Appendix A
EEA% Methodology to Calculate Fuel Economy Benefits of the Use of Multiple Technologies

OVERVIEW

Fuel economy behavior of a vehicle is dependent not only on individual technologies employed, but also on how they are applied and, to some extent, on what technologies are present simultaneously. In the EEA methodology, the fuel economy benefit due to technology changes in a given automobile is always calculated holding vehicle size, as measured by interior volume, and vehicle performance constant. The second term is more complex to define; but each technology that affects horsepower or torque of the engine or weight of the vehicle is examined in detail, and appropriate tradeoffs to measure fuel economy benefit on a constant performance basis are identified and defined.

Individual technology benefits are defined relative to a base technology and are expressed as percent benefits to fuel economy. If the technology represents a change to a continuous variable (e.g., weight), the impact of a specific percent change in the variable (e.g., 10) on fuel economy is estimated. If the technology represents a discrete technology, the percent benefit for that technolog is defined relative to replacing abase technology (e.g., four-valve engine replacing a two-valve engine), holding the size and performance parameters constant. Table A-1 provides a list of technologies discussed in this report and the

Table A-1 –Technology Definitions

Technology	Definition
Front-wheel Drive	Benefits include weight reduction and engine size reduction starting from a late 1970's rearwheel drive vintage design
Drag Reduction I	Based on C_D decreasing from 0.375 in 1987 to 0.335 in 1995, on average[1]
Drag Reduction II	Based on C_D decreasing from 0.335 to 0.30 in 2001, on average[1]
Torque Converter Lock-up	Lock-up in gear 2-3-4 compared to open converter
Four-speed Auto Transmission	Three-speed automatic transmission at same performance level
Electronic Transmission Control	Over hydraulic system, with electronic control of shift schedule and lock-up of torque converter
Accessory Improvements	Improvements to power steering pump, alternator, and water pump over 1987 baseline
Lubricants (5W-30)	Over 1OW-4O oil
Overhead Camshaft	OHV engine of 44-45 bhp/liter replaced by OHC engine of 50-52 bhp/liter but with smaller displacement for constant performance
Roller Cam Followers	Over sliding contact follower
Low-friction Pistons/Rings	Over 1987 base (except for select engines already incorporating improvement)
Throttle-body Fuel Injection	Over carburetor (includes air pump elimination effect)
Multipoint Fuel Injection	Over carburetor; includes effect of tuned intake manifold, sequential injection and reduced axle ratio for constant performance
Four-Valve Engine (OHC/DOHC)	Over two-valve OHC engine of equal performance; includes effect of displacement reduction and compression ratio increase from 9.0 to 10.0
Tires	Over 1987 tires, due to improved construction
Intake Valve Control	Lift and phase control for intake valves; includes effect of engine downsizing to maintain constant performance
Advanced Friction Reduction	Includes composite connecting rod, titanium valve springs, light-weight reciprocating components

[1] To exploit the benefits of drag reduction, the top gear must have a lower (numerical) ratio to account for the reduced aerodynamic horsepower requirement.

baseline technology against which benefits are measured.

Of course, no technology will be used in isolation, and synergistic and non-additive constraints must be recognized: engineering analysis is used to identify technologies that simultaneously contribute to reduction of the same source of energy loss and quantify the loss of total benefit when both technologies are used in the same vehicle; and the sum of market penetration of two non-additive technologies is not allowed to exceed 100 percent, since both technologies cannot be present in the same car.

The computational methodology uses a linear form of the exact engineering equation. Although the method is an approximation to simplify calculations, it yields results that have historically been accurate to 0.2 mpg. In projecting a maximum technology boundary case for the post-2000 time-frame, it is believed that these approximations could cause larger errors and a more rigorous engineering model is required. The current model is described below.

