $620, and an RPE of $950. However, these are low volume productions costs and with increased volume and design improvements, costs can be reduced to $450, and the RPE can fall to $660.

6.3 CRANKSHAFT MOUNTED ISAD SYSTEM

The integrated starter-alternator damper (ISAD) system is a trade name used by Continental for the device which is motor-generator mounted at the end of the engine crankshaft, typically replacing the flywheel. The starter-alternator is considerably more powerful than the BAS system described above, and currently available devices are typically in the 10 to 15kw power range. Because the ISAD is directly mounted to the crankshaft, it must be capable of generating the high torque required for start without the benefit of torque multiplication. The cold start torque requirement of 150 to 250 N-m for engines in the 2 to 3L displacement range requires a large magnetic machine that does not provide other hybrid benefits. Both GM and Daimler-Chrysler have chosen in the past to introduce the ISAD system on very large truck engines, one a 5.3L V-8 and the second, a 5.9L diesel engine. These engines impose much larger starting torque requirements, about 2 to three times the 200±50 N-m range cited, and require very large ISAD machines.

Typically mounting the ISAD in a transverse front-wheel drive design is difficult because there is limited space available to accommodate the ISAD between the engine and transmission. The space problem is less critical with a longitudinally mounted engine. The ISAD has been accommodated in the bell housing that contains the flywheel and torque converter for the automatic transmission. However, the ISAD can provide electrical driveline vibration damping and it is possible to reduce the torque converter size as less torque multiplication is required at vehicle launch.

The components of an ISAD are the starter-alternator, the inverter/controller, battery and battery charge management system, and an electric oil pump for the transmission to maintain hydraulic pressure during idle-off periods. These hybrid systems operate at higher voltages like 42V, so that a 42 to 12V DC/DC inverter is also required. It is possible to eliminate the 12V alternator and starter as well as the 12V battery but current designs often retain the starter for cranking in very cold weather and the 12V battery for compatibility and jump-start requirements.

The fuel economy potential of the ISAD type system includes all of the elements contributing to fuel economy improvements on the BAS system, plus additional gains afforded by the higher power capability of the ISAD and the driveline damping function. The GM and D-C trucks used a 12kw ISAD on a vehicle weighing 5000 and 5500lbs respectively, and the battery used was a lead acid battery that does not have the capability to absorb large regenerative braking or power assist related current spikes. Moreover, these models did not utilize the braking system that uses regenerative braking first and then the mechanical brake, but apportions a part of the braking energy at all levels to both braking systems. Hence, regenerative braking and acceleration power assist provided an additional 1.5 to 2 percent benefit on the city cycle over a BAS system, and only a 0.5 to one percent benefit on the highway cycle. However, the driveline damping allows reduction in torque converter loss (by converter downsizing and early lock-up) and earlier shifting to high gears. These features can provide another 3 ± 1 percent benefit in city cycle fuel economy and about one percent in highway fuel economy. Both GM and D-C have chosen to not downsize the i.c. engine to maintain continuous power capability, but engine downsizing is possible if only acceleration capability is to be kept constant. Under these conditions, the ISAD system can provide 13 ± 2 percent benefit in city fuel economy and 3 ± 0.5 percent benefit in highway fuel economy, for an EPA composite fuel economy benefit of about 8 to 9 percent.

The Honda "Integrated Motor Assist" or IMA system is functionally identical to the ISAD but attains much higher fuel economy benefit as shown in the table below, comparing the MY 2007 Civic 1.8L conventional vehicle to the Civic 1.3L hybrid.

Table 6-1 Fuel Economy Improvement for MY 2007 Honda Civic Models.

Model	**City FE (mpg)**	**Highway FE (mpg)**	**Composite (mpg)**
Civic 1.8L L5	32.8	50.9	39.0
Civic Hybrid 1.3L ECVT	54.6	65.0	58.8
FE Improvement [%]	66.5	27.7	50.8

The Civic Hybrid attains more than 4 times the benefit estimated for the GM and D-C designs under city condition and over 9 times the benefit under highway conditions. This is due in large part to the fact that the engine in the Civic hybrid is about 25 percent smaller and much less powerful than the one in the conventional model and has other features such as lean burn. In addition, the vehicle also features better aerodynamics, low rolling resistance tires and electric power steering.

