Chapter 3

Where Does Improved Fuel Efficiency Come From?

Automobile fuel economy can be improved by two basically different kinds of measures—reducing the loads on the automobile, thus reducing the work needed to move it; and increasing the efficiency of converting energy contained in the fuel to work. The loads consist of the force needed to accelerate the auto (to overcome inertia), air resistance, and rolling resistance of the tires. The efficiency of conversion is determined by the efficiencies of the drivetrain components—engine, transmission, and axles, and all auxiliaries, including cooling system, alternator, fuel pump, lighting, power steering, and so forth.

In city driving, the three types of loads on the automobile are comparable.[1] In steady, level driving, the inertia load is essentially zero, but most urban driving consists of repeated acceleration and deceleration, making the inertia load high. Because the force needed to accelerate a vehicle is purely a function of weight, weight reduction through improved design, acceptance of less space, or materials substitution is a critical factor in fuel economy, especially for the urban part of the cycle. On the highway, however, air resistance tends to dominate the total load, because resistance increases with the square of velocity-wind resistance at 60 mph is 9 times resistance at 20 mph [(60/20)2]. Thus, reducing the aerodynamic load on the auto by increasing its "slipperiness" (reducing its drag coefficient) or reducing its cross-sectional area will greatly improve highway fuel economy and have a small but important effect on all but very low-speed urban driving.

Aside from reducing the loads, fuel economy can be improved by improving the engine's efficiency in converting fuel chemical energy into mechanical energy delivered to the wheels. The conversion of chemical to heat energy and then to mechanical energy results in an energy loss inversely proportional to combustion temperature (i.e., the higher the temperature, the lower the loss). Current limitations in the ability of materials to function at very high temperatures (as well as emissions regulations, especially for nitrogen oxides) limit combustion temperature to a level that results in a theoretical 70-percent maximum utilization of the total energy available in the fuel. Other practical considerations related to the combustion cycle result in gasoline engines having an efficiency of only 35 to 38 percent at their optimal operating points (i.e., this is their peak efficiency). Since the Federal Test Procedure driving cycle has variable loads and speeds, engines operate well below their peak for significant portions of the test cycle (this is true as well for most normal driving). At idle, for example, engine "efficiency" is zero. On average, over the entire fuel economy test, the engine operating efficiency is about one-half peak efficiency.

The engine average efficiency can be improved by three different methods: increasing thermodynamic efficiency, reducing frictional losses, and reducing pumping losses (pumping losses are the energy needed to pump air and fuel into the cylinder and push out the products of combustion). The first, increasing thermodynamic efficiency, is limited by the characteristics of the spark ignition engine. Increasing the compression ratio increases thermodynamic efficiency; but other parameters related to fuel octane, nitrogen oxide emissions, and friction (emissions and friction increase with increasing compression ratio, and the octane level limits how high the ratio can go without obtaining premature combustion) result in declining benefits as compression ratios in-

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[1] M. Ross, "Energy and Transportation in the United States," *Annual Review of Energy 1989*, vol. 14, pp. 131–171, figure 9.

[2] Energy & Environmental Analysis, Inc., *An Assessment of Potential Passenger Car Fuel Economy Objectives for 2010*, draft final report to 'he Environmental Protection Agency, Air and Energy Policy Division, February 1991.

crease from today's 9.0 to 10.0 and beyond. Combustion chamber redesign can provide small increases in thermal efficiency. Higher thermodynamic efficiencies can also be achieved with compression ignition (diesel) engines.

Mechanical friction can be reduced by improving design of rubbing and sliding surfaces or using new materials and lubricants. Decreasing the weight of the piston, connecting rod, valves, and valve springs also reduces frictional losses. Replacing sliding contact surfaces with rolling contacts can provide significant benefits in friction reduction. No theoretical limit currently exists for reducing mechanical friction, and historically, engine friction has declined 8 percent per decade.