ENGINEERING MODEL

The model follows the work of Sovran (1,2) who produced a detailed analysis of tractive energy requirements on the EPA fuel economy test schedule (i.e., the city cycle and the highway cycle). Each driving cycle specifies speed as a function of time. The force required to move the vehicle over the driving cycle is easily derived from Newton's laws of motion:

$$F = M(dv/dt) + R + D$$

where F is the force required

M is the vehicle mass

dv/dt is the acceleration rate

R is the tire rolling resistance

D is the drag force

From the knowledge of physics, it can be shown that

$$F = M(dv/dt) + gMC_R V + C_D A p V^2/2 \qquad (1)$$

where C_R is the tire rolling resistance coefficient

CD is the drag coefficient

g and p are the gravitational acceleration and air density respectively

V is the vehicle speed

A is the vehicle cross-sectional area

Over the fuel economy test, V is specified as V(t), and the energy required E is the integral of

$$F\, dS = F\, V\, dt$$

where S is the distance traveled.

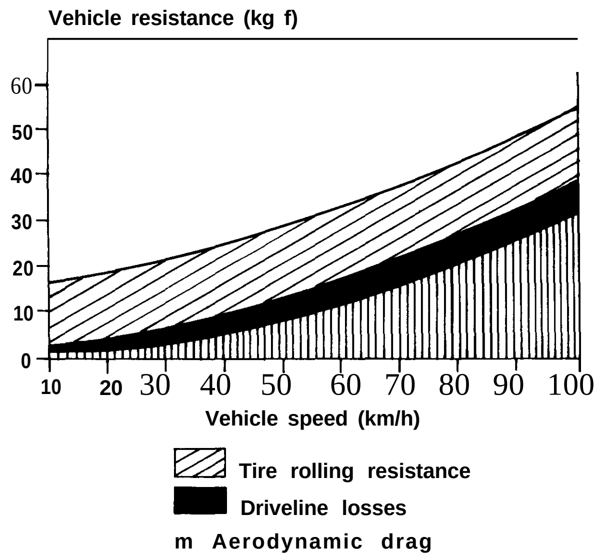
In the car, energy is provided only when F is greater than zero, while energy during deceleration is simply lost to the brakes. Taking these factors into account, Sovran and Bohn (2) showed that energy per unit distance

$$E/S = Q\, M\, C_R + ß\, C_D A + ðM \qquad \textit{(2)}$$

where ð, ß, and ð are constants virtually independent of vehicle characteristics, but differ for city and highway cycles. In essence, each term represents one component of the total force: the first term represents E_R the energy to overcome tire rolling resistance, the second represents E_A the energy to overcome aerodynamic drag, and the third represents E_K kinetic energy of acceleration. In the absence of acceleration (during steady speeds) E_K is zero. Figure A-1 shows the drag and the rolling resistance forces for atypical car at steady cruise, as well as the driveline loss described below.

Sovran (1) also related tractive energy to fuel consumption by adding the work required to drive accessories and the energy wasted by the engine during idle and braking. He defined the average engine brake specific fuel consumption

Figure A-1 -Vehicle Resistance in Coastdown Test



SOURCE: Energy & Environmental Analysts, Inc., 1991

over the test cycle as bsfc, and derived the following equation for the total fuel consumption over the test cycle:

$$FC = bsfc/n_d \times [E_R + E_A + E_K] + bsfc\ E_{AC} + G_i(t_i + tb) \quad (3)$$

where n_d is the drivetrain efficiency

E_{AC} is the accessory energy consumption

G_i is the idle fuel consumption rate

t_i, t_b is the time at idle and braking in the test cycle

The above equation shows that reductions in rolling resistance, mass, drag and accessory energy consumption, and idle fuel consumption cause additive reductions in fuel consumption.

The engine output energy is supplied to match the tractive energy requirements. If total energy required is defined as

$$E = 1/n_d \times [E_A + E_R + E_K] + E_{AC} \quad \textbf{(4)}$$

then $E = BHP \times t$

where BHP is engine power output.