Based on 2005 data, the Honda IMA hybrid system uses a permanent magnet motor instead of the induction motor used in the ISAD and is rated at 10kw on a vehicle with a weight of about 2,900lb. It operates at 144V and the energy storage device is a Nickel Metal Hydride battery capable of providing over 10kw peak power. These factors allow the IMA system to provide a larger percent of energy during acceleration and recapture more of the energy during braking. Based on data provided by Honda, we estimate that the hybrid IMA system improves fuel economy by about 18 ± 2 in the city cycle and 4 ±

1 percent on the highway cycle. It is difficult to apportion the benefits between engine and hybrid system due to the obvious interaction, but the engine downsizing and lean burn should contribute to about 14 percent and engine friction reduction about 2 percent (or 16 percent total) on the city cycle. The vehicle related modifications and transmission differences should account for the remainder of the fuel economy benefit.

The 2007 Honda Accord offers an IMA hybrid variant, that utilizes a similar design, but the motor output is increased to 12kW and the battery is rated at 13.8kW. Unlike the Civic, the Honda uses a 3L V-6 engine identical in displacement to the conventional Honda V-6, and it delivers higher horsepower (255 vs. 240) in the hybrid vehicle. The engine used in the hybrid has cylinder cut-off and disables 3 of the 6 cylinders at part load. Data on the Accord hybrid shows that it is 38 percent more fuel-efficient in the city and 23 percent more efficient on the highway. The IMA system on the Accord also allows the cylinder cut-off to function over a wider part of the operating map, contributing to positive system synergies.

Costs for the one motor hybrid system are based on inputs from Continental-ISAD, and EEA estimates costs for a 42V ISAD system with a VRLA lead acid battery and 10Kw motor at $1200. With the lack of progress on 42V systems, it now appears that the higher voltage systems of the IMA type are more likely and the cost of the system with a Nickel Metal hydride battery and 12Kw motor is estimated at $1850 currently, reducing to $1350 by 2012 due to economies of scale and learning. This cost corresponds to a long term retail price increment of $2150, although current increments are closer to $3000.

6.4 DUAL MOTOR “FULL” HYBRIDS

The so-called full hybrid of the Toyota Prius-type uses an architecture that requires the use of two electric motor-generators. In general, only two motor systems can have a pure electric propulsion mode, since one motor can propel the vehicle while the second motor can be used to restart the i.c. engine, if the driver demands more power. Hence, at low speeds and acceleration rates, the engine can be shut down, resulting in a much longer engine-off condition over the city test cycle in comparison to a single motor system of the ISAD or IMA type. The engine also operates at higher average load when running, contributing to a further efficiency gain. In addition, the electric motors typically have a much higher power rating than those used in the ISAD and IMA hybrids so that very significant downsizing of the I.C. engine is possible. Finally, the Toyota design uses an innovative electric CVT that consists of a planetary gear set, with the electric motor and wheels connected to the outer (ring) gear, the engine to the planetary gear set and the generator to the inner (sun) gear. The RPM of the three gear sets are linked such that the RPM of any two sets automatically determines the third set's RPM. During certain modes, such as acceleration at moderate speed and at high-speed cruise, the generator provides power to the motor, which is not efficient. However, the simplicity of the transmission and the elimination of the torque converter relative to a conventional automatic transmission make the overall system very efficient. This type of architecture, using the planetary gear sets to replace the transmission, is also used by Ford and Nissan (under license from Toyota). Recently, GM has announced it will have a proprietary hybrid architecture using a similar concept with two planetary gear sets that mitigates the efficiency problem at higher speeds.

A detailed study of the first generation Prius for the DOE listed the components of the hybrid drivetrain and these have not changed in type. However, the 2004 model Prius represents a significant improvement of the individual components over the previous design. Based on 2005 specifications, the vehicle has an interior volume of 96.2 cubic feet, approximately midway between the volume of the Corolla and the volume of the Camry. The i.c. engine used is a 1.5L 4-cylinder model using the Atkinson cycle and is rated at 76 HP and 82ft-lbs of torque, while the electric motor has an output of 50kw(67hp) with a maximum torque of 125ft-lbs. The battery is a third-generation nickel metal-hydride unit rated at 21kw peak power and 1.3kw-hr of energy storage. The system achieves acceleration performance similar to that of the MY 2005 Corolla, with a zero to 60mph time of about 10 seconds. A comparison of the EPA fuel economy test results is provided below

Table 6-2. Fuel Economy Improvement for MY 2005 Toyota Prius and Corolla Models.

