SUPPLY CURVES OF CONSERVED ENERGY FOR AUTOMOBILES

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SUMMARY

Concern about rising oil imports and the environmental consequences of growing energy consumption, especially global warming, have renewed the debate over improving automobile fuel economy. Questions about the technical and economic potential for improving automobile fuel economy are central to that debate. This paper addresses some of those questions.

A limited list of fuel economy technologies are analyzed to estimate how much new car fuel economy could be improved by the year 2000, and how much of this improvement is cost-effective for the car-buying public. The list of technologies analyzed is not exhaustive; it only includes technologies that are relatively well-understood, and for which fuel saving and cost information are available. Most have already been commercialized.

The analysis indicates that if average automobile size and acceleration performance were held constant at their 1987 levels, new car fuel economy could cost-effectively be improved to 40.1 mpg by the year 2000, at an average cost of 52 cents per gallon of gasoline saved. Use of two additional technologies that would change the feel of driving, aggressive transmission management and idle-off, would increase the cost-effective level to 43.8 mpg, at an average cost of 53 cents per gallon saved.

If an average new car fuel economy of 40.1 mpg were achieved by 2000, fuel use could be reduced by 1.6 to 1.7 quadrillion Btu (quads) by the year 2000. The lower level of savings is relative to a scenario in which new car fuel economy is allowed to rise in response to market changes, and the higher level of savings is relative to a scenario in which new car fuel economy is held constant at 1987 levels. If new car fuel economy reaches 43.8 mpg by 2000, fuel use would be reduced by 2.0 quads (vs. market scenario) to 2.1 quads (vs. frozen efficiency scenario).

Fuel savings in the year 2010 from use of these technologies are also estimated. These estimates do not incorporate the effects of additional fuel economy technologies that will surely become available after 2000. The estimates are simply based on a projection of the year 2000 technology list to the year 2010.

Year 2010 cost-effective new car fuel economy rises to 42.5 mpg because a higher fuel price makes additional fuel economy technologies cost effective. If aggressive transmission management and idle-off are included, cost-effective new car fuel economy rises to 46.5 mpg. Energy savings in the year 2010 from achieving 42.5 mpg are .9 quads relative to the market scenario and 4.2 quads relative to the frozen efficiency scenario. Energy savings from achieving 46.5 mpg are 1.7 quads relative to the market scenario and 5.0 quads relative to the frozen efficiency scenario.

INTRODUCTION

This report analyzes the cost effectiveness of automobile fuel economy technologies and the fuel savings that could result from their widespread use in the U.S. automobile fleet. Estimates are derived for the years 2000 and 2010. The technologies analyzed here do not exhaust the list of technologies that may be available for improving fuel economy. This is especially true for the 2010 estimates. If policies to push fuel economy to substantially higher than current levels are enacted, or if fuel prices rise substantially, many more new fuel economy technologies than analyzed here will surely be developed. This analysis thus represents the technological potential for a limited list of technologies that are relatively well understood. Supply curves of conserved energy are developed to illustrate the results of the analysis.

COSTS OF TECHNOLOGIES

Developing a supply curve of conserved energy for automobiles is difficult at best, largely because cost information on light vehicle technologies is very difficult to obtain. Vehicle manufacturers consider the information proprietary and therefore withhold it. For many fuel economy improvements and technologies, manufacturers themselves don't even have reasonable estimates of their costs. Furthermore, technologies that improve fuel economy often have benefits that serve other purposes. For example, multi-point fuel injection improves fuel economy, but it also decreases emissions and improves performance. Such multi-purpose benefits make it difficult to determine how much of the total cost of a technology should be allocated to fuel economy. Even further complications arise in trying to adjust costs for retooling expenses, amortization periods, and manufacturer markup.

Despite these and other unspecified difficulties, Energy and Environmental Analysis, Inc.(EEA), Arlington, VA, has compiled a set of cost estimates for fuel economy technologies that the U.S. Department of Energy uses to analyze fuel economy policies. These cost estimates and related information have recently appeared in several publications.[1] Given the amount of scrutiny and revisions to which these numbers have been subjected, and given the difficulty in developing alternative estimates of costs, this analysis relies heavily on the cost estimates derived by EEA.

EEA derived its costs using "normal costing," that is, estimates of variable manufacturing costs for each technology were multiplied by an estimate of an industry average ratio between variable costs and retail vehicle prices to determine consumer cost. Costs used in this analysis are thus estimates of the change in consumer car prices that would result from use of these technologies.

Despite the care taken in development of EEA's cost estimates, the reader is cautioned not to consider these numbers to be firm. These are reasonable estimates, given the difficulties and inaccuracies encountered in compiling these kinds of numbers. For fuel economy technologies that are pieces of equipment added to a car, such as fuel injection, costs are more easily determined. As noted above, however, if this equipment serves more than one purpose, the portion of the equipment costs that should be allocated to fuel economy is still difficult to determine and subjective. For fuel economy technologies that are simply a new way of building an existing part of the car and require little or no extra materials, such as some aerodynamic improvements, costs are more difficult to determine; and often times, the costs for these technologies disappear over time as initial costs are amortized.

Many of the technologies analyzed in this paper are relatively new technologies whose costs are likely to fall as manufacturers gain manufacturing experience with them. But to be conservative, the cost estimates used for the year 2000 were not reduced for the year 2010.

TECHNOLOGIES ANALYZED

Four supply curves of conserved energy are developed in this analysis. Two time horizons are used -- 2000 and 2010 -- for each of two technology groups.