Engine output power can be further decomposed to provide explicit recognition of engine internal losses. There are no conventions regarding the nomenclature of such losses. In general, the engine has two types of losses: one arising from the thermodynamic efficiency of combustion and heat recovery, and the second due to friction, both mechanical and aerodynamic. Aerodynamic friction is more usually referred to as pumping loss.[1] A third component that is sometimes excluded from the engine efficiency equation is the power required to drive some internal accessories such as the oil pump and the distributor. Items such as the water pump, alternator, and fan are usually (though not always) classified under accessory power requirements. In this analysis, power for all accessories—both internal and external-is classified under accessory power requirements, and the following relationship holds:

$$BHP = IHP\ (1 - P - F_R) \quad (5)$$

Where IHP is power generated by the positive pressure in the cylinder

P is the pumping-loss fraction

F_R is the mechanical-friction-loss fraction

Since fuel consumption can be written as

$$FC = \overline{bsfc} \times BHP \times t = isfc \times IHP \times t$$

where isfc is the indicated specific fuel consumption, that is, the fuel consumed per unit of horsepower prior to engine losses:

$$bsfc = isfc\ /\ (1 - P - F_R) \quad (6)$$

[1] We distinguish between throttling loss and pumping loss, using the latter term to include both throttling loss and frictional losses in the exhaust and intake system.

Substituting equation (6) into (3) we obtain

$$F = C\ isfc/[n_d(1-p-FR)] \times [E_R + E_A + E_K + n_d E_{AC}] + G_i[t_i + t_b] \quad (7)$$

The isfc is principally a function of combustion chamber design and compression ratio of the engine, and to a lesser degree, the air/fuel ratio. Since nearly all cars operate at stoichiometry, the air/fuel ratio is currently not a factor but could become one if "lean-burn" concepts are utilized.

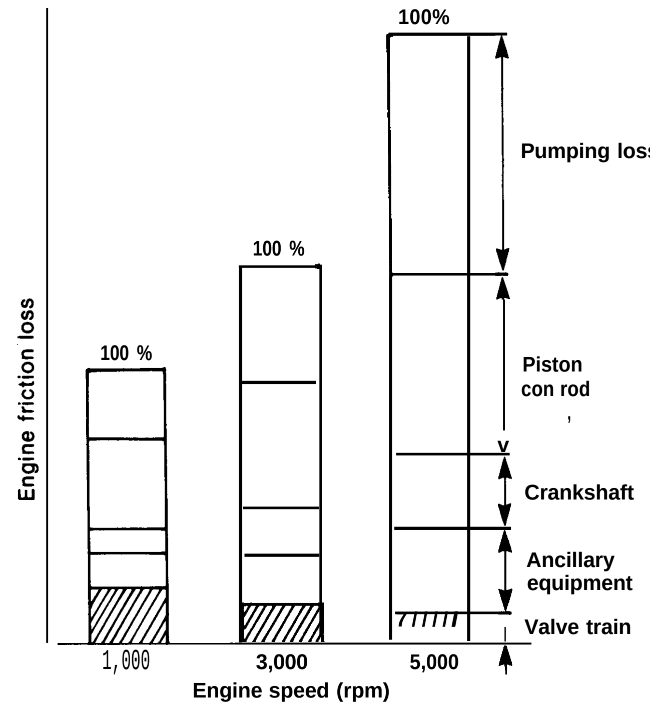
Pumping losses are dependent principally on the relative load of the engine over the cycle. The larger the engine for a given car weight, the lower the load factor and the higher the pumping loss due to throttling. Pumping losses are also incurred in the intake and exhaust manifolds and valve orifice. Use of tuned intake and exhaust manifolds and a greater valve area (e.g., by utilizing four valves/cylinder) reduce pumping losses. Losses other than throttling loss are not unimportant in the contribution to overall pumping loss.

Engine mechanical friction is associated with the valve train losses, piston and connecting rod friction, as well as the crankshaft friction. At low rpm, valve train friction is quite a large percentage of total friction, but decreases at higher rpm, while piston and connecting rod friction increases rapidly with increasing rpm. Total engine friction increases nonlinearly with engine rpm.