Pumping losses include losses due to throttling (i.e., restricting air flow to maintain proper air/fuel ratios when the engine must be operated at a fraction of its peak power capability) and losses due to aerodynamic friction. Throttling loss is proportional to the degree of restriction of the airflow (throttle setting); it is zero at wide open throttle. Throttling loss can be reduced by operating the engine at a lower rpm but higher load for a given vehicle speed, or by using "lean burn" combustion (where excess air is not a problem). For example, the diesel engine uses lean burn and is completely unthrottled. Throttling loss can also be reduced by controlling valve lift and timing or by deactivating cylinders at low loads (so the engine essentially becomes smaller and can operate closer to peak capacity).

Aerodynamic (pumping) losses are associated with the air/fuel mixture as it flows through the air cleaner, intake manifold, and valve orifices, as well as the exhaust as it flows through the valves, manifold, muffler, and catalyst. This loss is proportional to the airmass flow and increases at higher loads and speeds. Aerodynamic losses can be reduced by tuned intake manifolds, increased valve area (or increased numbers of valves), tuned exhaust manifolds, and reduced pressure drop in the catalyst and muffler.

Efficiency improvements in the remainder of the drivetrain can be obtained by reducing frictional loss in the gearbox, axle (or transaxle for front-wheel-drive cars), wheel joints, wheel bearings, brakes, and oil seals. Those improvements can be small individually but provide a measurable cumulative benefit. The use of more gears in the transmission, however, improves efficiency by allowing the engine to operate closer to peak efficiency, rather than by reducing drivetrain loss.

Finally, accessory drives can be made more efficient. Most front-wheel-drive cars already use an electric radiator fan which is engaged only when needed. "Smart" alternators that reduce the load when the battery is fully charged, more efficient water pumps, electric power steering, etc. can reduce the accessory loads that currently account for 8 to 12 percent of all fuel consumed over the test cycle..

Some specific technologies available to reduce vehicle loads and reduce losses include the following (fuel economy benefits were estimated by Energy and Environmental Analysis, Inc., EEA, which has been an OTA technical consultant for this study; for some of the technologies, magnitude of the benefits is controversial):

Weight ***reduction.*** Reducing vehicle weight without reducing practical space for passengers and cargo involves three strategies—substitution of lighter-weight materials without compromising structural strength (e.g., aluminum or plastic for steel); improvement of packaging efficiency, that is, redesign of drivetrain or interior space to eliminate wasted space; and technological change that eliminates equipment or reduces the size of equipment. The EEA analysis does not isolate weight reduction directly associated with other efficiency changes, for example, reduced engine weight due to the downsizing (decrease in engine displacement) made possible by engine efficiency improvement, but instead counts the weight reduction as part of the overall fuel economy increase associated with the efficiency change. Most weight reduction gains are expected after 1995. The fuel economy gain available from a 10-percent weight reduction is estimated to be 6.6 percent, including the effect of engine downsizing to maintain constant performance. Without downsizing, the fuel economy benefit would be **4.2** percent. Materials substitution could reduce average vehicle weight 9 percent under 1987 levels by 2001, and 18 to 25 percent under 1987 levels by2010, with additional weight reduction (3 to 8 percent, depending on market class) possible from improved packaging.

Aerodynamic drag reduction. Aerodynamic drag on a car is the product of its frontal area, its drag coefficient, and the square of its speed. The squared velocity factor means that drag increases very rapidly with speed, and aerodynamic drag is the most important power drain at highway speeds. Reducing frontal area is difficult because, with limited exception, this will compromise interior space. Reducing the drag coefficient involves smoothing out the basic shape of the vehicle, raking the windshield, eliminating unnecessary protrusions, controlling airflow under the vehicle (and smoothing out the underside), and designing the rear end to avoid turbulence and to control behavior of the "boundary layer (the thin layer of slow-moving air next to the vehicle's outer surface which exerts an important influence on drag). A 10-percent reduction in the drag coefficient will yield about a 2.3-percent fuel economy gain if the axle ratio or top gear ratio is adjusted to match the engine's operating point to the reduced power requirement. For cars redesigned between now and 1995-%, an average drag coefficient might be 0.335, down from 0.375; for cars redesigned between 1996 and 2001, average drag coefficient might be further reduced to 0.30, which is the level of the most streamlined cars in the U.S. fleet today. Further reductions should be feasible by 2010—drag coefficients of 0.23 to 0.24 seem attainable, and coefficients as low as 0.20 are possible.