Technology Group 1 is limited to those technologies appearing in a paper that summarizes some recent Department of Energy-sponsored research on automobile fuel economy, hereafter referred to as Difiglio, et. al.[2] (See Table 1) According to Difiglio, et. al., these technologies are proven technologies that are already available in existing cars or prototypes; other technologies were omitted because, "1) they are not market-ready, or 2) they do not presently meet vehicle emission standards, or 3) they detract significantly from performance, ride, or capacity, or in some other way are not acceptable to consumers." Furthermore, the selected technologies "would not reduce performance, ride, or capacity over 1987 levels." Estimates of fuel economy improvement associated with each of these technologies are the same or are very similar to those used in Difiglio, et. al. Some small adjustments were made to allow consolidation of some technologies into groups. In sum, Technology Group 1 is a close approximation of the technologies and their associated fuel economy improvements used in Difiglio, et. al.

Technology Group 2 includes all the technologies in Group 1, plus idle off and aggressive transmission management. Although these technologies were not included in the analysis by Difiglio, et. al., they are included here because they offer significant potential for improving fuel economy, they could be installed in production vehicles before 2000, and because, like other technologies in this group, they do not significantly degrade ride, performance, or capacity over 1987 levels.

These two additional technologies included in Group 2 will change the feel of driving a car. For example, more gear shifting will occur with aggressive transmission management and a car will operate in higher gears more of the time, causing a slight delay for downshifts needed to accelerate quickly. Electronic transmission control can minimize the effect these changes will have on the feel of driving.[3] The Technology Descriptions section describes each of the technologies in Technology Groups 1 and 2.

METHODOLOGY

All curves are calculated from a base year of 1987, i.e., improvements in fuel economy and costs are relative to 1987 levels. (The average nominal, or EPA-rated, fuel economy of all domestic and import new cars sold in the United States in 1987 was 28.3 mpg.) The average interior volume, and acceleration capability are held at their 1987 levels.[4]

The technologies and costs used in developing the Year 2000 Automobile Fuel Economy Supply Curves are listed in Tables 1-4. (A key to the acronyms used to identify the technologies can be found in Box A.) Some of the listed technologies are combinations of technologies (e.g., TRANS represents electronic transmission control and torque converter lock up), and some aren't technologies in the sense of new devices or equipment (e.g., aerodynamic improvements represent an advancement in design, not a new technology).

In Tables 1-4, the consumer costs estimated for each of these technologies are listed in the second column of the table (CONSUM COST), and are annualized in the third column (ANNUAL COST) using a 7% discount rate, a ten year estimated useful life, and a distribution for miles driven per year, by car vintage, as estimated by the U.S. Department of Transportation.[5] The costs are approximates of those developed by EEA (with the exception of the costs for idle off and aggressive transmission management, which were independently estimated). All costs are stated in constant 1989 dollars.

Estimates of the fuel economy increase associated with each technology were also derived from Difiglio, et. al.[6] (These estimates are listed in INDIVID NEW CAR MPG INCR - %.) The fuel economy increase associated with two technologies, aggressive transmission management and idle off, were independently estimated by the authors.[7]

Values in the fifth column in Tables 1-4 (MARKET SHARE INCREASE) reflect the projected increase in market share -- relative to the total new car market -- for each technology. Values in the sixth column (NEW CAR FLT MPG INCR-%) reflect the new car fleet mpg increase expected from use of each technology to the extent projected in MARKET SHARE INCR. Estimates of market share increase were taken from Difiglio, et. al., except for idle off and aggressive transmission management, which were estimated by ACEEE. Market shares taken from Difiglio, et. al. were taken from their maximum technology scenario because the authors believe these rates of new technology penetration better reflect the future of the rapidly changing automotive industry, where competitive pressures are forcing manufacturers to redesign car lines much more rapidly than in the past.

Estimates of how much each technology can increase new car fuel economy are found in the ninth column (ACTUAL NEW CAR FLT MPG). These values are estimates of actual, on-road fuel economy, calculated by adjusting EPA-rated combined city/highway fuel economy to account for its growing over-estimation of actual fuel economy. The EPA fuel economy test procedure substantially over-estimates on-road fuel economy because of differences between the official EPA driving cycle and actual driving conditions. Increased urban congestion, higher highway speeds, and a larger fraction of total miles being driven in urban areas are projected to increase the difference between EPA fuel economy and actual fuel economy from 15% in 1987 to 30% in 2010.[8] Based on this estimate, year 2000 fuel economy levels in this analysis are 23% below the EPA-rated level, and year 2010 estimates are 30% below. All fuel savings estimates in this paper are based on the adjusted EPA fuel economy ratings.

The marginal cost of conserved fuel (COST CNSRV FUEL, TECH N) was calculated using a 7% real discount rate and miles driven per year, by vintage, as specified by the U.S. Department of Transportation.[9] All technologies with costs lower than projected fuel prices are deemed cost effective. The projected price of gasoline for the year 2000 was $1.32, as estimated by the Energy Information Administration.[10] The projected price of gasoline in the year 2010 is $1.65, as stipulated by sponsors of this research.

The values in the cost of conserved fuel column can roughly be interpreted as the societal cost effectiveness of adopting the specified technologies in that the discount rate (7%) and the length of time over which fuel savings were estimated (10 years) more closely reflect a social perspective than a car buyer's perspective.[11] A truer test of societal cost effectiveness would value gasoline at a higher level, to include such things as the environmental, security, and health costs of consuming gasoline.

