Chapter 7

Technological Potential for Increased Fuel Economy

During the past year, Congress has heard a variety of testimony about the technological potential for improving new-car fuel economy. Most of this testimony—including OTA's[2]—focused on defining technological potential in a given year (generally 1995 or 2000) as a single "miles per gallon" value. OTA's motive for selecting a single value was to avoid complicating the fuel economy debate with complex and confusing discussions of scenarios and technical assumptions. We suspect the motives of other analysts discussing this issue were similar.

The problem with this approach is that analysts and others involved in the fuel economy debate have reached no consensus about what "technological potential" really means. Congress has been bombarded with a wide range of estimates of technological potential. Many differences among the various estimates result not from actual differences in technical judgment about the efficiency improvement of specific technologies, though such differences clearly exist, but instead from differences in assumptions about:

- the nature of regulations accomplishing the efficiency change;
- future shifts in the size mix of the fleet;
- changes in acceleration capabilities or other measures of vehicle performance (see box 7-A);
- passage of new safety and emission regulations;
- judgments about an acceptable level of economic disruption to the industry in responding to new fuel economy regulations;
- lead time available to the industry to redesign model lines;
- the time required to develop, perfect, certify, and bring to market new technologies; and
- judgments about consumer response to changes in vehicle costs and capabilities.

Assumptions about these factors must be made in calculating technological potential, since each factor will affect the ultimate fuel economy achieved by the fleet. In addition, there is ongoing argument about whether it is reasonable to expect future ***average*** levels of technology performance to equal the ***best examples*** present today, or whether current average performance is a good approximation for performance level five or more years from now. Unfortunately, the focus on developing a single number has tended to obscure assumptions underlying the numbers, with the result that Congress is confronted with estimates that ***appear*** **to** be about the same thing, but are not really comparable.

OTA is aware of four general groupings of recent estimates of fuel economy technological potential:

1. Values based on estimates of the efficiency increases associated with individual technologies developed by automobile engineers.[3]
2. Estimates based on statistical evaluations of the current fleet of automobiles. These evaluations try to find correlations between the presence or absence of specific efficiency technologies and differences in vehicle fuel economy. We are aware of two recent

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[1] From the Office of Technology Assessment, Department of Energy, International Association for Energy Conservation, American Council for an Energy-Efficient Economy, Ford Motor Co., Chrysler Corp., General Motors, and the United Auto Workers, among others.

[2] For example, S.E. Plotkin, Office of Technology Assessment, testimony to the Consumer Subcommittee, Committee on Commerce, Science, and Transportation, U.S. Senate, May 2, 1989, "Increasing the Efficiency of Automobiles and Light Trucks—A Component of a Strategy to Combat Global Warming and Growing U.S. Oil Dependence."

[3] These estimates have been made available to the Federal Government but have not been formally published.

Box 7-A–"Constant Performance" and Evaluating Fuel Economy Potential

Most technologies that can improve vehicle fuel economy can also boost performance. Generally, the vehicle designer chooses one to favor because there is a tradeoff between the two. This works as follows: technology might boost engine output without changing engine size (e.g., turbocharging, use of four valves per cylinder, fuel injection, etc.), or instead it might diminish load by reducing friction (e.g., roller bearings; advanced oils) or aerodynamic drag (flush windows, raked windshields). Both outcomes would allow either downsizing the engine to compensate for the power boost or load reduction, thereby improving fuel economy, or leaving the engine the same size and allowing performance to improve (with less or no improvement in fuel economy).

Today, automakers choose to boost performance at the expense of increased fuel economy, primarily because the market rewards performance with profits higher than those attained by adding to fuel economy. In other words, an automaker might be able to charge much more for a boost in acceleration ability than for an equivalent increase in fuel economy. Because many technologies available to improve fuel economy have been used instead to improve performance, measuring the potential fuel economy performance of these technologies demands that their measured fuel economy effects be adjusted to a baseline of constant performance. There are two important analytical problems associated with this adjustment.

First, the technology will have been developed for maximum performance rather than maximum fuel economy, so a simple adjustment to constant performance may hide some of the technology's potential. Second, there maybe disagreement about what "constant performance" actually means. As an example, 4-valve-per-cylinder engines allow a significant horsepower increase over baseline 2-valve engines without increasing engine displacement — 50-percent horsepower increases are not unusual. However, maximum horsepower is achieved in a 4-valve engine at significantly higher rpm than in 2-valves; also, the low end torque (torque achieved at low rpm) is only modestly higher for the 4-valve than for the 2-valve. This means that a downsized 4-valve engine with identical horsepower to a larger 2-valve will have a considerably different, probably inferior, driving "feel", and will have less low end response. Consequently, horsepower and the horse power/weight ratio are unsatisfactory measures of performance ***by themselves.*** To complicate matters, different automakers, all of whom aim to distinguish the driving feel of their vehicles from those of other makers, will reach different conclusions about how much engine downsizing, and thus how much added fuel economy, can be gained from a particular technology. Those willing to create a high-revving vehicle with an active automatic transmission might be willing to downsize engines considerably more than a maker intent on creating a vehicle with a smooth, low-revving feel.

This complexity creates a policy problem as well as an analytical one. Is it valid to argue that a new fuel economy standard is flawed because it would require changing the feel of a company's vehicles—especially when vehicles with the type of feel that maybe required are successfully marketed (though not necessarily to all types of customers)? This problem goes to the heart of the inherent tradeoff between regulatory goals and values such as consumer choice. Virtually any regulation that is at all stringent will tend to limit consumer choice. The issue is to define an acceptable limit.

statistical evaluations, both sponsored by the industry.[4]

3. Estimates based on extrapolation from experience with ultra-high-mileage vehicles in the fleet, vehicle prototypes, and laboratory results of specific fuel economy technologies, perhaps coupled with assumptions about possible shifts in consumer preferences. Early estimates by the energy conser-

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[4] J.O. Berger, M.H. *Smith,* and R.W. Andrews, "A System for Estimating Fuel Economy potential Due to Technology improvements," Sept. 24, 1990, Preliminary Report; and W.V. Bussmann, Chrysler Corp., "Potential Gains in Fuel Economy: A Statistical Analysis of Technologies Embodied in Model Year 1988 and 1989 Cars," Feb. 15, 1990.

vation community relied heavily on estimates of this types

4. Values based on estimates of efficiency increases associated with individual technologies and potential for increased penetration of these technologies developed by Energy and Environmental Analysis, Inc. (EEA), under the sponsorship of OTA, the Department of Energy, and the Environmental Protection Agency. DOE, OTA, and the American Council for an Energy-Efficient Economy (Ledbetter and Ross) have all presented estimates of technological potential based on the EEA estimates.[6]

In addition, two recently initiated efforts are considering the same issue. The Motor Vehicle Manufacturers Association (MVMA) has contracted with SRI International to conduct a study of the fuel economy potential of existing technology and has arranged access to confidential industry data and analysis to complete the work. The Department of Transportation has asked the National Research Council to undertake a similar study. Both studies are short-term in nature, due within the year.

Efforts thus far have produced results that fall roughly into three categories. First, estimates provided by the energy conservation community indicate a very high level of fuel economy potential for the fleet. The American Council for an Energy-Efficient Economy calls for a CAFE standard of 45 mpg for cars and 35 mpg for light trucks by the year 2000. Other estimates of technological potential range to 60 mpg and higher for the early 21st century.

Second, estimates produced by EEA for the automobile fleet are in the 30- to 38-mpg range depending on timeframe (1995 or 2001) and scenario (from no change in fleet size mix and power and conservative investment assumptions, to significant rollbacks in size and power and investment assumptions based on societal rather than private interests). Recent EEA estimates for 2010 project a considerably higher potential, to 45 mpg or higher.

Third, industry estimates and industry-sponsored statistical evaluations indicate minimal fuel economy potential for the near term (to 1995 or 2000/2001), with much of that potential required to offset fuel economy penalties associated with new emission controls and safety standards.

Both EEA estimates and available industry and industry-sponsored estimates for 1995 and 2000/2001 are basically conservative, at least from a technology standpoint, because they consider only technologies already introduced into the fleet. As discussed below, in considering a timeframe that extends to the year 2000 and a bit beyond, there is a distinct possibility-even a probability-that technologies not yet in the fleet will play a role in improving fuel economy.

ENGINEERING ANALYSES OF FUEL ECONOMY TECHNOLOGIES PERFORMED BY DOMESTIC AUTOMAKERS

The three domestic automakers—Chrysler, Ford, and General Motors–have attempted to duplicate the EEA fuel economy analyses using values derived by their vehicle engineers for the fuel economy potential of each technology. Results of these analyses were first presented and discussed at a meeting in Detroit on January 17, 1990, attended by representatives of the automakers, DOE, DOT EPA, and OTA and K.G. Duleep of EEA (the principal investigator for EEA's work).

Tables 7-1, 7-2, and 7-3 present, respectively, the Department of Energy's 1989 estimates of fuel economy for 1995 and three scenarios for 2000

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[5] For example, D.H. Bleviss, *The New Oil Crisis and Fuel Economy Technologies* (Westport, CT: Greenwood Press, 1988).

