FUEL ECONOMY POTENTIAL OF 2010 LIGHT DUTY TRUCKS

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1. INTRODUCTION

The Department of Transportation is developing new fuel economy standards for Light Duty Trucks for model years 2009 and 2010 under the statutory requirement to set Corporate Average Fuel Economy (CAFÉ) standards for cars and light trucks. Typically, new standards are determined by estimating the potential of technologies to improve fuel economy while holding the consumer desired attributes of vehicles constant relative to current vehicles. The statute also requires the Department of Energy (DOE) to comment on new CAFÉ standards, and over the last twenty years, the DOE has developed a comprehensive list of technologies available to improve fuel economy and estimated the costs and benefits of these technologies. This report documents the last set of revisions to the DOE technology list and the estimates of the technology attributes of interest. In addition, the report provides estimates of potential technology improvements to light trucks by size/market class for model year 2010 and the resulting fuel economy improvement relative to actual (measured) fuel economy for 2005 model year light trucks. It does not however, estimate fuel economy potential for each manufacturer, but this topic will be covered in subsequent reports to the DOE by its contractor, Energy and Environmental Analysis (EEA).

This update of technology characteristics is based on new data obtained by EEA from technology suppliers and auto-manufacturers, as well as data from studies conducted by the National Academy of Sciences (NAS) and the Northeast States Center for a Clean Air future (NESCCAF). Technologies have been grouped into three broad areas for the discussion in this report. Section 2 reviews the costs and benefits of spark ignition engine improvement technologies, while section 3 reviews improvements in vehicle body and accessory related improvements, including weight reduction. Section 4 reviews potential transmission and driveline related improvements. This report does not document the costs and benefits of hybrid and diesel technology as these have been documented in a recent EEA study for the DOE completed in 2004.

Section 5 summarizes the methodology used to estimate the benefits of multiple technological improvements to a particular vehicle representative of the size class, and the net fuel economy holding vehicle attributes approximately constant to baseline (MY2005) levels. Confidentiality and timing concerns have resulted in the size class specific forecast tables being submitted separately for this version of the report.

2. SPARK IGNITION ENGINE TECHNOLOGIES

2.1 OVERVIEW

Improvements to spark ignition engine efficiency have the potential to improve fuel economy by up to 20 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 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. Some improvements, notably the use of 4-valve engines, are now so widespread that they are not considered below but are included in cost curves for some classes where they have not been adopted.

2.2 STOICHIOMETRIC AND LEAN BURN GASOLINE DIRECT INJECTION

The stoichiometric and lean burn gasoline direct injection engines are treated together in this report because of their synergy. 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. 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 after-treatment, and the NO_x adsorber system capable of reducing NO_x from lean burn engines is both expensive and sensitive to sulfur poisoning,

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 on-road fuel economy. Most current GDI engine production programs in Europe have moved away from stratified charge mode toward stoichiometric operation. The Volkswagen Group is bringing the latest generation GDI engines to the US in 2005, although they are designed to operate at stoichiometric mode. Volkswagen is promoting the world's first, production 2.0L Turbo FSI (Fuel Stratified Injection) stoichiometric engine. Stoichiometric GDI eliminates the NO_x emissions issue and most developers have reported its engine-out emissions comparable to the conventional port injection engines.

The stratified lean burn development toward second generation models, however, continues, driven by significant fuel economy improvement potential. 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. Bosch, Siemens, Delphi and Denso are positioning themselves to supply the technology. Siemens has indicated that GDI could capture 10 percent of Europe's gasoline engine sales by 2008 and could be available in the US due to the availability of low sulfur gasoline starting in 2006.

Fuel Economy Improvement Potential

The fuel economy improvement potential and Retail Price Equivalent (RPE) for stoichiometric and lean-burn GDI technologies are summarized in tables below. The NAS study did not consider this technology.

Table 1. Stoichiometric GDI Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	7	300 to 450
NESCCAF-2004	-1 to 1	189 to 294
CARB ISR-2004	-1 to 1	189 to 294
NAS- 2001	N/A	N/A

Table 2. Lean-Burn GDI Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	12	550 to 700
NESCCAF-2004	4 to 10	728 to 1554
CARB ISR-2004	4 to 10	728 to 1554
NAS – 2001	N/A	N/A

Analysis

Stoichiometric GDI is now available in a number of European models and in four US models in 2005. Analysis of the actual certification data from Europe shows that GDI provides 3.5 $\pm$ 0.5 percent increase in fuel economy at constant displacement combined with a 5 percent increase in torque and horsepower, that 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 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. Total system RPE is now estimated by EEA at $125 for a 4-cylinder engine, $170 for a 6-cylinder engine and $210 for a 8-cylinder engine. The RPE is similar to but slightly lower than the NESCCAF study estimates but the fuel economy estimate is much higher.

A second 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. 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 11 to 13 percent range and the RPE of the turbocharger, intercooler and GDI package is estimated at $600. However, if a 6-cylinder engine is replaced by a 4-cylinder engine (like a 3L V6 being replaced by a 2L 4-cylinder Turbo/GDI engine), then the cost is about zero due to the engine cost savings.

2.3 VARIABLE VALVE TIMING AND LIFT

Technology Description

Historically most spark ignition engines use fixed valve timing and lift. That is, neither valve timing or 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. 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. Some engine designs feature linked intake and exhaust cams varied by one phaser. Yet others utilize dual cam phasers for independent exhaust/intake valve actuation.

Variable Valve Lift (VVL) technologies can be configured to make continuous variations in lift or make discrete valve height lift increments. 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.

Both VVT and VVL in various configurations have been commercialized in the US. However, Japanese OEMs overwhelmingly favor overhead cam configurations, which are more suited to VVT. 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. The system has been successfully expanded into the company's mainstream models, including the Civic, Accord and Odyssey. Another example, Toyota's main stream VVT technology, which utilizes a cam phaser for the intake valves, is used on all passenger car engines. Though Daimler Chrysler has been late with the VVT technology adoption, it will be the first company to offer dual VVT in the United States on entry-level vehicles, as a result of the Global Engine Alliance project with

Mitsubishi and Hyundai. The mass production of the new engine will start in September 2005.GM has recently announced the new Ecotec 2.4L engine, with VVT, will be launched in the MY 2006 Chevy Cobalt. The engine will also feature dual phasers to alter the relationship of the intake and exhaust camshafts up to 50° relative to the crankshaft.

Fuel Economy Improvement Potential

The fuel economy improvement potential and associated costs for variable valve timing and lift are summarized in tables below. The figures are provided for various engine sizes and valve train configurations.