Idle fuel consumption is also affected by changes in engine parameters. At idle, all fuel energy goes into driving the accessories and overcoming pumping and friction loss, since there is no output energy requirement. Hence, decreases in pumping loss or mechanical friction result in a much larger percentage reduction in fuel consumption at idle than at load.

Mitsubishi provided data on general components of engine friction (figure A-2). The pumping loss shown here is due to internal airflow and not due to throttling. At closed throttle, idle pumping loss is approximately equal to frictional loss.

Figure A-2-Proportion of Engine Friction Due to Valve Train



SOURCE. Energy & Environmental Analysis, Inc., 1991

Equation (7) also shows the general structure of the calculation procedure. A simple differentiation of (7) yields:

$$\frac{dFC}{FC} = \frac{d(isfc)}{isfc} + \frac{P}{1-P-F_r} \times \frac{dP}{P} + \frac{F_r}{1-P-F_r} \times \frac{dF_r}{F_r} + \frac{E_A}{E_A + E_R + E_k + n_d E_{AC}} \times \frac{dE_A}{E_A} + \ldots + \ldots \quad (8)$$

where each derivative is expressed as a percentage change. Thus, a one-percent change in isfc translates into a one-percent change in fuel economy, but a one-percent change in pumping loss must be weighted by the fraction that pumping loss is of total output energy. Similarly, aerodynamic tractive energy change must be weighted by the fraction that aerodynamic energy loss is of total tractive energy.

Two observations are required at this point. First, equation (8) assumes the vehicle can be reoptimized for any change, so that engine variables are not affected by tractive energy requirements. Sovran points out this is not always possible. For example, aerodynamic losses are near zero at low speed but high at high speed. Hence, an engine cannot be simply downsized as aerodynamic loss is reduced, since the smaller engine will not have enough power at low speed. A higher gear must be added along with engine downsizing to achieve a correct compromise. In theory, it is possible to reoptimize the entire drivetrain, but in practice compromises cause significant losses in fuel economy from the attainable maximum. In the long run, as for 201O, some factors can indeed be optimized to yield the full predicted value, while other factors cannot. For example, it appears that predicted fuel savings related to friction-loss reduction are unlikely to be obtained as the engine cannot be downsized to the point where low-speed torque is compromised. On the other hand, rolling resistance decreases may provide the predicted fuel savings, as their effect is felt uniformly throughout the speed range.

CALCULATION PROCEDURE

Methods to increase fuel economy (reduce fuel consumption) must rely on reduction of energy contributed by each of the terms shown in equation (7). Equation (8) is useful if the change in factors is small, but not applicable for large changes. Focusing on the terms in equation (7), it is easily seen that fuel consumption is decreased by:

- decreasing friction and pumping loss;
- decreasing weight;
- decreasing drag;
- decreasing rolling resistance;
- decreasing accessory power consumption; or
- decreasing idle fuel consumption.

Of course, a given technology can act on more than one of these factors simultaneously. Table A-2 shows the relationships between individual technologies and the terms listed in equation (7). Drivetrain efficiency, n_d, is not the major factor in the benefits associated with multispeed transmissions; rather, the reduction in pumping and frictional losses are the biggest factor. It should also be noted that all engine improvements affect idle fuel consumption, so that idle consumption can be assumed to follow the same trends as bsfc, allowing equation (8) to be rewritten as

Table A-2–Technology/Energy Use Relationship

	isfc	P	F_1	E_A	E_R	E_K	E_{AC}	G,	n_d
Weight reduction					!	!			
Drag reduction				!					
Four-speed automatic		!	!						!
TCLU									!
Electronic trans control		!	!						
Accessory improvements									
Tire improvement									
5W-30 oil			!						
Overhead cam	!	!	!						
Roller cam followers			!						
Low-friction piston/rings			!						
Fuel injection	!	!							
Four-valves/cylinder	!	!							
Intake valve control		!							!
Five-speed automatic		!	!						
Electric power steering							!		

$$FC = isfc \times [E_R + E_A + E_K + n_d(E_{AC} + E_I)]/\{n_d[1 - P - F_R]\} \quad (9)$$

where E_I is an "equivalent" energy at idle to drive the accessories and torque converter. E_I is simply a mathematical artifact to make the analysis simpler for forecasting.