[6] For example: C. Difiglio, KG. Duleep, and D.L. Greene, "Cost Effectiveness of Future Fuel Economy Improvements," *The Energy Journal*, vol. 2, No. 1, 1990, pp. 65-83; M. Ledbetter and M. Ross, "Supply Curves of Conserved Energy for Automobiles," *Proceedings of the 25th Intersociety Energy Conservation Engineering Conference*, American Institute of Chemical Engineers, New York, NY, 1990; and S.E. Plotkin, Office of Technology Assessment, op. cit.

Table 7-1 -Passenger-Car Fuel Economy Projections: Assessment of Technology Potential at Hypothetical Usage Rates*

(all figures given as percentages)

	Department of Energy 1985	2000		1995 v. 1987 DOE Product Plan		2000 v. 1995 DOE Product Plan		2000 v. 1995 DOE Cost-Effective		2000 v. 1995 DOE Max. Technology	
Technology	1987 F.E.	I & 5 Gain	1987 Industry Usage	Usage	mpg Gain	Usage	mpg Gain	Usage	Gain	Usage	1%?
Engine improvement											
Intake Valve Control , ...	10.0	10.0				20	2.00	50	5.00	70	7,00
Overhead Cam Engine	6.0	6.0	24	69	2.70	99	1.80	99	1.80	99	1.80
Roller Cam Followers	1.5		55	95	0.60	95		95		95	
Low-friction Pistons and Ring	2.0		20	100	1.60	100		100		100	
Adv. Friction Reduction.		2.0				80	1.60	80	1.60	80	1.60
Throttle-body Fuel Injection	3.0		28	40	0.36						
Muitipoint Fuel Injection	3.0	3.0	48	60	0.36	100	1.20	100	1.20	100	1.20
4-Valve 6-Cyl. for 8-CyL	10.0	10.0		12	1.20	16	0.40	20	0.80	20	0.80
4-Valve 4-Cyl. for 6-Cyl.	10.0	10.0		18	1.80	24	0.60	30	1.20	30	1.20
4-VaMe 4-Cyl. for 4-Cyl.		5.0				10	0.50	40	2.00	50	2.50
Transmission improvements											
Electronic Control	1.5			80	1.20						
Torque Converter Lock-up	3.0		60	80	0.60						
4-spd Automatic (v. 3-spd L/Up) . . .	4.5		40	80	1.80						
5-spd Automatic		2.5				10	0.25	20	0.50	40	1.00
CVT		2.5				10	0.25	40	1.00	40	1.00
Other improvements											
Front-wheel Drive	10.0	10.0	74	86	1.20	95	0.90	99	1.30	99	1.30
Weight Reduction (Materials)		6.6								80	5.28
Aero. Drag Reduction I	2.3		20	100	1.84						
Aero. Drag Reduction II		2.3				10	0.23	10	0.23	80	1.84
Electric Power Steering.		1,0				5	0.05	5	0.05	60	0.60
Lubricants/Tires.	1.0			100	1.00						
Tires		0.5				20	0.10	100	0.50	100	0.50
Accessories	1.0	1.0	20	100	0.80						
Total FueilEconomy Increase					17.1		9.9		17.2		27.6

* Usage rates are for comparison only. Their use doee not Imply manufacturing or marketing feasibility.

SOURCE: General Motor% Ford, Chrysler

Table 7-2—Passenger-Car [illegible] Economy Projections: Assessment of Technology Potential at Hypothetical Usage Rates*
(all figures given as percentages)

	DOE		Chrysler							
	Fuel Economy Gain				1995 v. 1989		2000 v. 1995		2000 v. 1995 Max. Technology	
Technology	1995 v. 1987	2000 v. 1995	Engineering Assessment Fuel Economy Gain	1989 Usage	DOE Usage	Chrysler mpg Gain	DOE Usage	Chrysler mpg Gain	DOE Usage	Chrysler mpg Gain
Engine Improvements										
Intake Valve Control	[illegible]	[illegible]	2.0				20	[illegible]	70	1.40
Overhead Cam Engine	[illegible]	[illegible]	nil	98	69	–	99		99	
Roller Cam Followers	[illegible]		2.4	76	95	0.46	95		95	
Low Friction Pistons and Rings	[illegible]		0.5	50	100	0.25	100		100	
Adv. Friction Reduction		[illegible]	nil				80		80	
Throttle-body Fuel Injection	[illegible]		3.4 a	63	40	(0.78)		(1.36)		(1.36)
Multi-Point Fuel Injection	[illegible]	[illegible]	4.9 a	35	60	1.23	100	1.96	100	1.96
4-Valve 6 Cyl. for 8 Cyl.	[illegible]	[illegible]	5.0 b		12	0.60	16	0.20	20	0.40
4-Valve 4 Cyl. for 6 Cyl.	[illegible]	[illegible]	5.0 b		18	0.90	24	0.30	30	0.60
4-Valve 4 Cyl. for 4 Cyl.		[illegible]	5.0 b				10	0.50	50	2.50
Transmission Improvements										
Electronic Control	1.5		0.5	24	80	[illegible]				
Torque Converter Lock-up	3.0		3.0 c	79	80	[illegible]				
4-spd Automatic (v. 3-spd Lock-up)	4.5		2.0	24	80	[illegible]				
5-spd Automatic		[illegible]	2.0 d				10	0.20	[illegible]	[illegible]
CVT		[illegible]	2.0 d				10	0.20	[illegible]	[illegible]
Other Improvements										
Front-Wheel Drive	[illegible]	[illegible]	1.0 e	98	86	–	[illegible]	–	99	0.01
Weight Reduction (Materials)	[illegible]	[illegible]	5.0 f	base					80	4.00
Aero. Drag Reduction I	[illegible]		2.5 g	base	[illegible]	2.50				
Aero. Drag Reduction II		[illegible]	3.0 g	base			10	0.30	80	2.40
Electric Power Steering		[illegible]	1.0 h				5		60	0.60
Lubricants/Tires	1.0		0.5	base	[illegible]	0.50				
Tires		[illegible]	0.5	base			20	0.10	100	0.50
Accessories	[illegible]	[illegible]	nil i	100						
Total Fuel Economy Increase						7.[illegible]		2.8		14.6

*Usage rates are for comparison only. Their use does not imply manufacturing or marketing feasibility.

NOTES:
- a vs carburetor
- b Fuel economy effect of 10% displacement reduction with same power level
- c All 4- and 5-spd include Lock-up
- d vs 4-spd Lock-up
- e Net of drivetrain losses (-1%) and one TWC reduction (+2%)
- f Assumes 10% weight reduction
- g Aero I: C_D reduction of .05 from 1989, Aero II: .05 C_D reduction from 1995
- h Not counted pending resolution of feasibility issues
- i Gains offset by potential loss to CFC regulations

SOURCE: Ford, rys

Table 7-3—Domestic Industry Analyses of OTA Technology Assessment: Fuel Economy Benefit of Each Technology at OTA Penetration Increase Where Possible (all figures given as percentages)

	OTA				Domestic Industry Estimate Sales Weighted Average		
Technology*	OTA's Est Fuel Economy Gain	OTA's Est Fleet Penetration 1987	Fleet Penetration 1995	OTA's Est Fleet Fuel Economy Gain	Industry Fuel Economy Gain	Fleet Penetration 1989	Fleet Potential Fuel Economy Gain
Front-wheel Drive	12.0	78.0	88.0	1.2		8 .8	0.
● Drivetrain Efficiency					nil		
● Package, Weight (1 TWC)					2.0		
4-Cylinder/4-Valve	7.5	5.0	45.0	3.0	3.7	4.3	1.5
4-speed Auto/CVT	7.5	35.0	75.0	3.0	3.4	47.4	0.9
● 3-Speed Non-L/Up to L/Up							
● 3-Speed L/Up to 4-Speed L/Up							
Electronic Trans Control	1.5	2.0	82.0	1.2	0.2	3.4	0.2
Aerodynamics from 0.37 to 0.32	3.4	N/A	100.0	3.4	3.0	1.7	2.9
Tires	0.5	N/A	100.0	0.5	0.5	4.8	0.5
so	1.0	N/A	00 0	1.0	1.0	90.6	0.1
Engine Improvements							
● Overhead Camshaft	6.0	40.0	60.0	1.2	1.1	24.8	0.4
● Roller Cams	1.5	40.0	80.0	0.6	2.2	47.0	0.7
● Low-friction Rings/Pistons	1.5	N/A	80.0	1.2	1.5	61.1	0.3
● Throttle-body Fuel Injection (over carburetor)	3.0	31.0	41.0	0.3	2.4	34.0	0.0
● Multipoint Fuel Injection (over carburetor)	7.0	45.0	55.0	0.7	1.3	64.8	0.0
Total 1995 Fuel Economy Improvement				17.3			7.6

* OTA Assumption of Attainable, Cost-Effective Fuel Technologies: 1995 gasoline price - $1.10/gallon (1987$); 4-year timeframe for fuel savings, 10% discount rate (OTA considers these technologies to be off [illegible]

These improvement percentages are overly optimistic because they do not consider the applicability to a full-line manufacturer's product line and penetration rates or the effect of more stringent emissions and proposed safety standards.

SOURCE: General Motors, Ford, Chrysler

(these estimates have since been revised); Chrysler Corp.'s alternative estimates for 1995 and two of the three year-2000 scenarios, assuming the same technology penetrations used by EEA, for comparison; and a direct comparison between an earlier OTA fuel economy estimate for 1995 and the three automakers' combined estimate. DOE's and OTA's estimates were produced by EEA.