Front-wheel drive. Shifting from rear- to front-wheel drive provides a number of fuel-saving benefits, including the ability to mount engines transversely, reducing engine compartment length; elimination of the transmission tunnel, which provides important packaging efficiency gains in the passenger compartment; and elimination of the weight of the propeller shaft and rear differential and drive axle. Counterbalancing these benefits, front-wheel drive changes vehicle handling characteristics in ways objectionable to some drivers (though it offers clear advantages in slippery conditions) and compromises trailer-towing capability. There has been controversy about overall fuel economy gain, because some shifts to front-wheel drive have been made at the same time other downsizing measures were taken, and also because some shifts have been accompanied by increases in vehicle size and in power-to-weight ratio. Total fuel savings available from a shift to front-wheel drive are about 10 percent for vehicles replacing 1970's vintage designs (body on frame), and about 5 percent for those where some potential benefits had already been gained through 1980's redesign (unit body). Because current levels of penetration of front-wheel drive are high and because many remaining rear-wheel-drive vehicles occupy market niches that may favor rear-wheel drive, additional gains available are moderate.

Overhead cam engines. Overhead cam (OHC) engines are used in all imported vehicles; only U.S. manufacturer's still sell overhead valve (OHV) engines. Older OHV engines produced less than 40 bhp/liter, but more modern OHV engines provide 45 bhp/liter. In contrast, modern OHC engines provide 50 to 55 bhp/liter in non-sports car applications. The higher specific output is due to the low mass of the valve train that makes it easier to open and close the valves, thereby improving breathing efficiency. A modern OHC engine providing equal performance (i.e., smaller displacement) will yield a 3-percent benefit in fuel economy over a modern OHV engine and up to 6 percent over an older OHV engine.

Four-valve-per-cylinder engines. Adding two extra valves to each cylinder improves an engine's ability to feed air and fuel to the cylinder and discharge exhaust. Four-valve engines typically have sharply higher horsepower than two-valve engines of the same displacement, though peak horsepower is reached at much higher engine speeds, and torque (pulling power) at low engine speeds generally is not improved nearly as much. The major fuel economy gain of a four-valve engine is achieved by downsizing the engine, since this can be done without performance loss; the greater valve area also reduces pumping losses, and the more compact combustion chamber geometry and central spark plug location allows an increase in compression ratio. However, engine downsizing cannot be proportional to horsepower gain because of the resulting lack of low end torque. An important area of uncertainty is the extent to which automakers will be willing to use aggressive transmission management to compensate for a four-valve engine's lack of low end torque by rapidly increasing engine speed when power is needed. This would allow more engine downsizing than if the automaker wanted to maintain the driving "feel" of a high torque, "low revving" engine. Available fuel economy gain over a two-valve overhead cam engine with the same number of cylinders is 5 percent; the gain is 8 percent if a four-cylinder engine replaces a two-valve six cylinder engine, or a six replaces an eight. The gain includes the effect of using a compact combustion chamber and increasing compression ratio from 9.0 to 10.0, which by itself is responsible for a 2-percent gain. By 2010, an increase in compression ratio to 11.0 should be possible, yielding an additional l-percent gain in fuel economy. These benefits do not include the effect of downsizing to the extent where aggressive transmission management would be necessary.