Table 3. Variable Valve Timing Fuel Economy Improvement Potential and RPE

Study		RPE Change [$]					FE Improvement [%]				
EEA - 2003		Cars		Trucks			Cars		Trucks		
(Single phaser)		50	90	50	90	50	2	2	2	2	2
NESCC AF 2004	Engine	2.2L L4 DOHC	3.0L V6 DOHC	3.3 L V6 OHV	3.4L V6 DOHC	5.3L V8 OHV	2.2L L4 DOHC	3.0L V6 DOHC	3.3 L V6 OHV	3.4L V6 DOHC	5.3L V8 OHV
	Intake	49	98	49	98	49	2	1	1	1	2
	Exhaust	49	98	49	98	49	2	3	2	2	3
	Dual	98	196	196	196	196	3	4	2	3	4
	Coupled	70	161	49	161	49	3	4	2	2	4
CARB ISR 2004	Intake	49	98	290	98	311	2	1	1	1	2
	Exhaust	49	98	49	98	49	2	3	2	2	3
	Dual	98		388	196	409	3	4	2	3	4
	Coupled	70	161	49	161	49	3	4	2	2	4
NAS-2001	Intake	35	70	35	70	35	1	1	1	1	1
	Dual	70	140	NA	140	NA	2	2	NA	2	NA

Table 4. Variable Valve Lift Fuel Economy Improvement Potential and Costs

Study		RPE Change [$]					FE Improvement [%]				
EEA 2003 (Discrete)		Cars		Trucks			Cars		Trucks		
		170	260	260	260	330	5	5	5	5	5
NESCCAF 2004	Engine	2.2L L4 DOHC	3.0L V6 DOHC	3.3 L V6 OHV	3.4L V6 DOHC	5.3L V8 OHV	2.2L L4 DOHC	3.0L V6 DOHC	3.3 L V6 OHV	3.4L V6 DOHC	5.3L V8 OHV
	Discrete	105-168	161-252	161	161-252	210	4	4	3	4	4
	Continuous	210	385	385+ DOHC	385	420+ DOHC	5	6	4	5	5
CARB ISR 2004	Discrete	105-168	161-252	161	161-252	210	4	4	3	4	4
	Continuous	210	385	385+ DOHC	385	420+ DOHC	5	6	4	5	5
NAS -2001	Not specified	70 to 210					5.5 ± 2.5				

Analysis

The NESCCAF report provides data on more variants of the variable valve timing mechanism, although the costs are in line with using one cam phaser per camshaft. The CARB assessment is different for OHV engines because it includes the cost of conversion from OHV to OHC, which is not necessary since it is possible to have a coupled phasing of both intake and exhaust valves on either an OHV or SOHC engine. Fuel economy improvements quoted for CARB and NESSCAF are rounded to whole numbers in percent, which makes a significant difference in this case since the expected improvement is only in the 2 percent range. All available test data on paired comparisons of engines with and without variable valve timing suggest a 1.5 to 2.2 percent improvement for an intake valve timing and a 3 ± 0.5 percent improvement for intake and exhaust valve timing. A coupled approach on a single camshaft engine is expected to yield results similar to an intake only system. It should be noted that the system provides low RPM torque improvements of about 5 percent which can be used to improve fuel economy by re-calibrating transmission shift points. The observed differences in the estimates of fuel economy potential of 0.5 percent or so may be associated with the inclusion or exclusion of this re-calibration.

The estimate of fuel economy benefits of discrete step Variable Valve Lift Systems appears to be more homogenous across studies at about 5 percent , while the cost estimates show a little more variation. The upper ends of the ranges from CARB, NESCCAF and NAS are similar to the EEA estimate after accounting for the CARB estimate including the cost of conversion to OHC. The data support an average estimate of $150 for discrete VVL for a 4-cylinder engine, $200 for a V6 and $250 for a V8, since the costs should increase in proportion to the number of intake valves controlled. It is not clear if the NAS considered a V8 engine with VVL in its estimates. Only the NESCCAF and CARB reports include continuous control, but the selected mechanism is not described, making it difficult to comment on cost. The benefit in fuel consumption is estimated to be only one percent better than the discrete VVL system, which is not in agreement with claims from BMW, the only manufacturer to offer such a system in the marketplace currently. BMW's "Valvetronic" system is claimed to provide a 10 to 11 percent benefit in fuel economy, which is significantly better than the CARB/NESCCAF estimate and appears to be more accurate given the cost of the system.

2.4 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 in optional V8 engines available in US extended-length Chevrolet TrailBlazer and Envoy SUVs. It will also be used in the Vortec V6, likely starting from MY 2006. Other models will be announced in the near future. DaimlerChrysler, which calls its system "Multi-Displacement," offers cylinder deactivation on some US versions of its V8

Hemi engine on the Chrysler 300 sedan, Dodge Magnum RT and Jeep Grand Cherokee. Honda has introduced the "Variable Cylinder Management" system on certain Odyssey and the Accord HEV V6 engines.

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 moding, power train and exhaust system modifications were 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.

GM's implementation of cylinder deactivation is made relatively simple by virtue of their pushrod 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.

Daimler-Chrysler's Hemi V8 Multi-Displacement mechanical implementation is similar to GM's. 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 I3 engine. 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.

Fuel Economy Improvement Potential

It should be noted that the benefits of cylinder deactivation are not additive to those of VVT, VVL, or lean burn GDI since these technologies all reduce pumping losses. GM and DaimlerChrysler claim fuel economy increases of approximately 8-10 percent for their V8 cylinder deactivation systems under standard fuel economy test conditions. Honda claims that their 3.0L V6 Cylinder Management system's fuel economy performance is comparable to that of 2.4L I4.

EEA-2001 analysis considered cylinder deactivation as available technology for larger displacement V8 engine. The technology was considered feasible for V6 engines, as long as the loss in transitional smoothness is handled by alternative means. The recent Honda announcements indicate that the problem was solved by using Active Engine Mounts, as well as Active Noise Control, designed to create an opposite phase sound to increased engine vibrations.

Table 2-5 presents the cylinder deactivation costs and fuel economy improvements in the studies examined.

Table 5. Cylinder Deactivation Fuel Economy Improvement and Cost

Study	F/E Benefit (%)	RPE ($)
EEA-2001	7.5	250 (V8)
NESCCAF-2004	4 to 6	161 for V6 to 210 for V8
CARB ISR-2004	4 to 6	113 for V6 to 147 for V8
NAS -2001	3 to 6	112 to 252

Analysis

Since actual production engines with various cylinder deactivation designs are now commercially available, the estimated fuel economy benefits for the technology can be checked against official fuel economy test data. Honda, for example, offers the Variable Cylinder Management (VCM) system on MY 2005 Odyssey EX and Touring models, together with i-

VTEC, as standard equipment. The LX and EX come without VCM and the valve control is basic VTEC. When comparing these models, the resulting EPA reported unadjusted combined fuel economy improvement for vehicles equipped with VCM and i-VTEC is 6.2 percent. If the i-VTEC and VTEC fuel economy advantage is subtracted (about 1 percent), the VCM fuel economy improvement potential of about 5 percent is expected, but this is on top of the existing variable valve lift system. Because both systems reduce pumping loss, the effectiveness of the cylinder deactivation system is reduced by about a third. In contrast the large engine Chrysler 300 is reported to provide a 8.5 percent benefit. Based on these data, the EEA fuel economy improvement estimate of 7.5 percent is most defensible, but cost numbers are relatively consistent across the NAS and NESCCAF estimates. Hence a cost of $160 for a V6 and $210 for a V8 are selected.