Levels of fuel economy deemed cost-effective here assume that automobile size and acceleration performance are held constant at their 1987 levels. Since both performance and size have increased slightly since then, this analysis assumes a small reduction of vehicle size and acceleration performance, relative to current levels.

Before proceeding it is worthwhile to note that increasing acceleration performance has a negative effect on fuel economy. A recent EPA analysis concluded that the decrease in the average 0 to 60 miles per hour acceleration rating -- from 14.4 seconds in 1982 to 12.5 seconds in 1989 -- has caused a 2 MPG decline in the average fuel economy of new cars.[12] Thus, the fact that existing use of many of these technologies hasn't produced the fuel economy gain identified here doesn't disprove these estimates of fuel economy potential. In fact, many of these technologies are now being used to enhance acceleration performance rather than fuel economy.

The fleet fuel economy in the next to the last column (ACTUAL FLEET MPG) was calculated using a vintaging model based on survival probability data and annual-miles-travelled-by-vintage data.[13] The model calculates fleet fuel economy on the basis of each vintage's new car fuel economy, and assumes a fixed distribution of new and old cars for each year. The new car fuel economies specified in the ninth column (ACTUAL NEW CAR FLT MPG) are assumed to be achieved by the year 2000, after a straight line ramp up in new car fuel economy over the period 1992 to 2000. For example, row 10 in Table 1 specifies a new car fuel economy of 29.3 mpg. New car fuel economy in 1996 is thus assumed to be 25.5 mpg [(29.3-21.7)/2]. Calculating the new car fuel economy similarly for all years from 1992 to 2000, and knowing or estimating the new car fuel economy for other vintages, yields, after use of the vintaging model, the fleet fuel economy estimate of 25.6 MPG in the year 2000.

The energy savings associated with each technology (2000 ENERGY SAVINGS) are based on the assumption that light vehicle miles traveled in the United States grow at the rate of 2.5% per year to the year 2000, and 2% per year to the year 2010.[14] Two-thirds of light vehicle miles traveled in 2000 and 2010 are assumed to be attributable to automobiles, with the remaining one-third attributable to light trucks. Cumulative energy savings are calculated relative to a vehicle fleet whose new car fuel economy is frozen at the 1987 level.

Energy savings estimates for the year 2010 do not assume a higher rate of penetration of these technologies in new cars by the year 2010 (a high degree of penetration in the new car fleet is already achieved by the year 2000). The year 2010 savings estimates, however, are based on higher penetration of these technologies into the entire vehicle fleet, i.e., the new cars with these technologies will comprise a large fraction of all vehicles on the road in the year 2010.

RESULTS

The marginal cost of conserved fuel estimates in Tables 1-4 are plotted in Figures 1-4. The supply curves in Figures 1-4 illustrate how much fuel could be saved in the year 2000 or 2010 (horizontal axis) and the cost of achieving this level of savings (vertical axis). Each step on these curves represents a technology from Tables 1-4, and reveals the cost of the technology, and the potential savings associated from its adoption. As can be seen, the technologies are ranked in order of cost effectiveness. For Figures 1 and 2, technologies whose costs are less than $1.32 per gallon saved are cost effective. For Figures 3 and 4, technologies whose costs are less than $1.65 per gallon saved are cost effective.

Care should be taken in interpreting the results of these supply curves. The order in which these curves suggest technologies be adopted is not necessarily ideal or reasonable. Schedules for vehicle redesign and introduction, amortization schedules for capital equipment, and other industry characteristics will probably dictate a different order of adoption. Furthermore, other technologies not considered in the development of this curve are likely to become feasible and cost effective by the year 2000, especially if the federal government mandates substantial fuel economy improvements in automobiles.

Supply Curves for the Year 2000 (Figures 1 and 2)

Table 1 shows that, using Technology Group 1, the maximum cost-effective level of new car fuel economy in 2000 is 30.7 mpg (40.1 mpg, EPA-rated). Only two technologies on the list, weight reduction and Tires II are more expensive than EIA's projected gasoline price in 2000, and thus fail this test of cost effectiveness. The cost and energy savings of each technology in Table 1 are plotted in Figure 1 as a supply curve of conserved energy. As can be seen, this mix of fuel economy technologies and costs yield cost-effective fuel savings in the year 2000 of about 1.7 quads (quadrillion, 10^{15}, Btu). This level of savings represents an 18% reduction in the fuel that would be consumed by automobiles in the year 2000, relative to a scenario in which new car fuel economy is held to its 1987 level of 28.3 mpg (21.7 mpg actual in 2000).

Using the cost-effective technologies in Technology Group 2 (Table 2) would result in a new car fuel economy level of 33.6

mpg (43.8 mpg EPA-rated). The costs and energy savings for each technology in Table 2 are plotted in Figure 2. As can be seen, all but the last two technologies are cost effective. Fuel savings of 2.1 quads (22%) are achievable using cost-effective technologies. Again, this level of savings is relative to how much fuel would be used if new car fuel economy were held at 1987 levels.

Supply Curves for the Year 2010 (Figures 3 and 4)

As seen in Tables 3 and 4, technology Groups 1 and 2 are entirely cost effective in the 2010 time frame. This is a consequence of a higher projected fuel price for 2010.