STATISTICAL ANALYSES OF FUEL ECONOMY PERFORMANCE OF TECHNOLOGIES IN THE EXISTING FLEET

The domestic industry has sponsored two statistical analyses of the existing auto fleet to derive regression equations relating the fuel economy of autos to both measured variables (vehicle weight, engine displacement, and so forth) and the presence or absence of specific technologies. The equations can be used to estimate the fuel economy impact of the technologies, and this in turn can be used to project the fuel economy impact of a fleet employing these technologies to a different degree. The Bussmann (Chrysler) analysis[7] uses data from the 1988 and 1989 fleets; the Ford-sponsored Berger, Smith, and Andrews, or BSA, analysis[8] uses 1988-90 data.

The BSA analysis derives regression equations for fuel economy in a form having the dependent variables as the natural logs of city and highway fuel economy and the independent variables as the natural logs of such vehicle-related variables as test weight, the ratio of engine rpm to vehicle velocity in top gear, engine displacement and compression ratio, and so forth. The natural log form was chosen because, according to the authors, many improvements associated with various technologies should be multiplicative rather than additive. A number of the independent variables are "indicators," set to 1.0 if a certain technology (multipoint fuel injection, overhead cam engine) is present and zero if it is not. Since adding technologies to the fleet has often been accompanied by changes in performance, the equations are adjusted to find the effect of each technology at constant performance. This is accomplished by asking Ford engineers, "If this technology improvement is added to a vehicle, in order to keep performance constant, what other characteristics of that vehicle will have to change, and by how much?" Asking this question rather than the more direct, "If this technology is added, what will be the impact on fuel economy?" minimizes bias on the part of industry engineers who might answer conservatively if the question were in the latter form.

The BSA analysis estimated that the U.S. fleet would obtain an increase in fuel economy from 1987 to 1995 of 7.19 percent from the technologies in table 7-1, not counting the effects of low-friction pistons and rings, lubricants, and accessories, which were not modeled. The comparable DOE value[9] is 13.66 percent, whereas the corresponding industry values range from 7.23 to 7.64 percent. For the 1995-2000 period, BSA estimates a 12.91 percent gain for the technologies in table 7-1 not counting intake valve control, advanced friction reduction, five-speed automatic transmission, continuously variable transmission, and electric power steering. Comparable figures are 16.42 percent for DOE's analysis and between 9 and 11 percent for the analyses of the three domestic automakers.

The Bussmann analysis consists of a multiple regression analysis of data from 1,400 cars in the 1988- and 1989-model-year EPA databases, supplemented with industry-supplied information on camshaft arrangement, number of valves per cylinder, type of fuel injection, use of low-friction internals, and turbocharging.[10] Unlike the BSA analysis, Bussmann uses no engineering judgments –his is a purely statistical approach,

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[7] See footnote 4.

[8] See footnote 4.

[9] According to the BSA analysts.

[10] V. Bussmann, op. cit.

with the only judgment being the selection of independent variables. Of particular interest in this selection is Bussmann's dividing engines into four basic categories that incorporate groups of engine technologies. He found that, given a paucity of data on separate engine technologies, this arrangement yielded a more reliable statistical model than one using individual engine technologies as the independent variables.

The group of technologies that OTA calculated would yield a 17.3-percent fuel economy increase from 1987 to 1995 would instead, according to Bussmann's model, give a 5.4-percent increase from 1989 to 1995. Although the baseline years are different, there is no doubt the OTA (EEA) model and Bussmann's are radically different. For example, Bussmann's estimate of the unit gain for aerodynamic improvements is 1.8 percent versus EEA's 3.4 percent; and Bussmann's estimate for all engine improvements is 6.2 percent versus EEA's 17 to 20 percent.

ARGUMENTS OF THE ENERGY CONSERVATION COMMUNITY

Analysts from the energy conservation community have marshaled a variety of arguments supporting the proposition that efficiency of the U.S. light-duty new car fleet can be greatly increased over the next *20* years.[11] In general, they assert that U.S. auto fleet fuel economy can be raised to 45 mpg or higher by 2000, and considerably more within the following one or two decades. Unlike the industry and EEA analyses, which focus primarily on technological change,[12] the conservation community clearly envisions change in ***both*** technology and customer preferences.

First, the conservation community argues that government action could change market pressures that have held down gains in fleet efficiency during the 1980s. In particular, lower gasoline prices have reversed trends toward smaller cars and dropped the market shares of fuel efficiency leaders such as the VW Rabbit diesel. Presumably, government actions to raise gasoline prices, raise the purchase price of fuel-inefficient vehicles, and possibly lower the purchase price of fuel-efficient vehicles could substantially increase fleet efficiency even without new technologies, by encouraging purchasers to choose cars in lower size classes or more fuel-efficient models in each size class, and encourage manufacturers to use available fuel efficiency technologies more widely in their fleets. In the longer run, these actions would encourage manufacturers to develop new technologies and consumers to purchase them.

Second, the conservation community claims a variety of fuel efficiency technologies exist, in fully commercialized form, that are not disseminated through the fleet as widely as they could be. Table 7-4 lists technologies whose introduction or wider use offers a potential to improve fleet fuel efficiency.

Third, several car manufacturers have produced vehicle prototypes reported to achieve very-high fuel efficiency (see table 7-5). The conservation analysts contend the existence of these prototypes provides concrete evidence of the

Table 7-4-Developed and Near-Term Fuel Economy Technologies

- Engine Improvements
    - 4 valves per cylinder
    - Overhead camshaft
    - Roller cam followers
    - Low-friction rings/pistons
    - Throttle-body fuel injection
    - Multipoint fuel injection
    - Intake valve control
- Four-speed automatic transmission
- Electronic transmission control
- Aerodynamics, $C_D = 0.30$
- Tire improvements
- Lubricants (5W-30)
- High-efficiency accessories

SOURCE. Energy & Environmental Analysis, Inc

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[11] See F. Von Hippel and B. Levi, "Automobile Fuel Efficiency: The Opportunity and the Weakness of Existing Market Mechanisms," *Resources and Conservation*, pp. 103-124, 1983, and D.L. Bleviss, *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s* (WestPort, CT: Quorum Books, 1988).

[12] Though these analyses do allow the potential for a rollback in performance and size to 1987 levels.

Table 7-5–High-Efficiency Automobile Prototypes

Prototype	Fuel	Fuel Economy (mpg)	Passenger Capacity
VW Auto 2000	diesel	66	4-5
Volvo LCP 2000	multifuel	69	2-4
Renautt EVE+	diesel	70	4-5
Toyota Ltwt Compact . .	diesel	98	4-5

NOTE. Fuel economles converted to equivalent EPA test values, using conversion factors recommended by the Internatlonal Energy Agency. Details and further descrlptlons of the vehlcles are In the source document. Vehicles do not necessarily meet all U,S, emissions or safety requirements

SOURCE: Table 10. "Fuel Economy for Passenger Automobiles," In J Goldemberg et al,, *Energy for a Sustainable World,* World Resources Institute, Washington, DC, September 1987.

high, long-term potential for improving fleet efficiency.

Finally, technologies at various stages of development have been identified that show promise of large efficiency gains. For example, new designs of a two-stroke engine for automobile applications are said to be capable of fuel economy gains of 20 percent or more over conventional four-stroke engines with concurrent reductions in manufacturing costs.[13] Another engine said to hold considerable promise is the direct-injection diesel. Table 7-6 lists potential efficiency technologies identified by one conservation analyst. Advocates of higher fuel economy standards and other efficiency-oriented policy actions believe such measures will speed development and introduction of these technologies.

Table 7-5-Future Technologies for Improving Light-Duty Vehicle Efficiency

Variable-geomet~ turbochargers. **Increases effectiveness of turbocharging at low loads, allows engine downsizing.**

Improved electronic controls. **Adjustment of engine operating parameters (e.g., ignition timing) based on direct measurement of cylinder pressure and other operating conditions.**

Advanced lubricants (solid and gaseous).

Oxygen enrlchnent of air intake. **Using membrane technology to enrich oxygen content of intake air. Effect similar to, but more effective than, turbocharging.**

Adiabatic diesel. Low-heat-rejection engine achieved by heavy use of ceramics. Couples removal of cooling requirement and capture of exhaust energy through turbocharging or supercharging.

Continuously variable transmisslons. **Allows engine to be kept at optimum operating speed throughout the driving cycle. Currently available for small engines only.**

Advanced materials. **Substantial weight reduction through use of improved plastics and future use of high-strength steels, aluminum, magnesium, ceramics.**

Advanced tires. **Reductions in rolling resistance through improvements in design or use of advanced materials (e.g., liquid-injection-molded polyurethane).**

Engine stop-start and energy storage. **Engine shutdown during idle and braking, coupled with flywheel storage to power accessories and aid to restart.**

SOURCE" D:L. Blevlss, *The New Oil CfisS and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 7990s* (Westport, CT: Quorum Books, 1988).

Analysts associated with the American Council for an Energy-Efficient Economy have proposed a year-2000 efficiency goal for new vehicles of 45 mpg (EPA) for autos and 35 mpg for light trucks.[14] Achieving these goals would raise average in-use fleet fuel economy to about 27 mpg by 2000, up from a projected level of about 22mpg. If total annual mileage traveled were 2.21 trillion miles, this efficiency improvement (27 v. 22 mpg) would save about 1.2 mmbd of oil or, at $l.OO/gallon, over $20 billion per year by 2000, and more in future years as the technology diffused into the fleet. The energy conservation community argues that these goals are both technically attainable and cost-effective even at today's gasoline prices, based on available vehicle prototypes and cost and performance analyses for a variety of individual technologies.