Model	City FE (mpg)	Highway FE (mpg)	Composite (mpg)
Corolla 1.8L (auto)	35.95	51.45	41.6
Prius	66.60	64.80	65.8
Difference %	85.2%	25.6%	58.2%

Considering the size difference between the Corolla and Prius, it appears the Toyota system provides a 60±% improvement in composite fuel economy with similar acceleration performance, but with significant loss of power under conditions such as hill climb or towing. Analysis of the sources of the benefits over the composite cycle shows that about 12 percent of the benefit is associated with engine-off, 15 percent with regenerative energy recovery (used in low speed propulsion and acceleration assist), and 28 percent from the engine efficiency improvement due to the Atkinson cycle and restricted operating range. It should be noted that the model also uses electric power steering, low rolling resistance tires and a very aerodynamic body that would account for 6 to 7 percent of the total gain.

In model year 2005, two new full hybrid models have been introduced: the Ford Escape hybrid and the Lexus RX400H. Both models are SUVs, and utilize i.c. engines with no displacement decrease relative to their conventional counterparts.

Based on MY 2005 data, the Ford Escape hybrid uses an Atkinson cycle version of the 2.3L engine and is rated at 133HP which is about 15 percent lower than the output of the 2.3L engine in the conventional Ford Escape. The electric motor is rated at 94HP, but the system's maximum combined output is 155HP, quite similar to the output of the conventional model. Due to the electric motor's superior low speed torque, the low speed acceleration performance of the hybrid is more similar to the conventional Escape powered by a V-6 engine. City fuel economy is about 65% better than the 4-cylinder conventional Escape while the highway fuel economy is about 25% better. In comparison to the V-6 model (a comparison of approximately equal performance vehicles), the fuel economy benefit is 55 percent for the two-wheel drive version, and 62.1 percent for the four-wheel drive version. These figures are quite similar to those for the Prius. In comparison to the model with the same displacement engine, the FE benefit is 42 percent.

Once again, based on MY 2005 data, the Lexus RX400H has an i.c. engine rated at 208HP, which is about 10% lower than the output of the engine in the RX330, but the hybrid engine does not use the Atkinson cycle. Rather, the output reduction is associated with changes to valve timing and calibration (details may show that it is similar to the Atkinson cycle). The electric motor is rated at 167HP and the system's maximum combined output is about 270HP. Hence, the acceleration performance is significantly better than that of the conventional RX330, although the continuous power capability may be more similar. The data shows that the RX400H has a city fuel economy improvement of about 65% but almost no improvement in high fuel economy. The RX400H also offers an innovative electric four- wheel drive, where the rear axle is powered solely by a 68HP electric motor, eliminating the need for a center differential and driveshaft from the engine. Data for a detailed fuel economy comparison of the conventional and hybrid four-wheel drive models show that the hybrid attains a 43 percent improvement in F/E in both 2WD and 4WD versions which is similar to the value for the Ford Escape.

6.5 SUMMARY

Based on the information discussed in subsequent sections, Table 6-5 summarizes the fuel economy benefits and PRE values for various hybrid technologies. It should be noted that the fuel economy improvement values do account for additional hybrid synergistic benefits and reflect vehicle designs that are optimized for fuel economy, not performance benefits. For example, the BAS system total benefits include the IC engine, transmission and accessory possible improvements, as well as low rolling resistance tires and drag reduction benefits. While the BAS-only fuel economy benefit, as discussed above, is about 5%, other vehicle and powertrain improvements can achieve additional improvement of as much as 25%, for combined estimate of over 30%.

Table 6-3 Hybrid Component RPE and System Fuel Economy Benefits

Baseline Vehicle is 3,000lb. IW with 1.8L 4-valve I4 and 4-speed AT. Benefits include engine downsizing, transmission upgrade to CVT and other vehicle improvements.