Fuel savings relative to frozen efficiency rise substantially above the year 2000 savings. This occurs because new, high fuel economy cars dominate the fleet in the year 2010, whereas they didn't in the year 2000. Cost-effective savings in the year 2010 are 4.2 quads for Group 1 and 5.0 quads for Group 2. Cost-effective new car fuel economy levels are 42.5 MPG for Group 1 and 56.3 MPG for Group 2.

Comparison of Fuel Saving Results to Market Scenarios

Up to this point, fuel savings have been calculated relative to how much fuel would be consumed in the years 2000 (or 2010) if new car fuel economy were frozen at 1987 levels through the year 2000 (or 2010). It is also useful to calculate fuel savings relative to a market scenario, in which new car fuel economy is allowed to rise above 1987 levels in response to market mechanisms.

Researchers at the Argonne National Laboratory recently developed some projections of market driven increases in fuel economy that were used by the U.S. Department of Energy in estimating future energy conservation potential.[15] They estimate in their base case market scenario that average automobile fleet (all cars on the road) fuel economy will reach 21.8 MPG (actual) in 2000, and 26.6 MPG (actual) in 2010. These estimates are based on a fuel price projection for the year 2000 that is the same as this study's ($1.32/gallon), and on a projection for the year 2010 that is higher than this study's ($1.87/gallon vs. $1.65/gallon). The year 2010 fuel price difference between Argonne's and this study's is small enough not to require adjustments to make the market fuel economy levels projected in the Argonne study match those used in this analysis.

In the year 2000, fuel savings from using all cost-effective technologies in Group 1, relative to the market scenario, are only slightly less than fuel savings relative to the frozen efficiency scenario (1.7 quads vs. 1.6 quads). This small difference is attributable to the very small increase Argonne projected in new car fuel economy by 2000 for their base case market scenario. Likewise, savings for Group 2 relative to a market scenario is only slightly less than savings relative to a frozen efficiency scenario (2.1 quads vs. 2.0 quads).

In the year 2010, fuel savings relative to the market scenario fall well below fuel savings relative to the frozen efficiency scenario because Argonne projects a very substantial increase in fuel economy between 2000 and 2010. For Group 1, savings are only .9 quad relative to the market scenario (4.2 relative to frozen efficiency), and for Group 2, savings are only 1.7 quads relative to the market scenario (4.9 relative to frozen efficiency).

All results are summarized in Table 5.

DESCRIPTION OF TECHNOLOGIES USED IN GROUPS 1 AND 2

The following section contains brief descriptions of the technologies and their fuel savings estimates used in this analysis. The primary source for this information is the documentation developed for the Difiglio, et. al. analysis.[16] Other sources used are as noted.

Intake Valve Control

Intake valve timing and lift are optimized for a particular engine speed and load in conventional engines (typically in the high rpm, high load range). At other engine speeds and loads, less than optimal valve timing and lift can substantially reduce fuel economy. New valve control systems that vary timing and lift over a range of engine speeds can largely overcome these problems. These new systems are currently the subject of much research and development activity. With complete control of intake valves, it may be possible to eliminate the throttle plate, a major cause of energy loss at low engine speeds. Without a throttle plate, the efficiency of a gasoline engine can approach that of a diesel. Intake valve control also offers substantial emissions reductions.

Several manufacturers, including Honda and Nissan, currently offer intake valve control systems, but these systems are rudimentary compared to the more advanced electric, hydraulic, or pneumatic systems being developed by numerous companies. New systems are estimated to provide a 6% fuel economy benefit.[17]

Roller Cam Followers

The interface between a cam and flat-faced cam followers is the second largest source of engine friction (the largest source is the piston rings) and may account for 25% of total engine friction. Roller cam followers can reduce this friction. They are now used in over half of new engines. They are estimated to provide a 1.5 percent increase in fuel economy.[18]

Multi-point Fuel Injection

Carburetors are rapidly being replaced by fuel injection systems. Fuel injection systems offer more control over fuel metering, resulting in more power, better fuel economy, lower emissions, and better drivability. One form of fuel injection, throttle body injection (TBI), uses one or two injectors to inject fuel upstream of the intake manifold. These systems offer about a 3 percent gain in fuel economy. A more precise form of fuel injection, called multi-point fuel injection (MPFI), injects fuel just upstream of the intake valves. MPFI can improve fuel economy an additional 3 percent above TBI.[19]

For this analysis, both TBI and MPFI were used to displace carburetors. MPFI, however, was used to displace all TBI by the year 2000. After adjusting for existing levels of use of both technologies, the combined estimated fuel economy increase associated with full use of MPFI is 3.5%.

Four Valves Per Cylinder Engines

Conventional spark ignition engines contain two valves per cylinder, one intake and one exhaust. In recent years, four valves per cylinder engines have become commonplace. Gasses entering and exiting cylinders in four valve engines encounter less friction, providing better volumetric efficiency. Smaller and lighter valve train parts reduce valve train inertia, and allow higher engine speeds. Four valve engines can typically produce 25 to 35 percent higher horsepower than their two valve counterparts (although, this is achieved at higher rpm). This higher power output allows a smaller engine to be substituted for a larger engine.