Intake valve control. ***All*** engines have traditionally utilized fixed valve timing since a simple, reliable mechanism to vary timing had not been designed until recently. Thus, valve timing has always been a compromise between high rpm power output and low rpm torque. At part load, it is more efficient to close the intake valves early rather than pump air across the throttle. New devices to vary both valve timing and lift have been commercialized, and such systems have provided 5- to 8-percent gain in lowspeed torque and 20-percent gain in specific power. A valve lift and timing control system can provide 6-percent benefit in fuel economy if the engine is downsized to provide equal low-speed performance, although there may be unfavorable synergies with more advanced transmissions that also reduce pumping loss (these transmissions reduce the amount of time that engines operate at inefficient low-load conditions, when intake valve control is most effective). Valve control systems are most easily incorporated into a double overhead cam, four-valve engine.

Torque converter lockup. Current automatic transmissions utilize a hydraulic torque converter, where an impeller pushes fluid pasta turbine to transmit engine torque to the wheels. This hydraulic connection is useful at idle and during acceleration, where it can provide torque multiplication. At higher speeds and low acceleration rates, the system is wasteful as there is some "slippage" between the impeller and turbine. A rigid mechanical link, called a lockup, prevents this slippage and provides a 3-percent benefit in fuel economy if employed in all gears except first. The lockup mechanism also transfers more vibration to the driveline, creating some negative response toward its use. Lockup is now widely used, so available gains are limited.

Accessory improvements. Accessories driven by the engine include the airconditioner, water pump, oil pumps, hydraulic power steering pump, alternator, and, in some cases, the radiator fan. Modest benefits are available in the redesign of all those systems to reduce total energy use. For example, a "smart" alternator can be electronically controlled to provide battery charging only when desirable. Power steering pumps are very wasteful at speed, as they are sized for idle, when steering loads are greatest. Most cars already employ electric fans for the radiator which are switched on when necessary, but further improvement is possible if their speed can be varied. Individually, these accessory benefits are very small but together they can provide a 0.5- to l.O-percent benefit in fuel economy. One possibility is completely eliminating the hydraulic power steering pump and replacing it with electric power steering. This action alone can increase fuel economy by 1 percent. However, the electrical power demand is so large that electric power steering is thought to be impractical for intermediate and large cars.

Four- and five-speed automatic transmission and continuously van-able transmissions. A particular power demand can be met by an engine at different operating points since:

power = torque x speed.

At any level of power demand, the highest torque and lowest engine speed combination—up to a certain point —offers the best fuel economy. Adding gears to an automatic transmission allows operation closer to the optimal combination of torque and speed for any given power demand. Theoretically, a continuously variable transmission (CVT) can keep engine speed at optimal rates for all vehicle speeds. Current CVT designs appear practical only for smaller cars, with two-liter engines or smaller, because of limitations on the amount of power that can be transmitted by the flexible belts in the transmission. Average fuel economy improvement in moving from three-speed transmission with lockup to four-speed with lockup is 4.5 percent, with an additional 2.5 percent available from adding a fifth gear, or an additional 3.5 percent available from moving to a CVT.

Electronic transmission control. Most automatic transmissions currently use mechanical controls to shift gears or engage the torque converter lockup. The controls have been highly developed over the years to match the requirements of the test cycle. Electronic controls can offer a minor benefit by shifting gears and engaging the lockup more efficiently, but the fuel economy gain on the cycle is only 0.5 percent. Under real-world conditions, it is expected to provide greater benefits, especially at operating points outside the test cycle envelope.

Throttle body and multipoint fuel injection. Most vehicles already utilize fuel injection systems that have replaced carburetors. Fuel injection systems are of two types: throttle body, that essentially replaces a carburetor with one or two injectors that supply fuel to all cylinders; and multipoint, that utilizes one injector per cylinder metering fuel directly into the intake port. Fuel injection allows more precise control of fuel quantity metered during transient operation (e.g., acceleration or deceleration) and also atomizes fuel more completely. These factors allow less fuel to be used during cold starts and transients and also improve emissions. The throttle body system provides a 3-percent benefit over a carburetor, if adopting the system eliminates the air pump required to meet emission standards. Widespread use limits available fleet gains, however. A multipoint fuel injection system allows the inlet manifold to be tuned to maximize airflow, as no fuel flows through the manifold. The tuned inlet manifold can increase torque by 3 percent. A multipoint fuel injection system allows fuel shutoff during deceleration. The multipoint system also mitigates fuel distribution problems, allowing leaner mixtures during warmup and slightly more aggressive spark timing after warmup. The combination of a multipoint system with a tuned intake manifold and deceleration fuel shutoff provides a 3-percent benefit in fuel economy relative to the throttle body system.