THE EEA ESTIMATES

EEA has developed estimates for 1995 and 2001 fuel economy (under alternative conditions) for that portion of the U.S. automobile fleet manufactured by General Motors, Ford, and Chrysler, and the portion manufactured by the five largest Japanese manufacturers. Estimates for

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Is'' Detroit Gets Serious About Two-Stroke Engines, "*Business* Week, July 18, 1988. Also, see D. Plohberger, L.A. Mikulic, and K Landfahrer, AVL-List GmbH, Graz, Austria, "Development of a Fuel Injected Two-Stroke Gasoline Engine," SAE Technical Paper Series #880170, 1988.

[14] W.U. Chandler, H.S. Geller, and M.R. Ledbetter, *Energy Efficiency: A New Agenda,* American Council for an Energy-Efficient Economy, Washington, DC, July 1988. The authors suggest several policies to complement and help achieve this goal, including gasoline taxes, new "gas-guzzler" taxes, and a "gas-sipper" rebate program. They also suggest that efficiency standards be carefully structured to avoid past problems of unfairness, for example, by basing them on vehicle interior volume.

the entire fleet can be developed by estimating relative market shares and adjusting for vehicles manufactured by automakers not included (e.g., Volkswagen, Hyundai).

EEA's methodology, described in more detail in appendix A, first specifies a baseline of fuel economy and vehicle technology attributes for each market class.[15] For each vehicle type, EEA has identified individual fuel economy technologies applicable to that type and the fuel economy benefits associated with each technology.[16] The methodology then adopts these technologies and calculates total fuel economy benefits subject to constraints about synergism between technologies and non-additivity of certain types of benefits. Selection of the technologies is also subject to a variety of assumptions adopted by the client, including lead-time constraints and rules defining cost-effectiveness (discount rates, total years of fuel savings in the analysis). For the near term (1995), announced company product plans are used to define minimum technology improvements associated with major subsystems. As a last step, the estimates of total fuel economy benefits are adjusted for expected changes in weight and performance of the fleet, and changes in emissions and safety standards.

The list of technologies and fuel economy benefits used in the analysis was compiled using data from research papers, actual benefits from vehicles already featuring the technology, manufacturer submissions to the Department of Transportation, and in some cases, information obtained directly from manufacturers. The EEA estimates of individual technology benefits have been extensively discussed with domestic manufacturers and some foreign manufacturers as well, and EEA has revised some of their individual estimates on the basis of manufacturers' comments.

Tables 7-7 through 7-11 provide EEA's projections for 1995 domestic and Japanese new car fleet fuel economy assuming a "product plan" scenario wherein industry installs technology at rates that correspond to published plans for most major components and make economic sense from a purely market-driven perspective for minor components.[17] The projection further assumes a continuation of current trends in increasing vehicle size and performance and application of expected emissions and safety standards. In other words, in 1995:

- With no new fuel economy regulations nor other policies that could alter fuel economy (e.g., gasoline taxes), and no significant changes in market forces, domestically manufactured new car fleet fuel economy will be about 28.3 mpg. The import car fleet will beat about 31.1 mpg. Total new car fleet fuel economy will be about 29.2 mpg assuming a 35-percent import share.
- If the size and performance of the new car fleet could somehow be rolled back to 1987 levels, and if emission and safety standards could be met without fuel economy penalties, the domestic and total new car fleet fuel economies would be about 31 mpg and 32.5 mpg. This is ***a theoretical case to show the effects of market and regulatory changes, not a realistic scenario.***

The above discussion focuses on attainable levels of fleet fuel economy in the absence of significant changes in consumer preferences for fuel economy, power, and other features that affect fuel economy. If buyer preferences ***do*** change, in response to higher oil prices, actual or expected gasoline shortages, or strong leadership on the part of the President or Congress, 1995 new car fleet fuel economies could be higher than the values cited. The mechanism for higher values would likely be an increased preference ***within***

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[15] The market classes are minicompact, subcompact, compact, sports, intermediate, large, and luxury.

[16] The fuel economy benefits are calculated at constant performance and interior volume. This is necessary becausefuel economy technologies can typically be used to increase performance or interior volume with lessor no improvement in fuel economy, if the vehicle designer so desires.

[17] Components are assumed to be adopted if they save enough fuel t. compensate for any increase in vehicle sales price caused by adoption, using a discounted cash flow calculation.

Table 7-7–Projection of U.S. Domestic Manufacturers Fuel Economy
1995 Product Plan Case (does not include test adjustments)

Teohnology	Penetration Fuel Economy Gain (%)	Increase from 1987(%)	1995 Penetration (%)	Fleet Fuel Economy Gain (%)
Front Wheel Drive	10.0	12	86	1.20
Drag Reduction ($C_D = 0.33$)	2.3/4.6**	65/15	100	2.19
Four-speed Automatic Transmission	4.5	40	80	1.80
Torque Converter Lock-up	3.0	20	80	0.60
Electronic Transmission Control	0.5	80	80	0.40
Accessory Improvements	0.5	80	N/M***	0.40
Lubricant/Tire Improvements	1.0	100	100	1.00
Engine Improvements				
Advanced Pushrod	3.0	(40)****	(30)	1.20
Overhead Camshaft	3.0	45	69	1.35
Roller Cam Followers	2.0	40	95	0.80
Low-friction Pistons/Rings	2.0	80	100	1.60
Throttle-body Fuel Injection	3.0	12	40	0.36
Multipoint Fuel Injection (over throttle body)	3.0	12	60	0.36
4-valves-per-cylinder-Engine				
4-Cylinder replacing 6-cylinder*	8.0	18	18	
6-Cylinder replacing 8-cylinder*	8.0	12	12	0.96
Total Fuel Economy Benefit (%)				15.66

● 1987 distribution, 20 5% V-8, 29,5% V-6, 50% 4 cylinder.

● *Drag reduction for large/luxury cars from $C_D = 0.42$ baseline.

***N/M - not meaningful

****( ) this Includes upgrades from old pushrods to both advanced pushrods and overhead cam engines (for which an Incremental benefit Is taken)

SOURCE. Energy & Environmental Analysis, Inc.

Table 7-8-Import Manufacturers Fuel Economy
Five Largest Japanese Manufacturers Only (does not include test adjustments)

Technology	Fuel Economy Gain (%)	Penetration Increase from 1988(%)	1995 Penetration (%)	1995 Fleet Fuel Economy Gain (%)
Front-wheel Drive	5.0	3	90	0.15
Drag Reduction I	2.3	80	100	1.84
Four-Speed Automatic Transmission	4.5	16	47	0.72
Torque Converter Lock-up	3.0	9	53	0.27
Electronic Transmission Control	0.5	44	47	0.22
Accessory Improvements	0.5	80	N/M***	0.40
Lubricant/Tire	1.0	100	100	1.00
Roller Cam Followers	2.0	50	50	1.00
Low-friction Pistons/Rings	2.0	80	100	1.60
Throttle-body Fuel Injection**	2.0	25	20	0.50
Multipoint Fuel Injection	3.0	20	75	0.60
4-valves-per-cylinder Engine	5.0	20	44*	1.00
Total Fuel Economy Benefit ('%0)				9.30

*Additional 6 percent are 3 valves/cylinder.

**Benefit of TBFI is lower than for domestic cars because air pumps are not used in carburetted Import cars.

***N/M - not meaningful

SOURCE Energy & Environmental Analysis, Inc.

Table 7-9–1995 Product Plan U.S. Domestic Auto Fleet (does not include test adjustments)

	(mpg)
1987 fuel economy	26.7
1995 fuel economy (without size or performance increase)	30.9
Size/weight increase	-1.4
Performance increase	-0.7
Effect of emission/safety standards	-0.8
1995 product plan fuel economy	28.0

SOURCE: Energy &Environmental Analyses, Inc.

Table 7-10–1995 Product Plan Import Manufacturers (does not include test adjustments)

	(mpg)
1988 fuel economy	31.4
1995 fuel economy (without size or performance increase)	34.32
Size/weight increase	-1.66
Performance increase	-0.90
Effect of emission/safety standards	-0.94
1995 product plan fuel economy	30.82

SOURCE Energy &Environmental Analyses, Inc

size classes for the more fuel-efficient models and a shift toward smaller, lower-power cars. The potential for increased fuel economy levels through changes in buyer preferences is examined in chapter 8.

Tables 7-12 and 7-13 present EEA's projections for the year-2001 domestic fleet under two scenarios: a "product plan" conceptually similar to the 1995 product plan, and a "max technology" case driven by extremely strong pressures to improve fuel economy–presumably new regulations. The product plan assumes automakers install technologies that pay for themselves in four years (the average length of ownership for a new car's first owner) assuming a 10-percent discount rate and $1.50/gallon (in 1989$) gasoline. The domestic fleet fuel economy of 32.1 mpg, import fleet fuel economy of 34.6 mpg, and total fleet fuel economy of about 32.9 mpg obtained under this plan presume current trends in fleet size distribution and performance continue until 1995 and then plateau. If gasoline prices remain at current levels and trends of increasing performance and vehicle size continue past 1995, these projections will prove overoptimistic.