Technology	**2010**	**2015**
BAS Hybrid Component RPE	800	660
BAS Vehicle System FE Benefit %	32.8	35.1
IMA Hybrid Component RPE	2,525	2,100
IMA Vehicle System FE Benefit %	53.6	55.8
2 motor Hybrid Component RPE	3,900	3,300
2- motor Hybrid Vehicle System FE Benefit %	65.0	70.1

Since the hybrid technology has reached mass production volumes in 2007, the newest EPA FTP testing data can be used to compare the fuel economy advantage trends for hybrids against their regular gasoline counterparts. While the baseline for comparison does not necessarily match the EEA basis, the EPA data shows that EEA estimates for the full 2-motor (such as Camry and Altima) and IMA-type (such as Civic) hybrids do match or even exceed the FTP figures on a competitive performance basis for models that are optimized for fuel economy performance.

It can be observed that the mild hybrids in 2007 do appear to report lower fuel economy advantage, if the FTP data is compared. Once again, some differences can be explained by the baseline differences and the fact that these vehicles do not appear to be fully optimized for the fuel economy. Also, the GM BAS hybrid fuel economy performance in 2007 is tricky to compare because the regular Vue and Aura models do not offer the 2.4L engine used in hybrid versions. When the hybrid Vue is compared with the lower power 2.2L regular model, the fuel economy difference is about 14%. If the hybrid Vue engine was downsized to match the regular 2.2L Vue performance and transmission was upgraded to CVT, the fuel economy difference would increase significantly, likely to approach EEA estimates. Similarly, the Aura BAS comparison to regular Aura is not meaningful since the regular model is only available with a V6 engine in 2007. When the Aura BAS is compared to 3.5L Aura, the fuel economy difference is 25%.

Table 6-4. MY 2007 Hybrid Vehicle Fuel Economy and Key Specifications Comparison.

FE – Fuel Economy – is EPA Combined Unadjusted;
*-With MY 2007, Toyota upgraded the Camry V6 to 3.5L. The previous, MY2006 3.3L V6, model provides better power rating match.
**-Ford markets the Escape and Mariner HEVs with de-rated power IC engine but claims the "V6-like" acceleration performance.
***The Altima V6 is rated 270hp so Saturn Aura is used to provide better performance match.

MFR	CAR LINE	DISP	CYL	TRANS	Fuel Economy [mpg]	FE Diff. [%]	Total Power [hp]	Curb Weight [lbs]
Honda IMA-Type Hybrid Comparison								
HONDA	CIVIC HYBRID	1.3	4	Auto(AV)	58.8		110	2875
HONDA	CIVIC	1.8	4	Auto(L5)	39.0	50.9	140	2690
2-Motor Hybrid Comparison								
NISSAN	ALTIMA HYBRID	2.5	4	Auto(AV)	46.7		198	3482
SATURN	AURA***	3.5	6	Auto(L4)	28.5	64.1	224	3578
TOYOTA	CAMRY HYBRID	2.4	4	Auto(AV)	45.9		192	3680
TOYOTA	CAMRY (MY 2006)*	3.3	6	Auto(S5)	27.8	65.3	190	3340
TOYOTA	PRIUS	1.5	4	Auto(AV)	65.8		110	2932
NISSAN	VERSA	1.8	4	Auto(AV)	37.7	74.6	122	2749
FORD	ESCAPE HYBRID FWD**	2.3	4	Auto(AV)	40.6		155	3627
FORD	ESCAPE FWD	3	6	Auto(L4)	25.4	59.7	200	3300
MERCURY	MARINER HYBRID 4WD**	2.3	4	Auto(AV)	36.5		155	3787
MERCURY	MARINER 4WD	3	6	Auto(L4)	24.1	51.5	200	3464
BAS Hybrid Comparison								
SATURN	AURA HYBRID	2.4	4	Auto(L4)	35.7		164	3529
SATURN	AURA	3.5	6	Auto(L4)	28.5	25.3	224	3578
SATURN	VUE HYBRID	2.4	4	Auto(L4)	34.0		170	3474
SATURN	VUE	2.2	4	Auto(L4)	29.8	14.1	144	3207
SATURN	VUE	3.5	6	Auto(L5)	26.5	28.3	248	3478