Improved tires and lubricants. Longstanding trends toward slipperier oil and tires with lower rolling resistance will continue. The recently displayed GM prototype electric car, the Impact, has tires with half the rolling resistance of modern radials. The fuel economy benefit of using the best available oils (5W-30 replacing 1OW-4O) and tires, now in use on about 20 percent of the 1988 fleet, is about 1 percent. Incremental improvements in tires beyond 1995, available to the fleet in 2001, should yield another 0.5-percent gain. Tires like those of the Impact, if they prove practical, would yield additional gains.

Engine friction reduction. Engine friction is predominantly in the pistons/rings, valve train, and crankshaft. On average about 20 percent of potential engine power is lost to friction; this represents one third of total output power. Engine friction reduction in the 1987 to 1995 timeframe will involve reducing piston ring tension, redesigning the piston skirts (or load bearing area), and improving manufacturing methods to reduce cylinder bore distortions. These efforts will provide a 2-percent fuel economy benefit. Roller cam followers reduce valve train friction by replacing the sliding contact between the roller cam and camshaft with a rolling contact, also providing a 2-percent fuel economy benefit. After 1995, friction reduction will involve the use of lightweight valves and springs, reduction in piston and connecting rod mass through the use of fiber-reinforced composite materials, and possibly, use of only two rings rather than three, with a potential 2-percent fuel economy gain by 2001.

“Reduced performance.” Reducing a car’s performance is not a “technology,” but it is a viable option for improving fuel economy. If a smaller, less powerful engine is used in a vehicle, fuel economy gains are obtained from both reduced engine weight and lower throttling losses, because the engine must be operated at full throttle for a greater portion of the driving cycle. For example, if a high-performance vehicle has a 0-to-60 mph acceleration time of 8 seconds, increasing this time by 10 percent—0.8 seconds—will increase fuel economy by about 3.5 percent, about 1 mpg for a 28-mpg car. For a family car with a 14-second 0-to-60 time, a similar increase of 10 percent (1.4 seconds) would add 5.5 percent to fuel economy, or over 1.5 mpg.

Lean burn. Current engines with catalytic controls operate under stoichiometric conditions, that is, using air/fuel mixtures with just enough oxygen to burn all the fuel. This operating environment is necessary to allow the current generation of catalytic controls for nitrogen oxides to work properly; they cannot operate in a “lean” environment, one with excess air. Operating lean, however, improves an engine’s thermodynamic efficiency and decreases pumping losses, with potential gains in fuel economy of 10 to 12 percent over current two-valve engines, or about 7 to 10 percent over current four-valve engines. Toyota and other companies are working on new catalyst technology to allow high levels of nitrogen oxides control with a lean burn engine. If development of this control technology is successful, advanced lean burn engines might begin to enter the U.S. fleet in the late 1990s. Although lean burn engines are not new and are in use in Europe, development of the necessary nitrogen oxide catalysts is by no means guaranteed, and this technology should be considered speculative.