The max technology plan represents a major industry shift: the 37.3 mpg domestic fleet fuel economy (about 38.3 mpg total fleet fuel economy) by 2001 is achieved by returning to 1987 levels of size distribution and performance; rapid diffusion of a range of fuel economy technologies throughout the fleet essentially regardless of cost (the technologies actually would pay for themselves in 4 years with gasoline valued at

Table 7-11–Technology Definitions

Technology	Base Technoiogy	Comment
Front-wheel drive	Rear-wheel drive	Assumes constant interior room
Drag reduction I	15°/0 drag reduction from 1987 base $C_D = 0.37$	Assumes drivetrain adjustment to capture benefit
4-speed automatic	3-speed automatic	Assumes no change in performance in lower 3 gears
Electronic transmission control	Mechanically controlled transmission	Assumes shift points optimized for FTP
Tires	Improved rubber formulation and design	Evolutionary improvements
Accessories	2-speed accessory drives, improved pumps, etc.	Combination of evolutionary improvements and new technology
A-cylinder/q-valve	4-cylinder/2-valve overhead cam engine	Engine downsized for constant performance
Overhead cam	Pushrod (overhead valve) engine	Engine downsized for constant performance
Roller cam follower	Sliding cam follower	Benefits up to 4% demonstrated
Low-friction rings and pistons	Low-tension rings and low-mass pistons	Includes effects of better manufacturing

SOURCE: Energy & Environmental Analysls, Inc

Table 7-12–Potential Domestic Car Fuel Economy in 2001 Under Alternative Scenarios
(does not include test adjustments)

	Fuel	Product Plan		Max Technology	
Technology	Economy % Benefit	% Market Pen. 1995-01	Fuel Economy % Gain	% Market Pen. 1995-01	Fuel Economy % Gain
Weight Reduction	3.3/6.6	80	2.64	80	5.28
Drag Reduction	1.15/2.3	80	0.92	80	1.84
Intake Valve Control*	6.0	40	2.40	70	4.20
Overhead Cam Engine	3.0	30	0.90	30	0.90
6 cyl./4-valve replacing 8-cyl.	8.0	4	0.32	8	0.64
4 cyl./4-valve replacing 6-cyl.	8.0	6	0.48	12	0.96
4 cyl./4-valve replacing 4-cyl.	5.0	10	0.50	50	2.50
Multipoint Fuel Injection (over TBI)	3.0	40	1.20	40	1.20
Front-wheel Drive	0.0	5	0.50	13	1.30
5-speed Automatic Transmission**	2.5	20	0.50	40	1.00
Continuously Variable Transmission**	3.5	15	0.52	30	1.05
Advanced engine friction reduction	2.0	100	2.00	100	2.00
Electric Power Steering	1.0	5	0.05	30	0.30
Tire Improvements	0.5	100	0.50	100	0.50
Total Fuel Economy Benefit (%)			13.03*		22.67*
Unadjusted CAFE (mpg)			31.65		36.9

NOTE, Product plan scenario starts from a different 1995 base than the maximum technology scenario which holds performance and size constant at 1987 levels.

● Synergy of Intake valve control with 5-speed/CVT transmissions results In a loss of 2 percent In fuel economy
**Over 4-speed automatic transmlssion with Lock-up

SOURCE Energy & Environmental Analysis, Inc.

Table 7-13-import Manufacturers Fuel Economy in 2001
Five Largest Japanese Manufacturers Only (does not include test adjustments)

	Fuel	Product Plan		Max Technology	
Technology	Economy % Benefit	% Market Pen. 1995-01	Fuel Economy % Gain	% Market Pen. 1995-01	Fuel Economy % Gain
Weight Reduction	3.3/6.6	90	2.97	90	5.94
Drag Reduction	1.15/2.3	80	0.92	80	1.84
Intake Valve Control*	6.0	30	1.80	60	3.60
4-valve Engine	5.0	10	0.50	50	2.50
Multipoint Fuel Injection	3.0	25	0.75	25	0.75
Front-wheel Drive	10.0	0	0.00	5	0.50
5-speed Auto Transmission	2.5	6	0.15	12	0.30
Continuously Variable Transmission	3.5	26	0.91	40	1.40
Advanced Friction Reduction	2.0	100	2.00	100	2.00
Electric Power Steering	1.0	10	0.10	35	0.35
Tire Improvements	0.5	100	0.50	100	0.50
Roller Cam Followers	2.0	30	0.60	30	0.60
Total Fuel Economy Benefit (%)			11.00		19.78
2001 CAFE (mpg)			34.2		40.0

*Synergy with 5-speed automatic transmission/Cm results In 2-percent loss In fuel economy when both technologies are used In the same vehicle.

SOURCE. Energy & Environmental Analysls, Inc

$2.50-$3.00/gallon, or in 10 years with gasoline at $1.55-$ 1.90/gallon);[18] and abandonment of product lines well before their normal replacement times. Alternatively, if the size-and-performance rollback were only to 1990 levels—the appropriate criterion for S.341, the Senate Energy and Natural Resource Committee's proposed energy bill–the max technology fuel economy levels would be closer to 36 mpg and 37 mpg, respectively, for the domestic and total fleet. Unless consumer demand shifts strongly to more efficient autos, the max technology plan could cause significant economic disruption to the industry, not unlike industry adjustments of the early 1980s-a

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[18] At 10 percent discount rates.

period in which the domestic manufacturers experienced considerable losses.

Note that this level of fuel economy can be obtained only if each company improves its fuel economy up to the technological potential of its fleet. A uniform standard such as the current CAFE standard is unlikely to achieve a total fleet fuel economy this high unless legislators set the standard at levels unattainable by companies whose fuel economy potential is lower than average—most likely including Ford and General Motors.

If the marketplace itself does not change, and if no new technologies are available to enter the fleet by the end of the 1990s,[19] the product plan and max technology scenarios represent extremes: atone end, a future with no changes from pre-Mideast crisis trends–possibly unacceptable considering today's oil situation; and at the other end, a major disruption to industry product planning, also possibly unacceptable considering the United States' current economic woes. A practical "technological potential" under existing market conditions and using only existing technology probably lies somewhere in between. Of course, the max technology scenario would not necessarily seem extreme if buyer preferences shifted dramatically towards higher fuel economy. This possibility is examined in the next chapter.

In practical terms, what would buyers of automobiles under the EEA max technology scenario actually get? They would pay more for their vehicles, but contrary to the grim picture drawn by some critics of higher mpg standards, vehicles would perform much the same as today. Box 7-B describes changes the max technology scenario would bring to one of the most popular U.S. cars, the Ford Taurus.

EEA has also taken a more speculative look at the long-range technological potential for fuel economy improvement, estimating the fleet fuel economy impact of a number of new technologies in the year 2010. This analysis is described in detail in a recent report to the Environmental Protection Agency.[20] The analysis substitutes a series of engineering equations for fuel consumption for the less exact approach used to develop the 1995 and 2001 forecasts. EEA obtained information on advanced technologies incorporated in the analysis primarily from detailed interviews with Toyota, Honda, Nissan, and Volkswagen. The analysis builds on the year-2001 max technology case, so that fleet size and performance are similar to the 1987 fleet.

Table 7-14 provides the EEA 2010 projections for three levels of technical and marketing risk:

- Level I—technologies most automotive engineers agree are likely to be commercialized by 2010.
- Level II—technologies about which opinion is sharply divided as to benefits or commercial prospects.
- Level III—technologies considered esoteric by most, but still within the realm of possibility.[21]

Values for Levels I and II in table 7-14 reflect the basically conservative assumption that the mix of cars sold in 2010 matches the year-2000 fleet, with no consideration of specialized vehicles such as a one-seat commuter vehicle or even a very-low-performance conventional vehicle. In other words, the analysis assumes the car market does not change in any basic fashion, and that consumers still seek features such as space, luxury features and options, smooth ride, and good acceleration and handling performance.[22] The only non-conservative assumption is use of the 1987

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[19] The year-2001 analysis incorporates only those technologies currently installed on at least one commercial car model; consequently, the analysis is basically conservative. New technologies could allow similar improvements in fuel economy to occur under less extreme conditions than the "max tech," or allow even higher levels of fuel economy to occur under max tech assumptions.

[20] Energy & Environmental Analysis, *An Assessment of Potential Passenger Car Fuel Economy Objectives for 2010*, draft final report prepared for the Environmental Protection Agency, February 1991.

[21] Energy & Environmental Analysis, February 1991, op. cit.

[22] Ibid.

Box 7-B—Fleshing Out the Maximum Technology Scenario: Transforming the Ford Taurus

In describing OTA's analysis of future fuel economy potential, we have presented lists of technologies and associated fuel economy improvements. These lists and numbers do not, we believe, deliver a readily understandable picture of the likely physical results of actually enacting new fuel economy legislation. We would like to make these results more understandable by tracking the changes that would probably occur to an actual car.

We have chosen a popular, current mid-size car model to track the changes required to satisfy the maximum technology scenario for 2001. We have used the Ford Taurus, as it is safe, relatively fuel-efficient, and can seat six passengers. The analysis could have selected other comparable cars such as the Buick Century or Eagle Premier with only slightly different results. The Ford Taurus is more efficient than the average domestic car as it already incorporates an aerodynamic design, a low-friction V-6 engine with multipoint fuel injection, and a four-speed automatic transmission. Hence, the percentage increase (from a 1987 or 1990 base) in fuel economy will be somewhat lower than the average for the fleet.