The relationship between fuel consumption and vehicle variables can be derived from equation (7) in exact terms if the coefficients are evaluated for the urban and highway driving cycles. In fact, Sovran utilized a detailed evaluation of these cycles to derive the sensitivity of fuel consumption to vehicle weight, aerodynamic drag, and tire rolling resistance coefficient. The general characteristics of the two cycles are shown in table A-3. One striking factor is that nearly 41 percent of urban time is spent in deceleration or at idle. In comparison, less than 10 percent of the time on the highway cycle is spent in braking or at idle. This difference, coupled with the different speeds and average acceleration rates in each cycle, leads to substantially different sensitivities between the two cycles.

In order to evaluate sensitivity of fuel consumption to changes in vehicle parameters, information is required on fuel consumption at idle and braking as well as fuel consumed by driving accessory loads. Sovran utilized data on 1979-80 GM cars and found that idle and braking fuel consumption was proportional to engine size. As an approximation, he assumed idle plus braking consumption to be a constant percentage of total fuel consumed and estimated this percentage at 16 for the urban and 2 for the highway cycle. He utilized a similar assumption for the accessory fuel consumption percentage, holding it constant at 10 and 9 respectively. This is equivalent to the approach in equation(9) where the term $[E_{AC} + E_I]$ bsfc is replaced by a constant percentage of FC. Utilizing these assumptions, he derived sensitivity coefficients that were dependent on the drag-to-mass ratio and the rolling resistance coefficient. Using typical values for the average 1988 car, with a mass of 1400 kg (3,1OO lb), C_D of 0.37, frontal area of 1.9 m^2, and C_R of 0.01, the fuel consumption sensitivity coefficients are as follows:

$$ð \text{ (for } C_D) = 0.28$$

$$ß \text{ (for Weight)} = 0.54$$

$$ð \text{ (for } C_R) = 0.24$$

The weight reduction sensitivity coefficient above does not incorporate the effect of engine downsizing, which reduces idle/braking fuel consumption proportionally. The coefficients assume that the engine and drivetrain are adjusted to provide constant bsfc (a factor which may not be realized in practice) but do not account for engine downsizing. Second, the constants are dependent to a certain extent on the assumptions for the fraction of fuel consumed at idle plus braking, and by accessory power demands (the smaller these fractions, the larger the sensitivity coefficients).

Table A-4 provides a summary of the values of sensitivity coefficients attained in actual practice as opposed to estimates derived purely from equation (8). In the application of these coefficients, it should be recognized that they can be

Table A-3–Fuel Economy Cycle Characteristics

	urban	Highway
Average speed (km/h)	38.4	77.60
Maximum speed (km/)h	91.5	96.80
Distance (km)	12.0	16.50
Time at idle (s)	249.0	3.00
Time of braking (s)	311.0	57.00
Total time for cycle (s)	1,373.0	765.00
Percent of time at idle and braking	40.8	7.84

Table A-4-Estimated Fuel Consumption Sensitivity Coefficients (Percent reduction in fuel consumption per percent reduction in independent variable)

Variable	Fuel Consumption Sensitivity	Fuel Economy Sensitivity
Weight reduction	0.62[1] (0.54)	0.66
Drag reduction (CD)	0.22	0.23
CR reduction	0.23	0.24
Thermal efficiency	1.00	1.00
Pumping loss	0.23	0.24
Friction loss	0.23	0.24
Drivetrain efficiency	0.78	0.81
Accessory power	0.10	0.11

[1] 0.62 Includes proportional reduction of displacement, 0.54 assumes constant displacement.

used only for modest variations for any variables involved.