2.5 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. The engine power impacts of supercharger technology and exhaust backpressure impacts of turbocharger technology are sufficiently equivalent to allow the two technologies to be treated identically from a fuel economy standpoint. Current state-of-the-art turbochargers incorporate a variable geometry 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.

Fuel economy impacts due to turbocharging/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 technology is "matched" to the engine. If the technology is sized to provide intake boost at low RPM with some sacrifice in top-end power, fuel economy benefits of approximately 7 percent 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.

Fuel Economy Improvement Potential

The fuel economy potential and cost estimates for turbocharging technology are presented in the table below.

Table 6. Turbocharging Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	7	650
NESCCAF-2004	6 to 9	560
CARB ISR-2004	6 to 9	-210 to 560
NAS – 2001	5 to 7	350 to 560

Analysis

The fuel economy improvement data for turbocharging are relatively consistent, with only the NAS study being slightly lower than other estimates of 7.5 + 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 that a turbocharger/intercooler package costs about $250 to 280 suggesting an RPE in the $400 to 450 range. Hence a $600 credit for downsizing from an 8-cylinder engine to a 6-cylinder engine (or a 6 to a 4) will result in a negative cost of about $150 to 200. However, emissions concerns with a port fuel injection and turbocharger package suggest that most manufacturers will pursue the GDI/turbocharger combination discussed above.

2.6 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 consumption 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. 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 high load, high 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.

Fuel Economy Improvement Potential

To date, the variable compression ratio technologies have not advanced beyond the prototype stage. In general the technology proved to be expensive and difficult to mass-produce, therefore, NESCCAF did not evaluate its fuel economy improvement potential. CARB staff, on the other hand, provide an estimate that the technology would be expected to provide about 8 percent fuel economy improvement benefits, although costs were not presented. In contrast, presentations by

Saab and FEV have forecast dramatically larger improvements of 35 to 30 percent in conjunction with supercharging. EEA has not specifically analyzed this technology in its 2003 report but simply used the mid-point of the NAS estimates for cost ad fuel economy.

The information from the studies examined is summarized in the table below.

Table 7. Variable Compression Ratio Fuel Economy Improvement Potential and Cost

Study	F/E Benefit (%)	RPE ($)
EEA-2001	4	350
NESCCAF-2004	Not Listed	448 to 616
CARB ISR-2004	8	Not Listed
NAS –2001	2 to 6	210 to 490

Analysis

Considerable uncertainty exists regarding both the costs and benefits of this technology and its synergy with other technologies. It is unlikely that manufacturers are pursuing such a complex technology for only a 4 to 8 percent gain in fuel economy, and gains of 20 to 30 percent would be required to justify its expense. Hence, the NESCCAF report strategy of not listing this technology for the time being may be appropriate.

2.7 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.

Camless valve actuation would open new possibilities to achieve optimum valve position and timing for maximum performance and fuel economy targets. These engines would not need intake air throttling and can deactivate any 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.

Valeo, a major French automotive systems supplier, has very recently announced acquisition of Johnson Control's engine electronics unit, which is a known expert in camless engines. Valeo believes that camless valve actuation has the potential to reduce fuel consumption by up to 35 percent and could be on the market by 2009.

Fuel Economy Improvement Potential

The fuel economy improvement potential and cost for camless valve actuation technology are summarized in the table below.

Table 8. Camless Valve Actuation Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	12	450 to 750
NESCCAF-2004	12 to 19	805 to 1540
CARB ISR-2004	12 to 19	564 to 1078
NAS – 2001	13 $\pm$ 5	360 to 770

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. 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 as no manufacturer has any public plan to introduce this system yet. The average of the NESCCAF and NAS study estimates suggests a fuel economy improvement potential of 14 percent, about 3 to 4 percent better than the BMW system. Costs should scale with number of cylinders. If we interpret the cost range provided as reflecting the cost for a 4-

cylinder engine at the low end and an 8 cylinder engine at the high end, the average cost is $580 for a 4-cylinder engine, $870 for a 6 and $1160 for an 8.

2.8 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 characterized 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 vehicles. 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.

Up to 20 percent reduction in FMEP is possible with further technology development at relatively low costs. 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.

Fuel Economy Improvement Potential

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 FEMP) 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. The table below summarizes these technology definitions.

Table 9. EEA-2000 Engine Friction Reduction Technology Definitions

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

*Baseline FEMP 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.

A table below summarizes the fuel economy potential and costs for EEA-2001 engine friction reduction technology evolutionary steps. The NESCCAF and CARB do not report costs and benefits for friction reduction separately. The figures are compared with only the NAS report

Table 10. Engine Friction Reduction Fuel Economy Improvements Potential and Costs

Study		F/E Benefit (%)	RPE ($)
EEA-2001	EFR I	2	25
	EFR II	1.5	38
	EFR III	1.5	50
	EFR IV	1.5	64
	Roller Cam	2	16 to 32
NAS -2001		1 to 5	35 to 140

Analysis

Since most engines now have improved to the EFR I level specified by EEA, the relevant comparisons are for the EFR II to EFR IV levels likely in the 2005 to 2015 time frame. Cumulatively they represent an improvement of 4.5 percent for cost of $152, and both these values are at the top end of the NAS estimate. Due to the greater specificity of the EEA estimate and the applicability in different time frames, the EEA estimates should be retained.

2.9 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:

- The oil separates opposing metal surfaces to prevent contact (hydrodynamic lubrication)
- 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 the primary factor affecting fuel economy.

Fuel Economy Improvement Potential

The fuel economy improvement potential and costs for improved lubricating oils are summarized in the table below.

Table 11. Improved Lubricating Oil Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	1	15
NESCCAF-2004	0.5	5 to 15
CARB ISR-2004	0.5	5 to 15
NAS –2003	1	8 to 11

Analysis

The NESCCAF and NAS studies do not specify exactly the type of lubricant that corresponds with the estimate, nor the term "RPE" for a technology that has to be periodically replaced over a vehicle's lifetime. EEA specifically referred to 5W-20 oil, and uses 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. BODY AND ACCESSORY TECHNOLOGIES

3.1 WEIGHT REDUCTION TECHNOLOGIES

Technology Description

A principal determinant of vehicle fuel economy is vehicle weight. Lower vehicle weight reduces the forces required to accelerate the vehicle and maintain steady speeds, which in turn reduces fuel consumption. 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.

Packaging reflects the ratio of interior volume to exterior size and total weight. Improved packaging is estimated to be a zero 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.

Fuel Economy Improvement Potential

The fuel economy improvement potential and cost for vehicle mass reduction technologies are summarized in a table below. The costs are expressed on per-pound basis. It should be noted that CARB was specifically directed by California legislature not to adopt any regulations that would require reduction in vehicle weight. As a result, the weight reduction information is omitted from the CARB report.