Two-stroke engines. In conventional four-stroke engines, the piston descends and ascends in the cylinder twice for every spark ignition and combustion: the first descent and ascent for combustion and power, and then forcing out the exhaust gases; and the second for drawing in air and fuel, then compressing the air/fuel mixture. In a two-stroke engine, the piston need descend and ascend only once for each spark ignition, thus offering significantly higher output per unit of engine displacement: 80 to 100 hp/liter compared to about 60 to 65 hp/liter for an advanced overhead cam, four-valve four-stroke engine. The two-stroke also produces high torque at low speeds, in contrast to multi-valve four-stroke engines; this allows engine downsizing corresponding to the difference in horsepower. The higher frequency of power strokes yields smoother operation, so that a three-cylinder two-stroke engine can replace a six-cylinder four-stroke with minimal change in operating quality and substantially reduced friction losses. Finally, an advanced two-stroke engine will use a direct injection system that will run very lean, adding substantial efficiency benefits (though with potential nitrogen oxide problems because of the inability to use conventional reduction catalysts). Somewhat offsetting these sources of increased fuel efficiency are:

- reduced thermal efficiency of the two-stroke cycle;
- power loss due to the supercharger/blower required for forced scavenging of exhaust gases;
- power losses from the high-pressure fuel injection pump; and
- potential increase in piston friction associated with need for a large piston skirt.

The net fuel economy benefit is likely in the range of 12 to 14 percent over a two-valve four-stroke engine, or perhaps only 3 to 4 percent over an advanced version of a four-valve engine with intake valve control, that will be available for the 2001 fleet. However, the two-stroke may be considerably less expensive than these engines. The key to realizing these benefits is to solve the two-stroke's remaining emissions control problems, especially for application to larger cars where the NO_x emission standards can be limiting. A further tightening of NO_x standards if Tier II standards go into effect will further complicate prospects for this engine.

Diesel ***engines.*** Diesel engines represent a proven technology available now to improve fuel economy substantially. However, diesels have not been very successful in the U.S. market for reasons that include performance limitations (most diesels have been significantly less powerful than competing gasoline engines), costs, noise, smell, delayed starting, emissions, and reliability problems associated with some domestic models. Although the 1990 Clean Air Act amendments allow diesels to meet a l.O-g/mi NO_x standard compared to a 0.4-g/mi standard for gasoline (spark ignition) engines,[3] it is questionable whether this degree of leniency would persist if diesels began to take a major share of the new-car market; and in 2004, diesels must meet the 0.4-g/mi standard (or O.2g/mi if Tier II standards are applied). Were NO_x catalysts capable of operating in a "lean," oxygen-rich environment developed, diesels could likely meet stringent NO_x standards. According to European manufacturers, diesels are significantly more efficient than gasoline four-valve engines even at constant performance: 15 to 18 percent more for naturally aspirated diesels, 24 to 28 percent more for turbocharged diesels, and 35 to 40 percent more for direct injection turbocharged diesels.[4] And although the baseline gasoline engine will improve, a portion of the improvements, especially engine friction reduction, may be applied beneficially to diesels as well.

Electric hybrid ***vehicles.*** Vehicles that combine an electric motor for city driving with an internal combustion engine for added power, when needed, and battery charging may represent a viable fuel economy alternative. In aversion designed by Volkswagen, an 8-hp electric motor powers the car at speeds up to 30 mph and a 1.6-liter diesel engine provides more power for highway driving and other purposes. The weight of the extra engine and batteries (nearly 300 pounds) cuts down on acceleration and fuel economy, but the Volkswagen prototype can still deliver nearly 100 mpg of hydrocarbon energy fuel economy, and 60-mpg (total) fuel efficiency.[5] This type of vehicle represents an interesting opportunity because its use of the electric motor during much of the urban cycle may allow the onboard diesel—or a two-stroke engine—to comply with stringent NO_x standards, such as those in California.

A SPECIFIC EXAMPLE OF THE APPLICATION OF FUEL ECONOMY TECHNOLOGY: HONDA'S NEW CIVIC VTEC-E MODEL

Honda Motors recently announced a new engine that combines Honda's variable valve timing and lift control (VTEC) with lean burn. The combination of technology will be available in model year 1992 in a hatchback model called the Civic VTEC-E, as a 49-state model. The Civic VTEC-E will also be available in California; but this model does not use lean burn. Rather, it uses a high EGR (exhaust gas recirculation) rate but maintains the mixture at a stoichiometric air/fuel ratio. California's stringent NO_x emissions standards are met with use of a three-way catalyst. The Civic VTEC-E in both Federal and California versions has performance very similar to the standard Civic, and the VTEC-E engine and standard DX engine are both rated at 92 hp. However, the Civic VTEC-E provides a substantial increase in fuel economy over the DX model.