When large reductions of any variable are likely to occur, the preferred form of analysis is to use equation ('7) with a "slippage" factor to account for benefits that cannot be attained in actual practice for some variables of concern.

The methodology used to calculate the fuel economy benefit due to the application of any set of technologies to the automobile is as follows. First, the technology set is examined to identify which energy-use factors are affected and areas of overlap are examined for synergy. Second, the net reduction in each specific energy-use area is estimated and the benefits to fuel consumption calculated with equation (8). In general, synergies occur primarily in pumping loss reduction, with smaller synergies in the area of friction reduction.

FORECASTING METHODOLOGY

The theoretical concepts behind the forecast have been explained through the engineering equations. The exact method of forecasting fuel economy involves the following sequence of steps:

- defining a baseline;
- identifying available technology;
- adopting technology at the proper level of market penetration; and
- calculating fuel economy after adoption of technology.

The analysis can be performed at the model-specific level (such as Ford Escort or Chevrolet Caprice) or at a more aggregate market class level, where vehicles within a market class are very similar in size, performance, and option levels.

All the analyses begin by defining a baseline of vehicle technology and fuel economy derived from actual data. For example, the choice of the 1988 Ford Escort as the baseline requires identification of all vehicle characteristics such as weight, drag coefficient, engine size and power, types of transmissions, acceleration performance, type of fuel system, etc. as well as the actual EPA composite fuel economy rating for 1988. If the analysis is at a market class level, these characteristics are averaged across all models in the given year, and discrete technologies such as fourspeed automatic transmissions are described by their market share within the class.

Once baseline technologies are detailed, available technologies are identified along with the potential availability dates. In the short term, most technologies available for improvement are dictated by the product plan for a particular model, and these are tracked through articles in the trade press. For the longer term, EEA selects available technologies based on both product lifecycle of the model as well as technology readiness. Continuing with the Ford Escort as the example, its product lifecycle is eight to nine years and a new design was introduced in 1990. This implies that major changes can be made when the next model is introduced in 1998-99.

Technology readiness is based on EEA's determination of when a technology is likely to be broadly adopted in the marketplace. For example, we expected that four-valve-per-cylinder technology could be broadly adopted by domestic manufacturers in the 1991-98 timeframe, whereas five- valve-per-cylinder technology is unlikely to enter the mainstream until 2001. Such determinations are based on interviews with auto manufacturers and involves some subjective judgment. It is recognized that technology availability does not guarantee its introduction in the marketplace; this depends on the costs of a technology and its benefits. A simple model of technology adoption by the manufacturers is one where technology is adopted in a carline if the value of fuel saved over a specific period exceeds its first cost to the consumer. Analysis of historical data suggests a period of four years (typical of new-car ownership) for payback provides a good approximation of past manufacturer behavior, and we have utilized this to represent scenarios of business as usual or "product plan" scenarios. Other scenarios can be easily constructed to evaluate technology adoption based on fuel savings over a vehicle lifetime (10 or 12 years), or in total disregard of any cost-effectiveness criteria where all available technologies are adopted to the maximum extent possible. Table A-5 presents the estimated costs of the existing fuel economy technologies included in the forecasts.

Technology adoption is usually associated with a level of market penetration. For most technologies, it is an "all-or-nothing" decision at the carline level, since, for example, a given car will either have anew lowdrag body or it will not. Technology non-additivity must be accounted for so two technologies (such as manual and automatic transmissions) that cannot be present in the same car are not assumed to each have 100-percent" market penetration. However, there are some technologies offered as options in a given model, where the consumer has a choice. Typically, these involve

Table A-5–EEA's Estimates of Incremental Retail Price of Fuel Economy Technology (1988$)