Table 12. Weight Reduction Technologies Fuel Economy Improvements and Costs (5% weight reduction)

Study	F/E Benefit (%)	RPE ($/lb)
EEA-2001 Material substitution	3.3	0.60 (HSLA) 0.90 (Composites)
NESCCAF-2004	2.8 to 3.0	1.30
CARB ISR-2004	Not Evaluated	Not Evaluated
NAS-2003	3 to 4	0.75

Analysis

The NAS and NESCCAF reports are not very specific about the type of weight reduction technology considered. There are some zero cost opportunities such as improved packaging and conversion to unit body architecture. However, material substitution is the most widely applicable technology and we expect that the estimates are based on this potential. The NAS cost estimate is consistent with EEA's estimates for a mix of HSLA and composite use (which is common in material substitution programs today) while the NESSCAF estimate of cost is close to EEA's estimate for aluminum use in sheet metal components. Fuel economy estimates for NESCCAF do not account for any engine size reduction and are, therefore, somewhat lower than the EEA and NAS estimates. The 3.3 to 3.5 percent reduction per 5 percent weight reduction at a cost of $0.75 per pound saved is a defensible estimate.

3.2 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 is directly proportional to the load supported by the tire, and the ratio of the force to the weight 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 5 to 7 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.

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. 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.

While tires with C_R values as low as 0.006 are commercially available (such as the ones used in the GM electric vehicle), the main issue has always been the tradeoff with other tire parameters that are desired by the customer, such as traction, braking in wet and dry conditions, noise and durability. 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 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. In addition, the value reported does not generally indicate which test has been used. Anecdotal evidence from experts indicates that most normal (i.e., not performance oriented) tires have C_R values of between 0.008 to 0.012 as measured by the SAE method.[1] Performance tires used in luxury and sports cars, and often in high performance versions of family sedans, use tires which have C_R values of (SAE) 0.011 to 0.013. Light truck tires for compact van applications have C_R values of 0.010 to 0.009 while four-wheel drive trucks and SUVs feature tires with C_R values of 0.012 to 0.014. Anecdotal evidence also suggest that current passenger car C_R is around 0.010, and light truck tire C_R is about 0.0115.

Fuel Economy Improvement Potential

The fuel economy improvement potential and costs for the rolling resistance reduction technologies are summarized in a table below.

Table 13. Rolling Resistance Reduction Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	2	45
NESCCAF-2004	2.2 to 2.5	20 to 90
CARB ISR-2004	2	20 to 90
NAS – 2001	1 to 1.5	14 to 56

Analysis

The NAS and NESCCAF reports are not specific about the extent of rolling resistance reduction assumed, but the EEA estimate is for a 10 percent reduction, which is the typical reduction per decade experienced since 1980. There is widespread agreement that 10 percent rolling resistance

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1 The Society for Automotive Engineers (SAE) has defined a test procedure for measuring the RRC of a tire alone, as opposed to the whole wheel.

reduction results in a 2 percent fuel economy gain and the $45 cost estimate by EEA is at the midpoint of the NESCCAF estimate range. These values can be used for the cost curves.

3.3 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 is 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 0.45 to 0.50, with vans typically having coefficients between 0.38 and 0.40. It is generally believed that each 10 percent reduction in drag is associated with a 2.3 percent increase in fuel economy, provided other changes are made to keep performance constant.

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. Auto manufacturers have generally agreed that a C_D level of 0.24 and 0.25 for cars is attainable without sacrificing consumer attributes.

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.

The potential for C_D reduction in trucks is quite different. 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 0.46/0.47. 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.

Fuel Economy Improvement Potential

The fuel economy improvement potential and costs for the drag reduction technologies are summarized in the table below.

Table 14. Aerodynamic Drag Reduction Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	2.3	40
NESCCAF-2004	1.6 to 1.9	0 to 125
CARB ISR-2004	1.6 to 1.9	0 to 125
ADL-2003	1 to 2	0 to 140

Analysis

As with the other body related technologies, the NESCCAF and NAS reports are not specific about the levels of drag reduction assumed and how cost numbers were derived. The fuel economy benefit appears to be for a 10 percent drag reduction, as is the case of the estimate by EEA. However, newer vehicles already have reduced drag co-efficient so that the contribution of drag to fuel consumption is smaller, Hence a 1.8 percent increase in fuel economy for a 10 percent drag reduction may be more defensible. An average cost of $65 could be associated with this drag reduction based on an average of the 3 estimates.

3.4 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.

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.

Fuel Economy Improvement Potential

Tables below summarized the fuel economy improvement potential of improved alternator and electric power steering as reported in the studies analyzed.

Table 15. Improved Alternator Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	0.3	15
NESCCAF-2004	0 to 1	56
CARB ISR-2004	0 to 1	56
NAS – 2001	1 to 2	84 to 112

Table 16. Electric Power Steering Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	2	50
NESCCAF-2004	1	28 to 56
CARB ISR-2004	1	20 to 39
NAS –2001	1.5 to 2.5	105 to 150

Analysis

The data for the alternator improvement is very inconsistent and the 1 to 2 percent improvement in FE appears impossibly high since the alternator does not consume very much energy during the FTP test. The 1 percent value may be reasonable for improvements to the alternator, water pump and oil pump combined as is the NESCCAF cost estimate of $28 to$56. These values can be selected for all accessories combined and the selected values are a 1 percent improvement for a cost of $42.

3.5 42-VOLT SYSTEM

Technology Description

The use of 42-Volt electrical systems can provide more electrical power, and associated benefits, for vehicles. In typical vehicle applications, wiring and connector designs limit maximum current to 250 to 300 amperes. So with current 12-Volt systems, peak available electrical power is 2.5kW to 3kW. Cabin comfort and convenience options in current luxury vehicles impose total electrical loads close to the available limit. Since the total available power can be increased by maintaining current wiring and connectors but raising system voltage, a move to 42 Volts is desirable.

In addition to providing more power for comfort and convenience options, 42 Volt systems also enable a number of fuel economy-related features, such as:

- engine off at idle
- launch assist
- regenerative braking

While any of these (except launch assist) can be accomplished using current 12-Volt systems, the margin of power available on current systems is a major limitation. However, in contrast to the 3kW available with current 12-Volt systems, 42-Volt systems can provide up to 12kW maximum power and, thereby, accommodate significant power-related upgrades.

In 42-Volt systems, the existing vehicle starter and alternator are replaced by a combined starter/alternator. The simplest implementation is a belt-driven starter alternator, but such systems cannot provide meaningful launch assist or regenerative braking. A more complex system (in terms of implementation) is one where the starter/alternator is sandwiched between engine and transmission. This type of system can provide launch assist, regenerative braking and other benefits such as reduction in required torque converter size, and a reduction in engine torque pulsation that would improve vibration and harshness levels. However, the space requirements for a crankshaft-mounted system require a redesign of the driveline, especially in transverse mounted front wheel drive vehicles, where driveline length is space constrained.