Detailed EPA test data were not available at the time of this analysis and preliminary data provided by Honda are used instead. The 1992

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[3] Temporarily for cars and light trucks below 3,750 pounds.

[4] Energy and Environmental Analysis, Inc., February 1991, op. cit.

[5] Ibid.

Civic model is somewhat larger and more aerodynamic than the 1991 Civic (for which detailed data are available), but differences are not large, so that a comparison between a 1992 Civic VTEC-E and a 1991 Civic DX is valid. Table 3-1 shows the relevant data. The 49-State Civic VTEC-E has approximately 44-percent better fuel economy than the 1991 DX, with near-equal acceleration performance, while the California model has 34-percent better fuel economy. The lean burn feature accounts for the 10-percent difference in benefit between the California and 49-State model.

This large increase in fuel economy comes not only from the engine but also a range of other technologies, some made possible by the VTEC engine characteristics. Items unrelated to the engine include:

- 5-percent weight reduction due to reduced options;
- improved aerodynamics due to the addition of an air-dam and removal of one external mirror;
- reduced rolling resistance through use of special tires;
- reduced accessory loads from use of a "smart" alternator; and
- use of fuel-efficient lubricants.

Table 3-1 –Comparison of the Civic VTEC-E and DX Models

	1991 Civic	1992 Civic
Test weight (lb)	2,500	2,375
C_D	0.33	0.32
Frontal area (m^2)	1.80	1.85
Engine displacement (cm^3)	91	91
Horsepower	92 @ 6,000	92@ 5,500
Axle ratio	3.89	3.25
Transmission	M-5	M-5 wide ratio/SIL
Acceleration time, 0-100 kph (secs)	10.6	10.5
City fuel economy (mpg)	36.5	53 (48.5)[a]
Highway fuel economy (mpg)	47.7	67 (62)[a]
Combined fuel economy (mpg)	40.8	59 (54)[a]

[a] California VTEC-E in parentheses. All VTEC-E fuel economy data are approximate

SOURCE. Energy & Environmental Analysis, Inc., 1991

These features, however, are responsible for less than 10 percent of fuel economy gain, and the EEA sensitivity coefficients reveal that 8 to 9 percent is appropriate for the non-engine/transmission-related benefits.

This suggests a 35-percent gain is possible from the engine/transmission/driveline combination (25 percent for the California car). Honda has reduced the axle ratio by about 16.5 percent between the VTEC-E and the DX. Normally this would reduce performance significantly, but the VTEC engine's variable valve timing enhances low-speed torque. At 2,500 rpm, the torque of the VTEC engine is about 10 percent higher than that for the DX engine. The maximum 92 hp rating is attained at 5,500 rpm in the VTEC engine, while it is attained only at 6,000 rpm in the DX engine. Hence, it appears the VTEC engine provides about 10 percent more power across the entire usable speed range to 5,500 rpm. A wide-ratio transmission with shift indicator light provides further fuel economy benefits, at some expense to shift quality and performance.

The engine also has other enhancements beyond VTEC, such as roller cams, low-friction pistons/rings, and other unspecified friction-reduction technologies. Honda claims that only 10 to 15 percent of the total fuel economy increase is due to the VTEC/lean burn combination. This claim, however, doesn't include the drivetrain optimization made possible by the engine's increased torque output. EEA estimates that at constant performance, the VTEC/lean burn combination may be capable of a 20- to 25-percent increase in fuel economy. This combination cannot meet current California or future Federal emissions standards. Without the lean burn feature, it appears that a 10- to 15-percent benefit may still be possible with VTEC technology, while maintaining all other vehicle attributes constant. This engine can meet both California and future Federal NO_X standards.