Holding horsepower roughly constant, and substituting a 4-valve 6-cylinder engine for an 8-cylinder engine, a 4-valve 4-cylinder engine for a 6-cylinder engine, and a 4-valve 4-cylinder for a 4-cylinder engine, fuel economy can be improved by approximately 10 percent, 10 percent, and 5 percent, respectively. Together, these substitutions will result in a fuel economy improvement of about 6.8 percent, assuming that 18 percent of the substitutions are 6-cylinder for 8-cylinder, 23 percent are 4-cylinder for 6-cylinder, and 64 percent are 4-cylinder for 4-cylinder.[20]

Aerodynamic Improvements

Aerodynamic drag is the resistance encountered by moving a vehicle through air, and is a function of both vehicle size and shape. The coefficient of drag is a measure of the shape-related resistance. The larger the coefficient, the higher the drag. The coefficients of drag for 1987 car models vary widely, but average about .37. Rounded, aerodynamic styling has become popular in recent years. Widespread use of more advanced aerodynamic designs could drop the coefficient to approximately .3 by the year 2000, and improve fuel economy by about 4.6 percent.

Transmission Improvements

Two transmission improvements are included here, torque converter lockup and electronic transmission control. A torque converter in an automatic transmission transfers drive power from the engine to transmission gears. It serves a purpose similar to the clutch in a manual transmission. The torque converter allows slippage between the engine and transmission when a vehicle begins moving and when it shifts gears. However, its also allows a small amount of slippage after cruising speed is attained, resulting in energy loss. A torque converter lockup prevents this unintended slippage, and yields a fuel economy improvement of about 3 percent.[21]

Electronic transmission control provides more precise control of gear shifting than conventional controls. Transmissions controlled electronically operate in more fuel efficient gears a larger portion of the time, resulting in about a 1.5 percent increase in fuel economy.[22]

When combined into the same measure in Technology Group 1, electronic transmission control and torque converter lockup produce a 2.2 percent increase in fuel economy.

Overhead Cam

Overhead cams have less parts and mass than their pushrod counterparts, and thus have lower inertia. Lower inertia reduces the energy required for valve operation, and allows the valves to stay open longer, improving engine breathing. Overhead cams provide about a 6 percent improvement in fuel economy, principally because a smaller overhead cam engine can be substituted for a larger pushrod engine of roughly equal performance.

Front Wheel Drive

Front wheel drive is a weight saving measure. The driveshaft is eliminated, and the resulting body redesign improves the interior space/weight ratio. Although the fuel economy improvement that results from converting to front wheel drive is large, 10 percent, the potential for improving automobile fleet fuel economy is relatively small because most cars, 76% in 1987, already use front wheel drive.

<u>Continuously Variable Transmission</u>

Manual and automatic transmissions use discrete gearing to adjust the ratio of engine to axle speed. Engine speed is often well above a speed that is sufficient for delivering the power needed at the wheels and that maximizes fuel economy. Continuously variable transmissions (CVT), on the other hand, have a continuum of gear ratios between a minimum and maximum gear ratio. Better management of engine speed is thus possible, resulting in improved fuel economy.

Several CVT designs have been researched, but the most common type contains variable diameter pulleys connected with a belt. A small number of CVTs of this design have been installed in production vehicles, including the Subaru Justy. Current materials and designs limit use of CVTs to small cars with low-torque engines. As analyzed here, CVTs are assumed to replace both three and four speed automatics, providing an average 4.7 percent increase in fuel economy.[23]

Improved Accessories

Engine accessories, such as the water pump, power steering pump, cooling fan, and alternator, can account for a significant fraction of fuel consumption. Improved accessories are thus an important target for fuel economy improvements. Electric cooling fans, which operate intermittently, reduce fuel consumption. Reducing heat rejection to the engine coolant can reduce the amount of work done by the water pump. Replacing a hydraulic power steering pump with an intermittently operated electric motor also reduces energy consumption. Variable displacement air conditioning compressors are also an important energy saving innovation. Together, these measures are estimated to improve fuel economy 1.7 percent.[24]

Advanced Friction Reduction

Internal engine friction is a significant cause of energy consumption. The largest source of friction in the engine is the interface between the cylinder walls and the piston/ring assembly. Low-tension piston rings; closer machining tolerances for pistons, cylinders and bearing surfaces; and improved piston designs, among other measures, can improve fuel economy an estimated 2 percent. Use of low-mass (ceramic) valves and pistons, and use of fiber reinforced connecting rods can improve fuel economy an additional 2 percent, for a total improvement of 4 percent.[25]

Five-Speed-Overdrive Transmission

As discussed above in the section on CVTs, automatic transmissions use discrete gearing to adjust engine to axle speed ratios, and because these ratios are fixed, the engine often operates at a speed that is not optimal for fuel economy. Adding an extra gear reduces the ratio difference between gears and/or increases the range of gear ratios, allowing the engine to operate closer to optimal speeds.

This measure includes a transition from three, to four, to five speed automatics. As analyzed here, the five-speed replaces some three-speeds and some four-speeds, resulting in an average fuel economy improvement of 4.7 percent.

Improved Lubrication and Tires

New lower viscosity lubricants (5W-30 for engine oil), with friction reduction additives can reduce engine and transmission friction. Furthermore, wider use of high-pressure P-metric radials would reduce rolling resistance. Together, these measures are estimated to improve fuel economy 1 percent.

Weight Reduction

Average new passenger car weight was reduced about 900 pounds in the late 1970s. Since then average inertia weight has remained at about 3100 pounds. (It has risen about 100 pounds since 1987.) Despite previous deep reductions in vehicle weight, weight can be reduced substantially more without reducing vehicle size. More use of lighter weight materials, primarily aluminum and fiber reinforced plastics, would enable manufacturers to reduce vehicle weight by 10 percent, resulting in a 6.6 percent increase in fuel economy.[26]

Tires II

Tire rolling resistance consumes about a third of the energy delivered to the wheels in the EPA urban driving cycle. Tires with lower rolling resistance would, therefore, improve fuel economy. Use of new low-profile radials would improve fuel economy about 0.5 percent.