In general, in order to achieve more economical package, the current technology trend is for manufacturers to only provide 42-Volt capability where needed on the vehicle rather than converting the entire vehicle to 42-Volts. The complete conversion of the vehicle systems to 42-Volts, widely discussed and anticipated a few years ago, did not materialize. For example, BMW and Daimler Chrysler have dropped plans to put 42-volt on-board electrical networks in their cars. Both companies indicated that costs for all the new components are too great because each electrical component from an interior light to the ABS sensor would need to be redesigned.

Another problem is that all plug and socket connections need to meet significantly higher standards. An electric arc, for example, could give off a hundred times as much energy through a loose contact than before.

Fuel Economy Improvement Potential

Tables below summarized the fuel economy improvement potential 42-Volt systems as reported in the studies analyzed.

Table 17. 42V with Engine Off at Idle: Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	4.5	800
NESCCAF-2004	4 to 8	Not Reported
CARB ISR-2004	4 to 8	559 (Small Car Only)
NAS -2001	NA	NA

Table 18. 42V Integrated Launch Assist and Regeneration: Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	7.5	1,400
NESCCAF-2004	5 to 11	1,582
CARB ISR-2004	5 to 11	1,107
NAS -2001	5 to 9	280 to 630

Analysis

The benefits of idle-off strategy with 42V has been examined in some detail by EEA and its costs and benefit estimates are consistent with those from CARB after adjusting for the fact that they reduced costs by 30 percent somewhat arbitrarily. For the 42V ISAD system, the EEA and NESCCAF numbers are in reasonable agreement and an estimate of 8 percent benefit with a cost of $1500 is selected.

4. TRANSMISSION TECHNOLOGIES

4.1 OVERVIEW

Technologies that affect the efficiency of the transmission and drivetrain offer opportunities for substantial fuel economy improvements. The following transmission technologies were examined in the report:

- Five and six-speed automatic transmissions
- Continuously Variable Transmission
- Automated manual transmission
- Early torque converter lock-up
- Aggressive shift logic

4.2 FIVE AND SIX-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 driveability 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. It is offered on such mainstream models as Toyota Camry and Honda Accord.

Six-speed automatic transmissions have been available for a few years and are transitioning into the mainstream market. Ford and GM have recently announced the joint development of a new 6-speed automatic transmission designed for wide variety of front wheel drive vehicles, including full size SUVs, with production starting in 2006.

Fuel Economy Improvement Potential

Tables below summarize the fuel economy improvement potential for five and six-speed automatic transmissions, as reported in the studies analyzed.

Table 19. 5-Speed Automatic Transmission Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	2.5	125
NESCCAF-2004	1 to 2	140
CARB ISR-2004	1 to 2	140
NAS -2001	2 to 3	70 to 154

Table 20. 6-Speed Automatic Transmission Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	4	210
NESCCAF-2004	2 to 3	70 to 112
CARB ISR-2004	2 to 3	70 to 112
ADL-2003	3 to 5	210 to 434

Analysis

The fuel economy benefit estimates by EEA and NAS for 5 speed automatic transmissions are in agreement, and all of the cost estimates fall within the range of uncertainty. The NESCCAF and ARB fuel economy benefit estimates for both 6 speed and 5 speed transmissions are lower than EEA and NAS estimates and likely incorrect as Ford and GM have publicly claimed benefits of 4 to 4.5 percent for the six speed unit. On the other hand, the EEA and NAS data on costs do not reflect the recent technology advances on 6 speed transmissions, which are now cheaper to produce than the 5 speed unit. Hence, the fuel economy benefit based on EEA/NAS estimates coupled with NESSCAF cost estimate is a reasonable compromise.

4.3 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, when gear shifting is 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.

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", is available on Audi TT and A3 and is a double clutch design. The technology was also announced for the new MY 2006 VW Jetta.

Fuel Economy Improvement Potential

The table below summarizes the fuel economy improvement potential for the automated manual transmissions, as reported in the studies analyzed.

Table 21. Automated Manual Transmission Fuel Economy Improvement and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	3.5	-185
NESCCAF-2004	5 to 9	0
CARB ISR-2004	5 to 9	0
NAS -2001	3 to 6	70 to 215

Analysis

It is not clear that the references are consistent in the technology definitions, as the EEA estimates refer to a single clutch unit while the NESCCAF report refers to a double clutch unit, while the NAS reference is not clear. The NESCCAF report's estimates are more consistent with recent information obtained from transmission suppliers and a fuel economy benefit estimate of 7 percent at zero cost is accepted for the cost curves.

4.4 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. 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.

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 has recently decided to discontinue its CVT, used in the Saturn Ion and Vue, after the 2004 model year. The CVT is standard equipment on the 2005 Ford Freestyle and optional on the 2005 Ford Five Hundred, but availability of the transmission has been limited. Toyota is using CVT on the Prius HEV. Audi offers it on the A4 line. Nissan is the only manufacturer to offer a full CVT lineup for small, medium and large class passenger vehicles. The company plans to quadruple the number of its vehicles worldwide equipped with CVTs to about 1 million per year, or 24 percent of its global sales, by 2008. Currently, the Murano SUV is the only Nissan or Infiniti vehicle equipped with a CVT sold in the U.S. market. A CVT is standard equipment on the Murano, mated to a 3.5-liter V6 that produces 265 horsepower.

Fuel Economy Improvement Potential

Nissan estimates its CVTs offer a 10 percent –12 percent improvement in fuel efficiency compared to a conventional 4 speed automatic. It should be noted, however, that this improvement is not as relevant, as other gear-based 5 and 6 speed transmissions become mainstream technology.

The CVT fuel economy improvement potential and its costs are summarized in a table below.

Table 22. CVT Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	6	130
NESCCAF-2004	3 to 4	210 to 245
CARB ISR-2004	3 to 4	210 to 245
NAS -2001	4 to 8	140 to 350

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 for smaller engines. Ford has acknowledged that the CVT and 6 speed automatic provide almost equivalent benefits, and the CVT costs a little more than the 6 speed. Hence, we believe that the CVT will be used only in small cars, where the fuel economy gains are in the order of six percent and cost is about $140. In larger cars and trucks, it is not clear if the CVT has any benefit relative to the 6 speed and may not be used if costs are not competitive.

4.5 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:

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

upshifts. However, earlier upshift result in some loss of driveability, 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.

Fuel Economy Improvement Potential

Tables below summarized the fuel economy improvement potential for early torque converter lockup and aggressive shift logic technologies, as reported in the studies analyzed.

Table 23. Early Torque Converter Lockup Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	0.5	8
NESCCAF-2004	0.5	0 to 10
CARB ISR-2004	0.5	0 to 10
NAS –2001	NA	NA

Table 24. Aggressive Shift Logic Fuel Economy Improvements and Costs

Study	F/E Benefit (%)	RPE ($)
EEA-2001	2	60
NESCCAF-2004	1.5	0 to 50
CARB ISR-2004	1.5	0 to 50
NAS – 2001	1 to 3	0 to 70

Analysis

All of the analyses are reasonably consistent for early lockup and aggressive shift logic, and fuel economy values of 0.5 and 2 percent can be selected along with cost of $5 and $30 as a mean of the estimates for early lockup and aggressive shift logic, respectively.