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7 DIESEL ENGINES

7.1 OVERVIEW

Light-duty diesel engines are not a new technology, although they have continued to improve over time much like gasoline engines. Diesel engines have achieved high rates of market penetration in Europe, but have very low sales in the US market. In 2004 model year, only VW was selling light-duty diesels in the U.S., while the "Big Three" US manufacturers offered light-heavy duty V-8 diesels in the 8500 to 10,000 lb. GWV range of vehicles.[/1] In 2005, diesel engines were offered in the Jeep Liberty and Mercedes E320 models in limited quantities. In MY 2007 new Diesel Particulate Filter (DPF)-equipped diesels were introduced by DaimlerChrysler and VW and major product expansion is expected in the future. .

VW historically priced the diesel at $1300 to $1600 over an equivalent gasoline model for their 1.9L four cylinder diesel engine rated at 110 to 130 HP. In contrast, the light-heavy diesels of about 6L displacement were priced at over $5000 increment over a V-8 gasoline engine of similar power.

The main reason cited by manufacturers for the lack of available diesel engine models in the US market is the cost and uncertainty of meeting US Tier II and California LEV II emission standards.[/2] While technologies capable of meeting these standards have been announced, their additional cost and durability uncertainty have raised sufficient concern and many introduction plans have been delayed. Emission control is examined in this report and the cost of emission controls explicitly accounted for in Section 7.3.

7.2 ENGINE PRICE AND PERFORMANCE

Based on 2005 information, the European diesel engine option prices for four cylinder diesels were at Euro 1100 to 1200 higher than a gasoline engine of similar power, at Euro 3 emission levels. Six and eight cylinder diesel engines are used only in luxury cars in Europe and their pricing is inconsistent, with some manufacturers pricing diesels below their gasoline counterparts, presumably subsidizing them for fuel economy credits. However, retail sticker price comparisons may be deceptive as gasoline models are often discounted, while diesel models are not. Many manufacturers interviewed believe that VW was not pricing its diesel engine in the US at "full cost" recovery and it is accepting lower profit margins on its diesel vehicles. Manufacturers also noted that diesels are being priced with lower profit margins in Europe as well, contributing to reduced margins for most European manufacturers.

Cost data from a detailed study by FEV, a German engine development organization, for EPA of diesel engine cost was reviewed by EEA with the manufacturers for their comments. In general, the FEV costs were considered to be a little low, but in the reasonable range, for most components. The diesel vehicle cost data is shown in Table 7-1, and is changed from the FEV estimate for some components where manufacturers believed the costs to be too low. /3 The diesel engine costs are partially offset by the savings from the evaporative system (not required for diesel) and the cost of advanced 3-way catalyst system and oxygen sensors used in gasoline cars.

Based on 2005 technology analysis, the cost data suggests that the "correct" incremental retail price should be about \$1600 for a 4-cylinder and \$2425 for a six cylinder diesel engine. In this context, the VW price appears a little low, but it should be noted that VW is possibly the lowest cost producer of diesel engines in the world due to scale economies and learning. VW currently manufactures over 2 million 4-cylinder diesel engines per year, which is twice that of its nearest competitor and about three times the European industry average. It is quite likely that VW has a 10 to 15 percent cost advantage over its rivals, suggesting that the \$1300 to \$1400 price does provide "normal" profit margins for

VW. Future costs of diesel engines will continue to increase as the cooled EGR system and advanced injection system to meet Euro 4/5 emission standards are widely adopted. EEA has estimated that a Euro 4 emission standard (approximately similar to the previous US Federal Tier I standards) compliant engine has costs that are about $120 higher for a 4-cylinder engine, and $170 higher for a 6-cylinder engine, with two-thirds of the price increase associated with the fuel injection system.