Aggressive Transmission Management

This measure includes far more aggressive management of the transmission than assumed in <u>Electronic Transmission Control</u> above. In this measure, gear shifting is controlled electronically with the gear chosen to maximize fuel economy at the needed power level. This means that engine speed will be substantially lower than is now typical. There would be some slight delay in down-shifting to gain power, and more shifting, but advanced electronic control would reduce the noticeability of these changes to a driver. Use of aggressive transmission management would improve fuel economy about 8 percent.[27]

Idle Off

In this measure, the engine is turned off and declutched whenever a conventional car would idle or decelerate. A second clutch between the crankshaft and the flywheel would allow the flywheel to continue spinning after the engine had been turned off. The flywheel would then be used to restart the engine. (For long off periods, electric boosting of the flywheel or electric starting would be necessary.) It would require more braking during deceleration -- because the engine wouldn't be used as a brake as it is now -- and would create a different driving feel. This technology has been fully developed for manual transmissions by Volkswagen. Idle-off would improve fuel economy about 9 percent.[28]

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2. Difiglio, et. al., "Cost Effectiveness of Future Fuel Economy Improvements."

3. The continuously variable transmission included in Technology Group 1 would also change driving feel, but it was left in Group 1 to produce a technology list identical to Difiglio, et al.

4. Average interior volume and performance levels have increased slightly since 1987. If performance and interior volume levels were held at their 1990 levels, a slightly lower fuel economy level would result.

5. A 7% discount rate was chosen to be consistent with the discount rate being used by the U.S. Department of Energy's studies to support development of the National Energy Strategy. The mileage distribution was taken from the U.S. Department of Transportation, Federal Highway Administration, "1983-1984 Personal Transportation Study," 1986. Since cars are driven many more miles in their first years of use than in their latter, capital recovery for technology improvements is slightly accelerated, resulting in a lower annual capital charge. Using the DOT mileage distribution results in an annual capital charge equal to 96% of what it would be were capital recovered in equal increments over ten years.

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24. Deborah Lynn Bleviss, The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s; Ulrich Seiffert and Peter Walzer, The Future for Automotive Technology.

25. U.S. Department of Transportation, "Low Tension Piston Rings and Roller Cam Follower for Engine Friction Reduction -- Costs of Retooling and Fuel Economy Benefits."

26. Deborah Lynn Bleviss, The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s.

27. David Ganoung, "Fuel Economy and Drive-by-Wire Control;" Ulrich Seiffert and Peter Walzer, The Future for Automotive Technology.

28. Deborah Lynn Bleviss, The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s; Charles Gray, Jr. and Jeffrey Alson, "The Case for Methanol," Scientific American, November 1989; Ulrich Seiffert and Peter Walzer, The Future for Automotive Technology.

BOX A

KEY TO TECHNOLOGIES LISTED IN TABLES 1-4
(Technology Groups 1 and 2)

IVC	Intake Valve Control
RCF	Roller Cam Followers
MPFI	Multi-point Fuel Injection
4V	Four Valves per Cylinder Engines
AERO	Aerodynamic Improvements
TRANS	Torque Converter Lockup and Electronic Transmission Control (Group 1 only)
TCLU	Torque Converter Lockup (Group 2 only)
OHC	Overhead Cam Engine
FWD	Front Wheel Drive
CVT	Continuously Variable Transmission
ACCESS	Improved Accessories, including Electric Power Steering
ADV FRIC	Engine Friction Reduction
5AOD	Five-Speed Automatic Overdrive Transmission
LUB/TIRE	Improved Lubrication and Tires
WT RED	Weight Reduction
TIRES II	Advanced Tires (Improvements Beyond that included in LUB/TIRE)
TRANS MAN	Aggressive Transmission Management (Group 2 only)
IDLE OFF	Idle off (Group 2 only)

BOX B

KEY TO COLUMN HEADINGS IN TABLES 1-4

TECHNOLOGY - Fuel economy technology (or measure)

CONSUM COST - Retail cost of each technology, per car

ANNUAL COST - Retail cost of each technology, annualized over ten year period at 7% discount rate

INDIVID NEW CAR MPG INCR - % increase in fuel economy attributable to each technology

MARKET SHARE INCR - Projected % increase (relative to total new car market) in the use of each technology

NEW CAR FLT MPG INCR (%) - Estimate of how much the technology can increase the new car fleet mpg, calculated by multiplying the INDIVID CAR MPG INCR by the MARKET SHARE INCR

CAR FLT MPG INCR (MPG) - Same as above, but expressed in MPG

NEW CAR MPG INCR - Increase in an individual car's MPG as a consequence of using specified technology

NEW CAR FLT MPG INCR - Average new car fleet mpg increase caused by use of specified technology

ACTUAL NEW CAR FLT MPG - Actual fuel economy of new car fleet after adoption of specified technology

EPA-RATED NEW CAR FLT MPG - Federal test procedure MPG rating of new car fleet, after adoption of specified technology

COST CONSRV FUEL, TECH N - Cost of conserved fuel of specified technology, per gallon saved

AVG COST CNSRV FUEL, TECH 1..N - Average cost of conserved fuel for specified and all preceding technologies, per gallon saved