5. FORECASTS OF LIGHT TRUCK FUEL ECONOMY BY SIZE CLASS

The forecasts of fuel economy potential by size class rely on an established methodology developed by EEA over the last 20 years. The analysis starts from a known baseline of vehicle attributes, technology level and measured fuel economy so that the estimates always are referenced to an observed, not theoretical, set of vehicle characteristics. In this analysis, we have combined vehicles by market class where each market class is defined by size and type. The light truck market is divided into four types : pickup trucks, vans, sport utility vehicles (SUV) and "crossover" utility vehicles. Each vehicle type is further subdivided by size into three size classes: small, midsize and standard. Vehicles are not present in all 12 combinations of size and type but 10 of 12 possibilities have models (there are no standard size crossover utility vehicles or small vans).

For each size/type class, we have started with the reference as the most popular (i.e. highest sales) model as the "baseline" and used the EPA test car list based fuel economy values for 2005 as the starting point for the analysis. Technologies available for use on this specific model would include all applicable technologies identified in sections 2 to 4 of this report except for those already in use in the selected model. The combined fuel improvement from the simultaneous use of multiple technologies is estimated by three different methods

- the use of lumped parameter model developed initially by GM research staff and since expanded by EEA
- data from detailed second-by-second simulation models such as ADVISOR developed for the Freedom Car program
- actual data from some high fuel economy models already utilizing the same or nearly same combination of technologies

Each particular method has advantages and problems and the use of three separate techniques provides for a more balanced approach to forecasting.

The technologies have been divided into two groups for this analysis. The first group of technologies include those that are widely planned for introduction by manufacturers into a variety of products by 2010, though not all technologies may be planned for all products. The second group of technologies are those that have been introduced in some vehicles by some manufacturers but are not likely to be adopted across a majority of models by 2010 in the absence of an external forcing function such as CAFÉ standards. It should be noted that manufacturers are not in a position to adopt these technologies across all product lines by 2010 but could adopt them in some product lines. Tables 5-1 to 5-10 (submitted separately from this report) provide these forecasts for each of the 10 market classes described above. The tables show that improvements in the range of 10 to 15 percent are possible using only the first group of technologies, while improvements of up to 22 percent are possible using all available technologies. In addition, hybrid and diesel technologies can provide much higher improvements for some part of the fleet.

APPENDIX A: ABBREVIATIONS LIST

A/C	Air Conditioning
ABS	Antilock Braking System
ADL	Arthur D. Little
AMT	Automated Manual Transmission
ASL	Aggressive Shift Logic
CARB	California Air Resources Board
C_D	Drag Coefficient
CH_4	Methane
CO_2	Carbon Dioxide
CR	Compression Ratio
C_R	Rolling Resistance Coefficient
CVT	Continuously Variable Transmission
DISC	Direct Injection Stratified Charge
DOHC	Dual Overhead Cam
ECU	Electronic Control Unit
EEA	Energy and Environmental Analysis
EFR	Engine Friction Reduction
EPA	The US Environmental Protection Agency
ETC	Electronic Transmission Control
F/E	Fuel Economy
FE	Fuel Economy
FMEP	Friction Mean Effective Pressure
FSI	Fuel Stratified Injection
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GHG	Greenhouse Gases
GM	General Motors
GWP	Global Warming Potential
HEV	Hybrid Electrical Vehicle

HSLA	High Strength Low Alloy
I3	3-Cylinder "In-line" engine
I4	4-Cylinder "In-line" engine
ISAD	Integrated Starter Alternator Damper
ISR	Initial Statement of Reasons
i-VTEC	Intelligent Variable Valve Timing Electronic Control (Honda)
MY	Model Year
N_2O	Nitrous Oxide
NAS	National Academy of Sciences
NESCCAF	Northeast States Center for a Clean Air Future
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OHC	Overhead Cam
OHV	Overhead Valve
RPE	Retail Price Equivalent
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
SBR	Styrene Butadiene Rubber
SL	Secondary Loop
SUV	Sport Utility Vehicle
V6	6-Cylinder "V" configuration engine
V8	8-Cylinder "V" configuration engine
VCM	Variable Cylinder Management
VTEC	Variable Valve Timing Electronic Control (Honda)
VVL	Variable Valve Lift
VVT	Variable Valve Timing
VW	Volkswagen

APPENDIX B: REFERENCES

EEA-2001	*Technology and Cost of Future Fuel Economy Improvements for Light-Duty Vehicles*, prepared by Energy and Environmental Analysis, Inc. for the National Academy of Sciences, June 2001.
NESCCAF-2004	*Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles*, prepared by Northeast States Center for a Clean Air Future, September 2004.
CARB ISR-2004	*Staff Report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Gas Emissions From Motor Vehicles*, California Air Resources Board, August 6, 2004.
NAS-2001	*Effectiveness and Impact of Corporate Average Fuel Economy (CAFÉ) Standards*, National Academy of Sciences Report, 2001

TABLE 5-1: COMPACT UNIBODY SUV

2005 MODEL FUEL ECONOMY (ORDERED BY SALES FOR CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
FORD	ESCAPE		140	153	L4	27.11	25.99	133.9
HONDA	CR-V		144	160	L5	29.66	28.04	128.0
GM	VUE		134	140	CVT	29.05	27.84	117.1
TOYOTA	RAV-4		144	161	L4	30.87	28.30	111.2

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 FORD ESCAPE BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
DUAL VVT	2.5 ± 0.3	75	HP INCREASES BY 3%
FRICTION RED.	2.0 ± 0.5	25	FMEP REDUCTION: 10%
CVT	5.0 ± 0.5	150	
DRAG REDUCTION	1.8 ± 0.2	45	Cd REDUCTION BY 10%
TIRE IMPROVEMENT	0.7 ± 0.1	20	Cr REDUCTION BY 5%
NEW SAFETY EQPT.	-1.0		
SYNERGY EFFECTS	-1.0		
TOTAL	10.0 ± 0.8	315	ENGINE SIZE CONSTANT, WEIGHT INCREASE: 60LBS

NET FUEL ECONOMY : 29.8/ 28.6 MPG (2WD/2WD)

PACKAGE 2 (IN ADDITION TO PACKAGE 1)

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 ± 0.3	175	WT. REDUCTION 160 LBS.
VVLT	4.0 + 0.3	160	HP/CID INCREASE BY 10%
AUTOMATED MANUAL	1.0 ± 0.2	50	
DIRECT INJECTION	3.5 ± 0.5	125	CR INCREASE TO 12:1
ELEC. STEERING	2.2 ± 0.2	60	
SYNERGY EFFECTS	-0.5		
TOTAL	13.5 ± 0.5	445	ENGINE SIZE: 2L, NET WEIGHT DECREASE: 120LB

NET FUEL ECONOMY : 33.5/ 32.1 MPG (2WD/4WD)