The particular model used is the Taurus sedan with a 3-liter V-6 rated at 140 hp and 220 Newton-meters of torque. It can accelerate from 0 to 60 mph in 9.8 seconds and has a CAFE rating of 27.4 mpg. our analysis of future fuel economy potential traces possible technology improvements assuming that 1) new technologies are optimized for fuel economy and 2) the 2001 vehicle has the same interior room and acceleration performance as the current vehicle.

The most significant source of fuel economy improvement is advanced engine technology. The current 3-liter V-6 is a 2-valve pushrod type design. It can be replaced by an overhead cam 2.0-liter 4-cylinder engine that has 4 valves per cylinder, a compression ratio of 10:1, and intake valve control. This engine would actually have a higher horsepower rating (145 hp) but a lower torque rating (190 Newton-meters). Torque is a better measure than horsepower of low-speed performance (e.g., around town), and to compensate for decreased torque, a higher axle ratio must be used.

Car size (both interior and exterior) is held constant, but the weight is projected to decrease from 3,090 to 2,810 pounds.[1] Part of this will be due to the engine size reduction. If the new engine is made from aluminum, engine weight alone would be reduced by 100 pounds. Another 240 pounds would be eliminated by using advanced plastics for the front fascia, the fenders, hood, etc.; using aluminum, magnesium, and high-strength steel alloys in load-bearing structural components; and redesigning structure to capture secondary benefits. The 1990 Taurus already has an airbag but the future side-impact requirements and new emission standards will add about 60 pounds to the weight. The car is assumed to meet Tier I emission standards mandated in the Clean Air Act, but not Tier II standards that maybe imposed in 2003.

The hypothetical 2001 Taurus would be more aerodynamic than today's model, with a drag coefficient of 0.30 which is equal to the best of today's cars. It would use a five speed-automatic transmission electronically controlled to optimize gear shifts, and torque converter lock-up. The car would also feature improved tires with lower rolling resistance and low-friction oils in the crankcase and drivetrain. Table 7-B-1 summarizes major differences between the 1990 and hypothetical 2001 Taurus.

According to our estimates, these technologies will allow the 2001 Taurus' fuel economy to be 35.3 mpg, or a 29-percent improvement over the 1990 car. The vehicle is forecast to have nearly equal acceleration performance at low speed and slightly better performance at high speed. Physically, the car will have the same exterior and interior size, but will look sleeker due to reduced drag coefficient. We believe ride quality will be equal to or better than today's Taurus. Moreover, the 2001 car will save 470 gallons of

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[1] Ford argues that "customer-driven features" like better sound detenting and more powerful air conditioning will add 60 pounds to Taurus weight by 1995 and more by 2001. (D.L. Kulp, Manager, Fuel Economy Planning and Compliance, Ford Motor Co., letter to S.E. Plotkin, OTA, June 17, 1991). OTA agrees that continuation of current market trends toward increased luxury features will impede improved fuel economy.

Continued on next page

fuel over 50,000 miles, assuming on-road mpg is 15-percent lower than the EPA test mpg. Any forecast involves some degree of uncertainty, and we believe the fuel economy forecast is accurate to 0.5 MPG. It is possible that the technology changes could adversely affect drivability and maintainability, although we have no reason to suspect this.

We should note the technologies described are not the only way to attain 35.3 mpg. If, for example, the two-stroke engine is commercialized by 2001, the car may attain an even higher level of fuel economy in 2001 at lower cost.

The changes described in table 7-13 will not be easily made by 2001. The 2001 car as described will require completely new designs for the body, engine, and transmission, all involving substantial capital investment. On a discounted cash-flow basis, gasoline must cost over $2.00 per gallon for the consumer to recoup the increased first cost of the car over 50,000 miles. Hence, fuel economy improvements made to the Taurus will not be cost-effective to the buyer if gasoline sells at much lower than $2.00 per gallon.

The contemplated schedule will also adversely affect the manufacturer's ability to recoup his capital investment on the preceding Taurus model. The industry operates on a product cycle of at least eight years and the Taurus was first introduced in 1986. Industry analysts expect Ford to introduce anew-model Taurus in 1994/5, and the product cycle suggests that the next model will be introduced in 2002/3. It is too late to influence the new model planned for 1994/5; under normal circumstances Ford could introduce the car forecast under a maximum technology scenario only in 2002 or 2003. Forced to introduce on or before 2001, Ford will lose 2 to 3 years of product life, which will result in significant lost revenues for Ford. Since the capital investment is amortized over an expected sales volume, reduced product life will negatively impact Ford profits. The current 5-year lead time and 8-year product cycle suggest that 2005 is a better target year if legislation requiring the complete redesign of all products is considered.

It is important to be aware of these factors when considering mpg targets defined by a maximum technology scenario.

Table 7-B-1 –Comparison of Vehicle Technologies in 1990 and 2001

	1990 Ford Taurus	Hypothetical "2001 Taurus"
Weight	3,090	2,810
Interior volume (cu. ft.) (passenger + cargo)	100 + 17	100 + 17
Drag coefficient	0.33	0.30
Engine size	3.0-liter V-6	2.0-liter 11-4
Valve train	2-valve/ pushrod	4 valve/ DOHC with variable value timing
Compression ratio	9.3	10.0
Power	140 hp	145 hp
Torque	220 Nm	190 Nm
Transmission (automatic)	4-speed with lock-up	5-speed with electronic control and lock-up
0-60 mph time	9.8 sec.	10,0 sec.
Fuel economy (EPA Composite) a "maximum technology" scenario.	27.4 mpg	35.3 mpg

SOURCE Energy & Environmental Analysls, Inc

Table 7-14–Fleet Fuel Economy in 2010 at Different Risk Levels

Class	Mix*	Level I	Level II	Level III**
Minicompact	3.3	68.5	83.4	110.0
Subcompact	26.5	51.5	63.4	86.6
sports	7,3	39.7	47.8	68.9
Compact	23.2	46.4	57.0	74.0
Intermediate	22.4	42.2	51.3	69.7
Large	6.1	39.9	48.6	65.8
Luxury	11.2	37.2	46.2	62.1
Fleet	100.0	44.8	54.9	74.1

NOTE This table assumes no new emlsslon standards are legislated In the post-2000 timeframe Additionally, the table holds vehicle attributes constant at 1988 levels, except for Risk Level Ill

● Unchanged from 2001 estimate
●* Based on (fossil fuel + fossil equivalent) mpg

SOURCE Energy & Environmental Analysls, Inc

baseline for fleet size and performance, which implicitly assumes a moderate reduction from 1991 size-and-performance levels rather than the currently expected gradual increase in these attributes. This assumption is important—the fuel economy "penalty" associated with a continuation of trends to higher-power, larger, and more luxurious vehicles, as opposed to a reduction to 1987 levels of these attributes, is at least a few mpg in fleet fuel economy.

Tables 7-15 and 7-16 present, respectively, the basic assumptions on technologies for risk levels I and II, and a brief description of technologies included in all three levels.

The results presented in table 7-14 show that, given enough lead time and assuming successful diffusion of new technologies into the fleet, very high levels of fleet fuel economy can be reached without drastic shifts in size and performance often claimed as inevitable with such levels. For example, even using only technologies widely considered as high-probability candidates for commercialization after the turn of the century, a fleet fuel economy of 45 mpg can be achieved. Levels as high as 55 mpg can be reached without important changes in consumer attributes if certain medium-risk technologies can be moved into the fleet. And a fleet average of 75 mpg may eventually be feasible as well, though with ***both*** important technological advances and important changes in consumer preferences.

LEDBETTER/ROSS ANALYSIS

Marc Ledbetter of the American Council for an Energy-Efficient Economy and Marc Ross of the University of Michigan have estimated potential U.S. new car fleet efficiency for the year 2000 by using a variation of the EEA approach.[23] Ledbetter/Ross uses EEA fuel economy improvement estimates for individual technologies but alters the EEA analysis by:

- using a 7-percent discount rate rather than 10 percent as does EEA;
- calculating fuel savings over a 10-year estimated useful life; EEA's base case uses a 4-year fuel payback to simulate the average use by the first owner, but a 10-year payback for "max technology" cases;
- assuming a $1.37/gallon gasoline price;
- multiplying individual fuel economy percentage increases rather than adding them as does EEA; and
- for a specialized case, adding two technologies not on EEA's list of available technologies.

Ledbetter/Ross concludes new car fuel economy could be improved to 40.1 mpg by 2000, at an

Table 7-15–Assumptions on Technologies at Different Risk Levels for the Year 2010 (relative to baseline)

	Level I	Level II
Weight reduction	1870 weight reduction on all cars	25% weight reduction on all cars
Drag reduction	C_D= 0.24 for all cars	C_D= 0.20 for all cars
Frontal area reduction	0	0 for minicompact to 5 for iarge/luxury
Improved packaging	0 for minicompact to 5 for large/luxury	3 for minicompact to 8 for large/luxury
Engine friction reduction	As per table 7-16	As per table 7-16
Pumping loss reduction	450/0	6 6 %
Thermal efficiency improvement	5.3%	6.87%
Rolling resistance reduction	15%	25%
Diesel engine market penetration	0	20% of mini, sub, and compact classes

SOURCE. Energy & Environmental Analysls, Inc.