Table 7-1 Estimated non-Tier 2 Diesel Engine Incremental Cost and RPE

(Advanced After-treatment Costs Not Included)

	2L I-4	4L V-6
Engine Hardware	35	50
CR Fuel Injection System	750	1150
Variable Geometry Turbo	180	250
Inter-cooler	50	75
Electric EGR & Cooler	60	80
Larger Battery & Starter	25	40
Glow Plugs	15	20
Vehicle NVH Related	80	100
Evaporative System Savings	(75)	(95)
Catalyst/ Sensors Savings	(150)	(200)
Total Cost	970	1470
RPE	**1600**	**2425**

Source: FEV, auto-manufacturers

It appears that, in order to meet the Tier 2 Bin 5 emission standards, most diesel engine manufacturers will utilize a new form of combustion called “HCCI” for the light load and mid-load regimes of engine operation. Industry experts also expect that in the five year time frame beyond 2008, engines operating with HCCI combustion across much of the speed load range will emerge and eventually become the dominant technology. While these engines are unlikely to be more efficient than 2005 diesel engines, they will have very low engine-out emissions and offer the potential to meet emission standards with relatively low after-treatment costs. Since there are no engines with HCCI combustion in production, the cost of the HCCI engine is quite speculative. Based on comments received from manufacturers and suppliers on HCCI engine requirements for additional technology, EEA has estimated the following potential additional costs over current diesel engines:

	4-Cylinder	6-Cylinder
Advanced Injection System	110	150
Advanced EGR System	50	70
Individual Cylinder Pressure Sensors	40	60
Variable Valve Timing	120	160
Total	**320**	**440**

If the technology change estimates are correct, the cost increase for an HCCI engine over a current gasoline engine (before costs of HCCI after-treatment are considered) could be in the $1300 range for a 4-cylinder engine and $1900 for a 6-cylinder engine of. It is estimated that the Tier 2 standard implementation results in increased gasoline engine costs by $140 for a 4-cylinder engine to $200 for a 6-cylinder engine. Hence, the IRPE for a HCCI engine is likely to be in the $2000 range for a 4-cylinder engine and $2800 for a 6-cylinder engine in the 2010 time-frame.

Diesel engine fuel economy advantages over a gasoline engine can be examined from European data. The new European test procedure (ECE15 + EUDC) generates a fuel economy rating quite similar to the rating obtained on the EPA combined city-highway cycle. Assuming that the percentage difference in fuel economy between gasoline and diesel powered vehicles on the European cycle is similar to the one on the EPA combined cycle, an analysis of 2005 model year European vehicle fuel economy could provide a good estimate of the benefit of a diesel engine. EEA selected 44 matched pairs of cars where the manufacturer offers a diesel and a gasoline version of the same model with “similar” engine displacement and vehicle performance. The average engine displacement ratio was within one percent, but diesel engine torque was 39 percent higher, while horsepower and 0-100 km/hr acceleration time were about 14 percent lower.

The fuel economy of the diesel was 36 percent better on average, but there was substantial variability among different pairs. A regression analysis revealed that the high-end luxury vehicles with large diesel engines (like the Mercedes S400CDI and the Audi A8) had the lowest fuel economy benefit for the diesel, in the range of 20 ± 5 percent. In addition, the Opel 1.25L diesel (in two matched vehicle pairs) also showed exceptionally low fuel economy benefit of 15 percent. Dropping the 4 luxury vehicle pairs and the 2 Opel engine pairs from the data provided a diesel engine fuel economy benefit estimate of 38 ± 5 percent, with no significant trend as a function of the HP, torque, or displacement ratios between the pairs. This number is consistent with European manufacturer statements that diesel engine fuel consumption benefits are in the 25 to 30 percent range for “similar” performance vehicles, which equates to 33.3 to 42.9 percent benefit in fuel economy.

7.3 EMISSION CONTROL

LD Diesel after-treatment solutions have made substantial progress toward meeting the Tier II, Bin 5–level standards.[/4] PM control is no longer a technical question, but rather a cost issue. NOx control, on the other hand, still is a challenge, especially taking into account the severe SFTP US06 4,000-mile certification requirements

With conventional diesel combustion, assuming that engine-out emissions are optimized, using cooled-EGR and improved combustion/injection system designs, reduction of NOx emissions with the LNT remains the leading solution acceptable to EPA to reach Tier 2 Bin 5 levels for the lightest diesels.[/5] The need to install expensive LNT might fade away by 2015 (substituted by lower efficiency solutions), if engine manufacturers can successfully commercialize alternative combustion processes, like HCCI, over most of the engine map.