TABLE 5-2: MIDSIZE UNIBODY SUV

2005 MODEL FUEL ECONOMY (ORDERED BY SALES FOR CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
TOYOTA	HIGHLAND.		202	230	L5	25.00	24.07	144.5
HONDA	PILOT		212	255	L5	NA	21.73	176.9
D-C	PACIFICA		215	249	L4	22.35	21.73	156.3
NISSAN	MURRANO		213	245	CVT	25.85	25.50	142.5
FORD	FREESTYLE		182	201	CVT	26.51	23.73	169.0
GM	RENDEZV.		218	245	L4	24.90	23.81	156.5

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 D-C PACIFICA BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
VVT (COMBINED)	1.8 $\pm$ 0.3	50	HP INCREASES BY 3%
FRICTION RED.	2.0 $\pm$ 0.5	25	FMEP REDUCTION: 10%
CVT	5.0 $\pm$ 0.5	150	
DRAG REDUCTION	1.8 $\pm$ 0.2	45	Cd REDUCTION BY 10%
5W-20 OIL	0.5 + 0.1	15	
TIRE IMPROVEMENT	0.7 $\pm$ 0.1	20	Cr REDUCTION BY 5%
NEW SAFETY EQPT.	-1.0		
SYNERGY EFFECTS	-1.2		
TOTAL	9.5 $\pm$ 0.8	305	ENGINE SIZE CONSTANT, WEIGHT INCREASE: 75LBS

NET FUEL ECONOMY : 24.45/ 23.8 MPG (2WD/4WD)

PACKAGE 2 (IN ADDITION TO PACKAGE 1)

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 $\pm$ 0.3	240	WT. REDUCTION 210 LBS.
CYLINDER CUT	6.5 $\pm$ 0.5	180	INCLUDES NVH CONTROL
ALTERNATOR IMPR.	0.5 $\pm$ 0.1	20	HIGH EFFICIENCY
ELECTRIC POWER STEERING	2.2 $\pm$ 0.2	60	REQUIRES IMPROVED ELECTRICAL POWER
SYNERGY EFFECTS	0		
TOTAL	12.5 $\pm$ 0.6	500	ENGINE SIZE : 3.3L, NET WEIGHT DECREASE: 125LB

NET FUEL ECONOMY : 27.25/ 26.5 MPG (2WD/4WD)

TABLE 5-3: COMPACT VAN

2005 MODEL FUEL ECONOMY (ORDERED BY SALES IN CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
D-C	CARAVAN		231	215	L4	23.63	NA	170.3
TOYOTA	SIENNA		202	230	L5	25.07	23.92	177.4
HONDA	ODYSSEY		212	255	L5	26.45*	NA	184.1
FORD	FREESTAR		238	193	L4	23.42	NA	172.9
GM	UPLANDER		213	200	L4	23.64	NA	169.0
NISSAN	QUEST		213	240	L5	24.50	NA	182.0

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 D-C CARAVAN BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
VVT (COMBINED)	1.8 ± 0.3	50	HP INCREASES BY 3%
OHC 4-VALVE	4.0 ± 0.5	180	ENG. SIZE REDUCED 10%
CVT	5.0 ± 0.5	150	
5W-20 OIL	0.5 + 0.1	15	
TIRE IMPROVEMENT	0.7 ± 0.1	20	Cr REDUCTION BY 5%
NEW SAFETY EQPT.	-1.2		
SYNERGY EFFECTS	-1.7		
TOTAL	9.5 ± 0.8	305	ENGINE SIZE: 3.5L, WEIGHT INCREASE: 100LBS

NET FUEL ECONOMY : 25.9 MPG

PACKAGE 2

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 ± 0.3	260	WT. REDUCTION 210 LBS.
CYLINDER CUT	6.5 ± 0.5	180	INCLUDES NVH CONTROL
DIRECT INJECTION	3.5 ± 0.5	170	CR INCREASE TO 12:1
ALTERNATOR IMPR.	0.5 ± 0.1	20	HIGH EFFICIENCY
ELECTRIC POWER STEERING	2.2 ± 0.2	60	REQUIRES IMPROVED ELECTRICAL POWER
SYNERGY EFFECTS	-0.5		
TOTAL	15.5 ± 0.8	690	ENGINE SIZE : 3.2L, NET WEIGHT DECREASE: 100LB

NET FUEL ECONOMY : 29.5 MPG

TABLE 5-4: COMPACT SUV

2005 MODEL FUEL ECONOMY (ORDERED BY SALES IN CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
D-C	LIBERTY		226	210	L5	22.70	22.00	134.5
NISSAN	XTERRA		202	230	L5	25.07	23.92	135.0
D-C	WRANGLER		242	190	L4	NA	18.30	107.1
GM	BLAZER		262	190	L4	21.70	19.65	138.6

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 D-C LIBERTY BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
VVT (COMBINED)	1.8 ± 0.3	50	HP INCREASES BY 3%
6 SPEED AUTO.	2.5 ± 0.5	0	RELATIVE TO 5-SPD.
DRAG REDUCTION	1.5 + 0.2	45	Cd REDUCTION BY 8%
5W-20 OIL	0.5 + 0.1	15	
TIRE IMPROVEMENT	0.7 ± 0.1	20	Cr REDUCTION BY 5%
NEW SAFETY EQPT.	-1.0		
SYNERGY EFFECTS	-0.3		
TOTAL	5.7 ± 0.6	130	ENGINE SIZE: 3.7L, WEIGHT INCREASE: 65 LBS

NET FUEL ECONOMY : 24.0/ 23.25 MPG (2WD/4WD)

PACKAGE 2 (IN ADDITION TO PACKAGE 1)

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 ± 0.3	240	WT. REDUCTION 180 LBS.
CYLINDER CUT	7.5 ± 0.5	180	INCLUDES NVH CONTROL
ALTERNATOR IMPR.	0.5 ± 0.1	20	HIGH EFFICIENCY
DIRECT INJECTION	3.5 + 0.5	175	CR INCREASED TO 12:1
SYNERGY EFFECTS	-0.8		
TOTAL	14.0 ± 0.6	615	ENGINE SIZE : 3.3L, NET WEIGHT DECREASE: 110LB

NET FUEL ECONOMY : 26.95/ 26.1MPG (2WD/4WD)

TABLE 5-5: MIDSIZE SUV

2005 MODEL FUEL ECONOMY (ORDERED BY SALES IN CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
FORD	EXPLORER		244	210	L5	20.5	19.25	151.7
GM	TRAILBLAZ.		254	275	L4	20.9	20.03	154.1
D-C	GRAND CHEROKEE		242	195	L4	21.6	21.3	148.1
TOYOTA	4RUNNER		241	245	L5	23.42	21.68	145.2
NISSAN	PATHFINDER		241	270	L5	21.80	20.15	165.6