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[23] M. Ledbetter *and* M. Ross, *Supply Curves of Conserved Energy for Automobiles,* report prepared for the Lawrence Berkeley Laboratory, March 1990.

Table 7-16 –Fuel Economy Technologies at Different Risk Levels for the Year 2010

Level I
- Improved packaging efficiency
- Extensive use of aluminum and Fiberglas-reinforced plastics
- Advanced tires, reduction of rolling resistance coefficient to 0.0075
- Engine friction reduction (ceramic valves/titanium springs, two-ring pistons, 5-valve per cylinder engines, fiber-reinforced magnesium pistons and connecting rods)
- Increased compression ratio to 11

Level II
- All Level 1 technologies plus:
- Extensive use of graphite-reinforced plastics
- Advanced engines - *either* modulated displacement or lean burn or direct injection stratified charge 2-stroke, for smaller cars (to assure NO_x emission compliance)

Level III
- Level 1 and II technologies plus:
- All vehicles use turbocharged direct injection diesels
- Diesel/electric hybrid drive

SOURCE: Energy & Environmental Analysis, Inc.

average cost of $.52/gallon saved, if average automobile interior volume and acceleration performance were reduced to 1987 levels. Two technologies that would change driving “feel’ ’-aggressive transmission management and idle-off—would increase the fleet average to 43.8 mpg at virtually the same cost/gallon saved.

WHO IS RIGHT?

Substantial differences among the various estimates of fuel economy potential present policymakers with a significant dilemma: which analysis should seine as a starting point for making fuel economy policy. Examining the available estimates as well as evaluating the nature of projecting fuel economy potential convinces us that Congress cannot expect a technical analysis to deliver a fuel economy estimate that truly represents a “correct” value of industry potential. The reasons for this are:

1. There is a subjective component to all fuel economy projections, especially regarding the level of penetration of technologies.
2. Technology costs cannot be estimated without ambiguity because industry accounting “ traditionally involves some models subsidizing others; also, most (perhaps all) technologies affecting fuel economy affect other vehicle attributes as well, further complicating estimates of specific costs of improving fuel economy.
3. Fuel economy estimates are extremely sensitive to policy assumptions about appropriate risk levels, and to the proper role of nonconsumer (societal) costs in determining technology acceptability, and so forth, as well as to economic and market assumptions about consumer preferences, oil prices, etc.

A further problem is that the subjective nature of parts of the projection process (particularly estimating technology penetration), the lack of a publicly-accessible data base for automotive technologies, and the paucity of academic research on fuel economy during the past decade conspire to make adequate review of a particular estimate or set of estimates extremely difficult.

For this study, OTA has examined the various estimates of fuel economy potential; attended a meeting of industry engineers, EEA, the Departments of Energy and Transportation, and the Environmental Protection Agency, during which the industry and EEA methodologies and results were presented and debated extensively[24]; attended the 1990 Society of Automotive Engineers annual government-industry meeting where industry and EEA estimates were again presented and debated; and examined several reviews of the estimates. Based on this, we **conclude that the EEA analysis, modified recently to reflect new information provided by automakers, represents the best available basis for decisionmaking about fuel economy policy. However, we note that the EEA analysis must be used in context: each individual estimate of fuel economy potential for a particular scenario is associated with a set of critical assumptions that is a powerful determi-**

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[24] Held Jan. 17, 1990, at Ford Motor Co. World Headquarter, Dearborn, MI.

nant of the magnitude of the reported fuel economy values. The estimates have little value if used without understanding their associated assumptions.

The scenarios contain some assumptions that may be viewed as conservative, and others as optimistic. For example, in its 1995 and 2001 analyses, EEA includes only those technologies already in commercial production. To the extent that new fuel economy technologies might enter the fleet, especially by 2001, the EEA estimates of fuel economy potential will be conservative. Further, EEA has not included the potential for strong market penetration by advanced diesels, because diesels have not done well in the recent U.S. market. To the extent that diesels could overcome market resistance and emissions problems, fleet fuel economy could benefit. On the other hand, some EEA scenarios assume a strong increase in oil prices, early retirement of model lines (despite likely shortfall in cost recovery), adoption of technologies irrespective of cost-effectiveness, and rollbacks in vehicle performance, size, and luxury equipment, all of which may be viewed as quite optimistic from the standpoint of maximizing fuel economy potential. To the extent that policymakers do not agree with these assumptions, they must adjust the fuel economy projections associated with them upward or downward, or rely on alternative scenarios with more agreeable assumptions.

The strongest direct challenge to EEA methodology has come from domestic automakers. As discussed earlier, the automakers' estimates of fuel economy potential are much lower than corresponding EEA estimates. For 1995, the automakers' estimates for the potential percentage increases in fuel economy are about four-tenths of EEA estimates; for 2000, depending on the scenario, the industry estimates range from less than one-third to about one-half EEA estimates. Consequently, the three automakers have rejected EEA's analysis. Briefly, the automakers claim the EEA analysis:

- fails to consider synergism between technologies;
- relies on a few empirical studies rather than basic physical and thermodynamic laws;
- ignores investment, lead time, and market-demand issues;
- counts benefits from certain technologies once as individual subsystems and then inadvertently counts them again as part of an overall separately identified system improvement; and
- estimates benefits inaccurately for actual models where the fuel economy technologies have been applied.[25]

In some instances, the automakers appear to have misunderstood EEA's methodology and technology descriptions. EEA's methodology does consider synergism between technologies, takes investment, lead time, and marketing issues into account (though probably not as manufacturers would), and has not counted twice as charged. On some technologies, the automakers have chosen very narrow definitions of what technologies entail (e.g., front-wheel drive including only drivetrain efficiency effects); in doing so, the automakers' own analyses omit potential fuel economy improvements, because they include ***only*** the (narrowly interpreted) EEA set of technologies. Further, part of the difference between the automakers' results and EEA's results are differences in baseline years—EEA used 1987 in the analyses examined by the automakers; the automakers chose 1989, which has higher average weight and performance than the earlier fleet. Finally, we do not believe that the automakers have uniformly applied the required assumption of constant performance and interior volume to their ***own*** analyses, thereby forgoing some potential fuel economy benefits of the technologies.

An important point of disagreement between EEA and the automakers is the EEA assumption that the average technology application in 1995

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[25] Workshop package distributed by Ford at industry/government/EEA review meeting held at Ford Motor Co. World Headquarters, Dearborn, MI, Jan. 17, 1990.

will be better than the average application in 1987; the automakers appear to assume technology performance will not improve over this timeframe. Another area of disagreement, discussed in box 7-A, is the extent to which automotive design can compensate for changes in driving "feel"—for example, a vehicle's ability to accelerate briskly without the necessity of flooring the accelerator pedal and attaining very high engine speeds—without reducing customer satisfaction. This disagreement can translate into differences in the degree of engine downsizing considered acceptable.

As discussed earlier, in addition to their engineering analyses, domestic automakers have produced or sponsored statistical analyses of U.S. fleet fuel economy. The use of statistical models raises troubling issues:

1. The current fleet contains vehicles and technology applications ***significantly*** inferior to the fleet average. The automobile industry's general direction toward fewer companies and more uniform technological and design capabilities implies that these inferior outliers bear little relationship to future technical capabilities—yet they are included in the data set.
2. Most fuel economy technology applications can be used for either fuel economy improvement or performance improvement, or a combination of the two. Generally, automakers prefer maximizing performance, because most of today's consumers strongly favor performance over fuel economy. When technologies are optimized for performance, adjustments to calculate fuel economy improvement potential from the technologies will not account for this optimization.
3. Even if a statistical model avoids normal pitfalls associated with attempting to model fuel economy improvements by searching for statistical correlations among strongly interdependent variables, ***at best*** it can predict the ***current*** fuel economy benefits associated with particular technologies. However, using such models for projection assumes that the average fuel economy benefits obtained in the fleet during the baseline year–probably 1989 or 1990-will apply to the predictive year, 1995 or 2001 in current analyses. It is almost certain, however, that 1995 or 2(X)1 technology designs will reflect significant learning over the earlier fleets, as well as manufacturers copying from the best examples of the technologies, with one possible result being that better-than-average outliers in the 1989-90 fleet might represent the 1995 or 2001 average. Unfortunately, some outliers were discarded from the data series used by the industry-sponsored statistical analyses.
4. Construction of useful statistical models demands not searching for correlations among variables, but a technical foundation of cause and effect. Although some engineering judgment was used to create some of this foundation in one of the two models, it was supplied by the industry itself rather than independent sources.

Aside from these general issues associated with statistical analysis of future fuel economy, the methodologies used by BSA and Bussmann raise further issues.

First, BSA assumes that using the judgment of engineers from their sponsoring organization (Ford Motor Co.) is legitimate because of the indirect nature of the questions BSA posed. The validity of this assumption is unclear, and using the expertise of the sponsoring organization in this manner is, at best, quite risky for the objectivity of the analysis. Further, there is some potential that engineers may be influenced by the basic design and performance philosophy imposed by their company. For example, U.S. companies may deem it critical that shift smoothness or avoidance of high engine speeds be maintained even though maintenance of these and other conditions can affect fuel economy potential, and despite evidence that such conditions could be relaxed under the right circumstances.