The Urea-SCR system seems to be the preferred method for some OEMs that market larger diesel engines in premium cars and also SUVs and trucks, as illustrated by recent European auto-manufacturer announcements. The US EPA was hesitant to accept this NOx emissions compliance scenario, which depends on customer's actions to maintain adequate supply of urea-based reductant on-board. However the recent EPA statements illustrated that the issues were resolved and the urea-SCR system will be adopted for light-duty diesels.

Estimated costs for different exhaust treatment scenarios are listed in Table 7-2. The estimates reflect 2005 data sources and assume that lower cost cordierite will become feasible for the DPF construction (as opposed to SiC material currently used in most DPFs). The integrated PM/NOx treatment configuration is based on the European 2005 Toyota Avensis D-CAT system estimated costs. [/6]

The cost estimates presented do imply that successful commercialization of HCCI would result in the lowest after-treatment system costs. At the same time, concepts like HCCI will require extensive engine-based modifications as well as increased control system complexity.[/7] The apparent exhaust after-treatment cost advantage for HCCI would be offset by increased engine costs. However, HCCI appear to offer significant advantages in terms of its superior fuel economy, as well as the potential to use simplified and more durable exhaust systems, like LNC or low efficiency LNT.

Table 7-2 Diesel Tier 2 Bin 5 After-treatment Cost Comparison (sales volume above 100,000 units)

Exhaust Treatment Component	Conventional Combustion/ DPF LNT After-treatment	Conventional Combustion / DPF/ Urea-SCR System	HCCI Combustion/ LNC-based After-treatment
Integrated DPF/LNT	550-650	-	-
Urea-SCR Catalyst	-	220-280	-
DPF (catalyzed cordierite)	-	100-140	100-140
DOC	45-55	45-55	45-55
LNC	-	-	130-170
Urea Dosing	-	85-115	-
Regeneration Control	170-230	85-115	85-115
Estimated Total	750 ± 85	620 ± 90	420 ± 60

Note: Estimates reflect technology levels expected for a typical light diesel vehicle weight category of 3,000/3,250 lb. IWT (2L Engine) capable of reaching the Tier 2 Bin 5-level tailpipe emissions.

7.4 COST AND PERFORMANCE SUMMARY

Since both engine-out emissions and engine costs are likely to change with new diesel introduction starting MY 2008-2009, EEA has summarized the incremental retail price of the light-duty diesel engine without after-treatment relative to the price of a gasoline engine with after-treatment in the same year, and then added the cost for a plausible after-treatment system. The estimated IRPE for a 4-cylinder engine is $1600 for a typical manufacturer, while a 6-cylinder engine of about 4 to 4.5L displacement will have an IRPE of $2425 relative to a V-6 gasoline engine rated at 240HP, assuming high volume production and normal cost recovery. These RPE values do not include any after-treatment costs.

By 2009, EEA expects improvements to injection system, reduction of compression ratio and the use of "HCCI – like" combustion light at loads will allow significant reduction in NOx, along with a similar reduction in PM. The total RPE increase for a 4-cylinder diesel engine is estimated at $2200 and the RPE for a six cylinder engine is estimated at $3200.

Table 7-3 summarizes the fuel economy and RPE estimates for diesels, as discussed above. The MY 2007 Mercedes diesel FTP data shows that the fuel economy benefit is consistent with EEA estimates. For example the E320 Bluetec 3L diesel provides 38% better fuel economy, when compared to the 3.5L gasoline E350 (based on the EPA combined unadjusted FTP data). The Mercedes R320 CDI fuel economy is 33% higher compared to the R350 gasoline with 3.5L V6.

Table 7-3. Light Duty Diesel Fuel Economy Improvement and $RPE Increase

	Fuel Economy Benefit [%]	Incremental Cost [$RPE]	Notes
I4 Engine	33 to 43	2,200	Compared to gasoline I4, includes aftertreatment
V6 Engine	33 to 43	3,200	Compared to gasoline V6, includes aftertreatment

More information is now available on the Tier 2 Bin 5-compliant exhaust configurations (for example Mercedes Bluetec) and further analysis would be required to confirm the detailed cost increases associated with these new configurations at the subsystem level.

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