Front Wheel Drive		240	
Drag Reduction	to CD = 0.33	32	
	to CD = 0.30	48	
4-Speed Automatic Transmission		225	
Torque Converter Lock-up		50	
Electronic Transmission Control		24	
Accessory Improvements.		12	
OHC Engine:	4-cylinder	110	
	6-cylinder .,	180	
	8-cylinder	200	
4-valve heads:	4-cylinder	140	
	6-cylinder	180	
	8-cylinder	225	
Roller cams		4	per cylinder
Friction reduction 1:	4-cylinder	30	
	&cylinder	40	
	8-cylinder	50	
"Advanced Pushrod"		40	(6-sylinder)
Throttle Body Fuel Injection (over carburetor)		42	(one injector)
		70	(two injector)
Multipoint Fuel Injection (over throttle body)	4-cylinder	48	
	8-cylinder	84	
	8-cylinder	80	
Tire Improvements		12	(4 tires)
Oil (5W-30)		2	
5-speed Automatic (over 4-speed)		100	
Continuously Variable Transmission (over 4-speed auto)		100	
Advanced Friction Reduction		same as Friction Reduction I	
Tire Improvements (1995-2001)		18	
Intake Valve Control	4-cylinder	140	
	8-cylinder	200	

SOURCE: Energy & Environmental Analysis, Inc., 1991

performance engines or engines using other fuels such as diesel engines. Evaluation of their market penetration is either developed by specific scenario assumptions, or else determined by trend analysis or results from consumer surveys if the object is to forecast fuel economy.

The calculation of fuel economy after technology adoption is relatively simple using the "linearized" method detailed earlier, but specific adjustments are made for synergistic effects between two technologies. The synergies are recognized through engineering analysis, as the operation of each technology is well understood and the source of its benefits is known (in terms of reduction of specific losses identified in the engineering equations). In brief, the model is

$$FC = FC_o [1 + \Sigma\Sigma s_{ij} m_i m_j]$$

where FC_o is the baseline fuel economy

m_i is the market penetration of the i^{th} technology

X_i is the percent fuel economy benefit of the i^{th} technology

S_{ij} is the synergistic effect between technology i and j on fuel economy

DATA SOURCES

The model of fuel economy shown above requires detailed estimates of the fuel economy effect of each technology, as well as estimation of non-additive and synergistic effects of each technology with other technologies. One factor aiding in the recognition of technology-specific fuel economy effects is the criteria utilized to select available technologies for 2001, which require that every technology be sold commercially in 1991 in at least one mass-produced car model. This, of course, makes it possible to scrutinize available models and their fuel economy to discern the effects of specific technologies.

In general, detailed estimates of technology characteristics are based on the following sources of information:

- data developed by the Department of Transportation (DOT) in the late 1970s and early 1980s;
- data submitted by manufacturers to DOT during the 1980s in response to new rulemaking on CAFE standards;
- data published in scientific journals or papers published by automotive engineering societies worldwide, or provided by auto manufacturers during interviews with EEA staff;
- data based on detailed vehicle-to-vehicle comparisons from available models; and
- engineering analysis concluded by EEA staff on the technologies.

Due to the maturity of the automotive engine, it is a relatively rare occurrence that data available for a given technology from different sources provide highly conflicting results when properly interpreted. Specifically, technology benefits are sensitive to how the technology is applied and the nature of the vehicle before and after technology application. As noted, any technology can be utilized to improve performance rather than fuel economy, and careful control of performance related variables is essential in making judgments about technology benefits. Another factor is the state of technology maturity; typically, a technology is not optimal at its introduction, but is developed more fully over a few years. These factors introduce uncertainties in car-to-car comparisons, and data from such comparisons are validated by data from other sources before technology characteristics are assigned.

Product plan information is often readily obtainable in trade publications. For example, recent issues of ***Automotive News*** have contained Ford product and engine plans (Sept. 10, 1990, and Dec. 10, 1990, respectively), Chrysler product plans (Oct. 1, 1990), and a variety of European product plans (July 8, 1991).

REFERENCES FOR APPENDIX A

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