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 FORD EXPLORER BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
VVT (COMBINED)	1.8 ± 0.3	50	HP INCREASES BY 3%
6 SPEED AUTO.	2.5 ± 0.5	0	RELATIVE TO 5-SPD.
DRAG REDUCTION	1.5 + 0.2	45	Cd REDUCTION BY 8%
3-VALVES/CYL.	4.0 + 0.4	160	HP INCREASED BY 20%
TIRE IMPROVEMENT	0.7 ± 0.1	20	Cr REDUCTION BY 5%
NEW SAFETY EQPT.	-1.0		
SYNERGY EFFECTS	-0.5		
TOTAL	10.0 ± 0.75	275	ENGINE SIZE: 4.0L, WEIGHT INCREASE: 75 LBS

NET FUEL ECONOMY : 22.5/ 21.2 MPG (2WD/4WD)

PACKAGE 2 (IN ADDITION TO PACKAGE 1)

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 ± 0.3	260	WT. REDUCTION 210 LBS.
CYLINDER CUT	7.0 ± 0.5	180	INCLUDES NVH CONTROL
ALTERNATOR IMPR.	0.5 ± 0.1	20	HIGH EFFICIENCY
DIRECT INJECTION	3.5 + 0.5	175	CR INCREASED TO 12:1
SYNERGY EFFECTS	-0.8		
TOTAL	13.5 ± 0.6	615	ENGINE SIZE : 3.5L, NET WEIGHT DECREASE: 125LB

NET FUEL ECONOMY : 25.3/ 23.8 MPG (2WD/4WD)

TABLE 5-6: STANDARD SUV

2005 MODEL FUEL ECONOMY (ORDERED BY SALES IN CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
GM	TAHOE		325	295	L4	19.65	18.34	184.3
FORD	EXPEDITION		330	300	L4	18.46	17.85	178.8
D-C	DURANGO		348	345	L5	18.15	17.34	175.2
TOYOTA	SEQUOIA		285	282	L5	19.36	18.84	180.6
NISSAN	ARMADA		339	305	L5	18.10	17.50	208.4

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 GM TAHOE BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
VVT (COMBINED)	1.8 ± 0.3	50	HP INCREASES BY 3%
6 SPEED AUTO.	4.5 ± 0.5	140	
DRAG REDUCTION	1.8 + 0.2	45	Cd REDUCTION BY 10%
CYLINDER CUT	6.5 + 0.4	160	
TIRE IMPROVEMENT	0.7 ± 0.1	20	Cr REDUCTION BY 5%
NEW SAFETY EQPT.	-1.0		
SYNERGY EFFECTS	-1.5		
TOTAL	12.8 ± 0.8	275	ENGINE SIZE: 5.0L, WEIGHT INCREASE: 90LBS

NET FUEL ECONOMY : 22.15/ 20.7 MPG (2WD/4WD)

PACKAGE 2 (IN ADDITION TO PACKAGE 1)

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 ± 0.3	310	WT. REDUCTION 250 LBS.
ALTERNATOR IMPR.	0.5 ± 0.1	25	HIGH EFFICIENCY
DIRECT INJECTION	3.5 + 0.5	225	CR INCREASED TO 12:1
SYNERGY EFFECTS	-0.3		
TOTAL	7.0 ± 0.6	615	ENGINE SIZE : 4.6L, NET WEIGHT DECREASE: 145LB

NET FUEL ECONOMY : 23.55/ 22.0 MPG (2WD/4WD)

TABLE 5-7: COMPACT PICKUP

2005 MODEL FUEL ECONOMY (ORDERED BY SALES IN CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
TOYOTA	TACOMA		241	245	L5	23.50	23.25	NA
GM	COLORADO		211	215	L4	24.40	23.01	NA
FORD	RANGER		242	207	L5	21.82	20.17	NA
D-C	DAKOTA		226	201	L4	21.55	19.65	NA
NISSAN	FRONTIER		241	270	L5			NA

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 GM COLORADO BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
6 SPEED AUTO.	4.5 ± 0.5	140	
DRAG REDUCTION	1.5 ± 0.2	45	Cd REDUCTION BY 8%
5W-20 OIL	0.5 ± 0.1	15	
NEW SAFETY EQPT.	-1.0		
SYNERGY EFFECTS	0		
TOTAL	5.5 ± 0.5	200	ENGINE SIZE: 3.5L, WEIGHT INCREASE: 55 LBS

NET FUEL ECONOMY : 24.80/ 24.50 MPG (2WD/4WD)

PACKAGE 2 (IN ADDITION TO PACKAGE 1)

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 ± 0.3	220	WT. REDUCTION 175LBS.
VVL	4.5 ± 0.4	180	HP INCREASE BY 20%
ALTERNATOR IMPR.	0.5 ± 0.1	20	HIGH EFFICIENCY
DIRECT INJECTION	3.5 + 0.5	175	CR INCREASED TO 12:1
SYNERGY EFFECTS	-0.8		
TOTAL	11.0 ± 0.6	595	ENGINE SIZE : 3.2L, NET WEIGHT DECREASE: 110LB

NET FUEL ECONOMY : 27.35/ 27.1MPG (2WD/4WD)

TABLE 5-8: STANDARD PICKUP

2005 MODEL FUEL ECONOMY (ORDERED BY SALES IN CY2005)

MFR.	MODEL		CID	HP	TRAN.	FE (2WD)	FE (4WD)	INT. VOL.
FORD	F-150		330	300	L4	19.40	18.28	NA
GM	SILVERADO		325	295	L4	20.48	19.18	NA
D-C	RAM		348	345	L5	17.44	15.97	NA
TOYOTA	TUNDRA		285	282	L5	20.32	18.96	NA
NISSAN	ARMADA		339	305	L5	18.10	17.50	NA

TECHNOLOGIES AND FUEL ECONOMY IMPROVEMENTS – 2005 FORD F-150 BASELINE

PACKAGE 1

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
6 SPEED AUTO.	4.5 ± 0.5	140	
DRAG REDUCTION	1.8 + 0.2	45	Cd REDUCTION BY 10%
CYLINDER CUT	6.5 + 0.4	150	
TIRE IMPROVEMENT	0.7 ± 0.1	25	Cr REDUCTION BY 5%
NEW SAFETY EQPT.	-1.0		
SYNERGY EFFECTS	-1.2		
TOTAL	11.3 ± 0.8	360	ENGINE SIZE: 5.4L, WEIGHT INCREASE: 90LBS

NET FUEL ECONOMY : 21.6/ 20.35 MPG (2WD/4WD)

PACKAGE 2 (IN ADDITION TO PACKAGE 1)

TECHNOLOGY	FE BENEFIT %	RPE $	COMMENT
WEIGHT REDUCTION	3.3 ± 0.3	300	WT. REDUCTION 240 LBS.
ALTERNATOR IMPR.	0.5 ± 0.1	25	HIGH EFFICIENCY
DIRECT INJECTION	3.5 + 0.5	225	CR INCREASED TO 12:1
SYNERGY EFFECTS	-0.3		
TOTAL	7.0 ± 0.6	615	ENGINE SIZE : 4.8L, NET WEIGHT DECREASE: 145LB

NET FUEL ECONOMY : 22.95/ 21.65 MPG (2WD/4WD)