Second, BSA adopted a log model because of the supposed multiplicative nature of the separate fuel economy effects of each variable. However, several factors affecting fuel economy do so in an additive, not multiplicative, fashion—e.g., rolling resistance, weight, aerodynamic drag, and accessory energy consumption.[26] Consequently, the form of the model adopted by BSA does not represent a good physical model of fuel economy dependence on vehicle attributes.

Third, BSA eliminated about half the available non-duplicative data points in the EPA data set because they were, in some sense, outliers.[27] The outliers included vehicles powered by rotary or diesel engines; police cars; vehicles with technologies that have only a few observations (5-speed automatics, turbochargers); and vehicles judged exotic and which did not fit the correlation coefficients of the model constructed without them in the data base. The implication of the need to drop so much data is that shifts in design can readily pull a vehicle away from the modeled results. This further implies that the modeled technology effects may not represent the true potential of the technologies, but simply the central tendency at the current time and for that partial group of vehicles used to create the model. This point offers strong support to point 3 above.

The Bussmann analysis apparently makes no attempt to correct for changes in performance and interior volume necessary if the fuel economy effect were measured using criteria of constant performance and interior volume inherent in the EEA estimates to which they are compared. For example, the analysis evaluates weight reduction at constant engine displacement and an increasing horsepower/weight ratio, whereas the appropriate evaluation would downsize the engine and keep horsepower/weight approximately constant.[28] Errors such as this can have a large impact on fuel economy estimates—a 10-percent weight reduction at constant engine displacement will produce about a 4-percent gain in measured fuel economy, whereas the same weight reduction at constant ***peeformance,*** with a smaller engine, will yield more than a 6-percent gain in fuel economy. Other problems include an important mistake in the grouping of automatic transmission improvements,[29] engine groupings that mix different engine types and cannot evaluate the benefits of individual technologies, and some internally inconsistent results that differ severely from Chrysler's engineering analysis.

Except for a small change in methodology and the addition of two technologies, the Ledbetter/Ross study is basically an application of EEA methodology to a more conservation-oriented scenario. The basic idea of exercising the EEA model with policy-oriented input assumptions is both sound and valuable, and OTA has adopted this approach in developing the scenario described in the next section. However, the Ledbetter/Ross study raises important concerns.

First, the methodological change—multiplying, rather than adding, individual fuel economy improvements— is theoretically incorrect. Although some fuel economy improvements may be multiplicative, others are not, including reductions in rolling resistance, weight reduction, improved aerodynamics, and improved accessory Efficiency.so EEA chose to be conservative by adding the individual effects, and, to conservation-oriented reviewers, this may be overly conservative. The difference in the two approaches leads the Ledbetter/Ross method to yield somewhat higher results. It would also yield higher results than a hybrid method combining additive and multiplicative terms according to the nature of the technologies.

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[26] Energy & Environmental Analysis, February 1991, op. cit.

[27] D.L. Greene, Oak Ridge National Laboratory, letter to J.O. Berger et al., University of Michigan, Ann Arbor, MI, Aug. 7, 1990.

[28] Except for technologies for which changes in the torque curve do not match changes in the horsepower curve (e.g., 4-valve-perc-ylinder engines).

[29] The appropriate comparison is a 4-speed transmission with lock-up versus a 3-speed transmission with lock-up; Bussmann compares the combination of 4-speed and 3-speed lock-up transmissions to a 3speed without lock-up.

[30] Energy & Environmental Analysis, February 1991, op. cit.

Second, the scenario may be more severe than many policymakers are comfortable with, though this judgment must await policymakers' review. In devising their conservation-oriented scenario, Ledbetter/Ross builds on the rates of technology penetration in the EEA "max technology" scenario, which EEA has openly characterized as an extreme case that represents "a heavy burden of retooling for the industry and would require unprecedented and risky changes to every product sold."[31] Even assuming costs do not rise with the rapidity of retooling necessitated and ignoring the impact on the industry of not recovering initial capital investment on models retired early, EEA has calculated that the max technology case would not be cost-effective (for a 10-percent discount rate, versus Ledbetter/Ross's 7 percent) until gasoline prices reached $2.50-$3.00/gallon for a 4-year payback and $1.50-$1.90/gallon for a 10-year payback.

Third, Ledbetter/Ross maybe overstating the probable effects of the two technologies they added. The effects of aggressive transmission management are unclear; and idle-off does not work well with gasoline engines and is not included in future plans of even the company (Volkswagen) that initiated it.[32]

The remaining estimates are a series of assertions by various conservation groups about the ability of the U.S. fleet to reach fuel economy level/s of 45 mpg or higher in a relatively short time.

To the extent these estimates are based, at least in part, on drastic changes in buyer preferences and fleet composition, these groups are right. As we show in chapter 8, changes in consumer preferences that result in movement toward the most fuel-efficient car in each weight or size class and in a shift toward smaller vehicles could yield large increases in the average fuel economy of the new car fleet. However, these changes are predicated on consumer acceptance of the loss in amenities—mostly interior space, acceleration capabilities, and automatic shifting—that consumers highly value, as shown by surveys and by actual vehicle purchasing patterns. Although significant shifting of consumer preference occurred during times of strong concern about gasoline availability and the potential for rationing and large future price increases, it is not clear that shifts could be achieved in the absence of pressure.

OTA believes that much of the reliance of high estimates on optimistic assumptions about new technologies and on the performance of high-efficiency vehicle prototypes is not firmly grounded. Performance projections about technologies not yet in mass production are extremely difficult-in some cases, impossible—to confirm at this time. However promising advanced technologies appear, their costs and performance will be highly uncertain until they are fully developed and in mass production and use. Similarly, the performances of "one of a kind" vehicle prototypes are instructive but far from conclusive in determining market acceptability. And we note that most high-efficiency prototypes use diesel engines, which have uncertain market acceptance and significant emissions problems in the United States. In a previous study, OTA concluded that increases in fuel efficiency to very high values "involve significant technical and economic risks," and an "increased risk that. . . insufficient development and testing will lead to poor on-the-road performance and/or product recalls."[33] In addition, OTA concluded in that study that the consumer costs of increased fuel efficiency, measured in dollars per gallon of gasoline saved, are quite speculative. For example, OTA's estimate of the consumer costs (in 1982 dollars) to achieve its 1995 new-car fuel efficiency targets varied from $.35/gallon saved to as high as $2.60/gallon

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[31] Energy & Environmental Analysis, *Analysis of the Fuel Economy Boundary for 2010 and Comparison to prototypes,* draft final report prepared for Martin Marietta Energy Systems, November 1990.

[32] It is felt to be too unnerving to drivers, especially in making a left turn against traffic. Joseph Kennebeck, Director, Government Affairs, Volkswagen of America, Inc., personal communication, June 19, 1991.

[33] U.S. Congress, Office of Technology Assessment, Increased *Automobile Fuel Efficiency and Synthetic Fuels: Alternatives for Reducing Oil Imports* (Washington, DC: U.S. Government Printing Office, September 1982).

saved.[34] These estimates range from economically attractive costs to costs that will be unacceptable to new-car purchasers without large increases in gasoline prices.

Although some elements of the EEA scenarios are distinctly optimistic, some elements of the basic EEA ***methodology*** will tend to yield conservative estimates of future fuel economy. These are:

1. ***Multiplicative vs. additive benefits.*** As noted in the discussion of the Ledbetter/Ross approach, some types of fuel economy benefits-efficiency improvements for transmissions, reductions in engine friction, improvements in engine thermodynamic and mechanical efficiency-are multiplicative, whereas EEA treats all as additive. This creates a small conservative bias.
2. ***Consideration of new technologies. The*** EEA projections for 1995/1996 and 2001/2002 examine only the effect of technologies currently present on at least one model in the fleet. Possibly by the mid-1990's, and certainly by 2001/2002, new technologies allowing improved fuel economy will begin to enter the fleet. Consequently, EEA projections for these years are overly conservative regarding the full array and penetration of fuel economy technologies. We note, however, that the levels of penetration of new technologies are unlikely to be high by 2001 because of lead time constraints, some imposed by automakers to guarantee reliability.
3. ***Technology performance.*** As discussed, in calculating the technology performance for individual technologies, EEA assumes that the better examples of fuel efficiency performance in the current fleet are likely to be reasonably representative of performance attainable by the ***average*** use of the technology by 2001-especially considering that many technology applications are optimized for maximum performance benefits rather than maximum fuel economy benefits. However, this shift in average performance levels is applied only to the incremental (new) use of these technologies over the intervening years. For that fraction of the fleet for which each technology is already in use, EEA does not assume any improvement in fuel economy performance levels. This is a conservative assumption.
4. ***Diesel engines.*** Although diesel engines provide higher fuel economy than spark ignition engines, they have not done well recently in the U.S. market and consequently have not figured in automaker planning. Also, although diesels are exempt from the 0.4 g/mi NO_x standard for automobiles until 2004, this exemption may be in jeopardy if diesels were to attain a bigger market share, and future emissions compliance is in doubt. EEA has not included diesel technology in their analyses of fuel economy potential, but large-scale penetration of diesels—especially advanced diesels such as turbocharged diesels or direct injection diesels—could increase fleet fuel economy to higher levels than possible with spark ignition (gasoline) engines.

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[34] Ibid. The cost range reflects an assumed moderate shift towards smaller cars.