ACTUAL FLEET MPG - Average actual fuel economy of all cars on road, given new car fleet cumulative adoption of specified technologies

2000 ENERGY SAVINGS - Energy savings in the year 2000 or 2010

Table 1
CONSERVATION SUPPLY CURVE, AUTO FUEL EFFICIENCY
TECHNOLOGY GROUP 1
SAVINGS IN 2000

TECH	CONSUM COST ($)	ANNUAL COST ($)	INDIVID NEW CAR MPG INCR (%)	MARKET SHARE INCR (%)	NEW CAR FLT MPG INCR (%)	INDIVID NEW CAR MPG INCR (MPG)	NEW CAR FLT MPG INCREASE (MPG)	ACTUAL NEW CAR FLT MPG (MPG)	EPA-RATED NEW CAR FLT MPG (MPG)	COST CNSRV FUEL TECH N ($/GALLON)	AVG COST CNSRV FUEL TECH 1..N ($/GALLON)	ACTUAL FLEET MPG (MPG)	2000 ENERGY SAVINGS (QUAD BTU
BASE, 1987 MPG								21.7	28.3			21.64	
1 RCF	15	2.06	1.5	37	0.56	0.33	0.12	21.8	28.4	0.25	0.25	21.70	0.03
2 OHC	74	10.14	6.0	69	4.14	1.31	0.90	22.7	29.6	0.32	0.32	22.20	0.22
3 IVC	80	10.96	6.0	75	4.50	1.36	1.02	23.7	31.0	0.37	0.34	22.75	0.23
4 FWD	150	20.55	10.0	23	2.30	2.37	0.55	24.3	31.7	0.42	0.36	23.04	0.12
5 4V	105	14.39	6.8	100	6.80	1.65	1.65	25.9	33.8	0.46	0.39	23.91	0.33
6 ACCESS	29	3.97	1.7	80	1.36	0.44	0.35	26.3	34.3	0.52	0.40	24.09	0.07
7 AERO	80	10.96	4.6	85	3.91	1.21	1.03	27.3	35.6	0.55	0.42	24.61	0.18
8 TRANS	39	5.34	2.2	80	1.76	0.60	0.48	27.8	36.3	0.57	0.43	24.85	0.08
9 MPFI	67	9.18	3.5	56	1.96	0.97	0.55	28.4	37.0	0.63	0.44	25.12	0.09
10 ADV FRIC	80	10.96	4.0	80	3.20	1.13	0.91	29.3	38.1	0.68	0.47	25.57	0.15
11 CVT	100	13.70	4.7	45	2.12	1.38	0.62	29.9	39.0	0.73	0.48	25.87	0.10
12 LUB/TIRE	22	3.01	1.0	100	1.00	0.30	0.30	30.2	39.3	0.77	0.49	26.02	0.04
13 5AOD	150	20.55	4.7	40	1.88	1.42	0.57	30.7	40.1	1.13	0.52	26.29	0.08
14 WT RED	250	34.25	6.6	85	5.61	2.03	1.72	32.5	42.3	1.42	0.62	27.11	0.24
15 TIRES II	20	2.74	0.5	100	0.50	0.16	0.16	32.6	42.5	1.51	0.63	27.18	0.02
													1.97

Figure 1

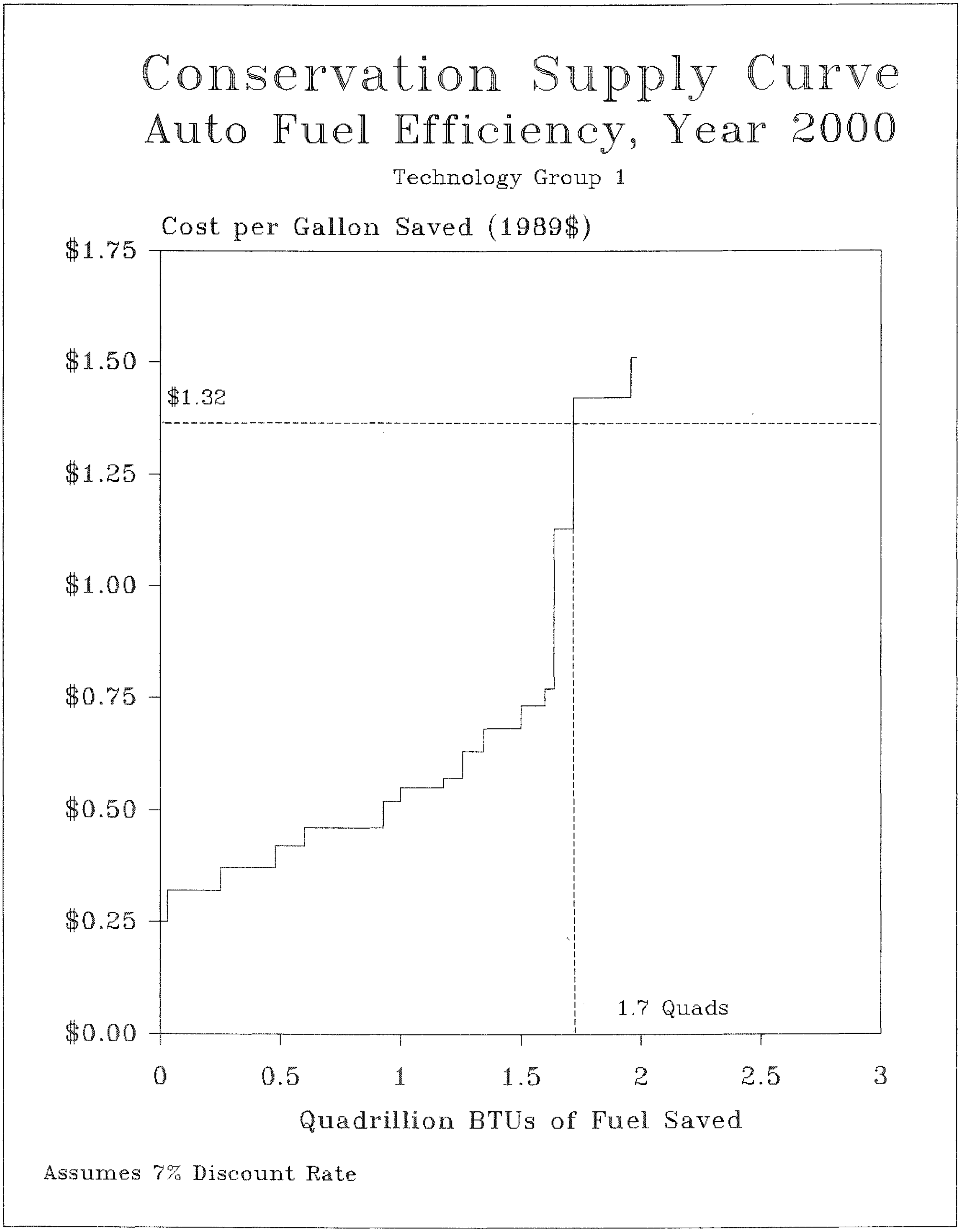
Conservation Supply Curve
Auto Fuel Efficiency, Year 2000
Technology Group 1
Cost per Gallon Saved (1989$)
$1.75
$1.50
$1.32
$1.25
$1.00
$0.75
$0.50
$0.25
$0.00
1.7 Quads
0
0.5
1
1.5
2
2.5
3
Quadrillion BTUs of Fuel Saved
Assumes 7% Discount Rate

Table 2

CONSERVATION SUPPLY CURVE, AUTO FUEL EFFICIENCY

TECHNOLOGY GROUP 2

SAVINGS IN 2000

TECHNOLOGY	CONSUM COST ($)	ANNUAL COST ($)	INDIVID NEW CAR MPG INCR (%)	MARKET SHARE INCR (%)	NEW CAR FLT MPG INCR (%)	INDIVID NEW CAR MPG INCR (MPG)	NEW CAR FLT MPG INCREASE (MPG)	ACTUAL NEW CAR FLT MPG (MPG)	EPA-RATED NEW CAR FLT MPG (MPG)	COST CNSRV FUEL TECH N ($/GALLON)	AVG COST CNSRVD FUEL TECH 1..N ($/GALLON)	ACTUAL FLEET MPG (MPG)	2000 ENERGY SAVINGS (QUAD BTU)
BASE, 1987 MPG								21.7	28.3			21.6	
1 TRANS MAN	60	8.22	8.0	75	6.00	1.74	1.30	23.0	30.0	0.20	0.20	22.4	0.310
2 RCF	15	2.06	1.5	37	0.56	0.35	0.13	23.1	30.2	0.27	0.21	22.4	0.029
3 TCLU	35	4.80	3.0	16	0.48	0.69	0.11	23.2	30.3	0.31	0.21	22.5	0.025
4 OHC	74	10.14	6.0	69	4.14	1.39	0.96	24.2	31.6	0.35	0.26	23.0	0.209
5 IVC	80	10.96	6.0	75	4.50	1.45	1.09	25.3	33.0	0.39	0.30	23.6	0.221
6 FWD	150	20.55	10.0	23	2.30	2.53	0.58	25.9	33.7	0.45	0.31	23.9	0.112
7 4V	105	14.39	6.8	100	6.80	1.76	1.76	27.6	36.0	0.49	0.36	24.8	0.317
8 ACCESS	29	3.97	1.7	80	1.36	0.47	0.38	28.0	36.5	0.55	0.37	25.0	0.064
9 AERO	80	10.96	4.6	85	3.91	1.29	1.10	29.1	37.9	0.59	0.39	25.5	0.178
10 MPFI	67	9.18	3.5	56	1.96	1.02	0.57	29.7	38.7	0.66	0.41	25.8	0.089
11 ADV FRIC	80	10.96	4.0	80	3.20	1.19	0.95	30.6	39.9	0.71	0.43	26.2	0.142
12 CVT	100	13.70	4.7	45	2.12	1.44	0.65	31.3	40.8	0.77	0.45	26.5	0.093
13 LUB/TIRE	22	3.01	1.0	100	1.00	0.31	0.31	31.6	41.2	0.80	0.45	26.7	0.044
14 IDLE OFF	250	34.25	9.0	50	4.50	2.84	1.42	33.0	43.0	1.06	0.51	27.4	0.191
15 5AOD	150	20.55	4.7	40	1.88	1.55	0.62	33.6	43.8	1.24	0.53	27.6	0.079
16 WT RED	250	34.25	6.6	85	5.61	2.22	1.89	35.5	46.3	1.56	0.62	28.5	0.228
17 TIRES II	20	2.74	0.5	100	0.50	0.18	0.18	35.7	46.5	1.65	0.63	28.6	0.020
													2.352

Figure 2

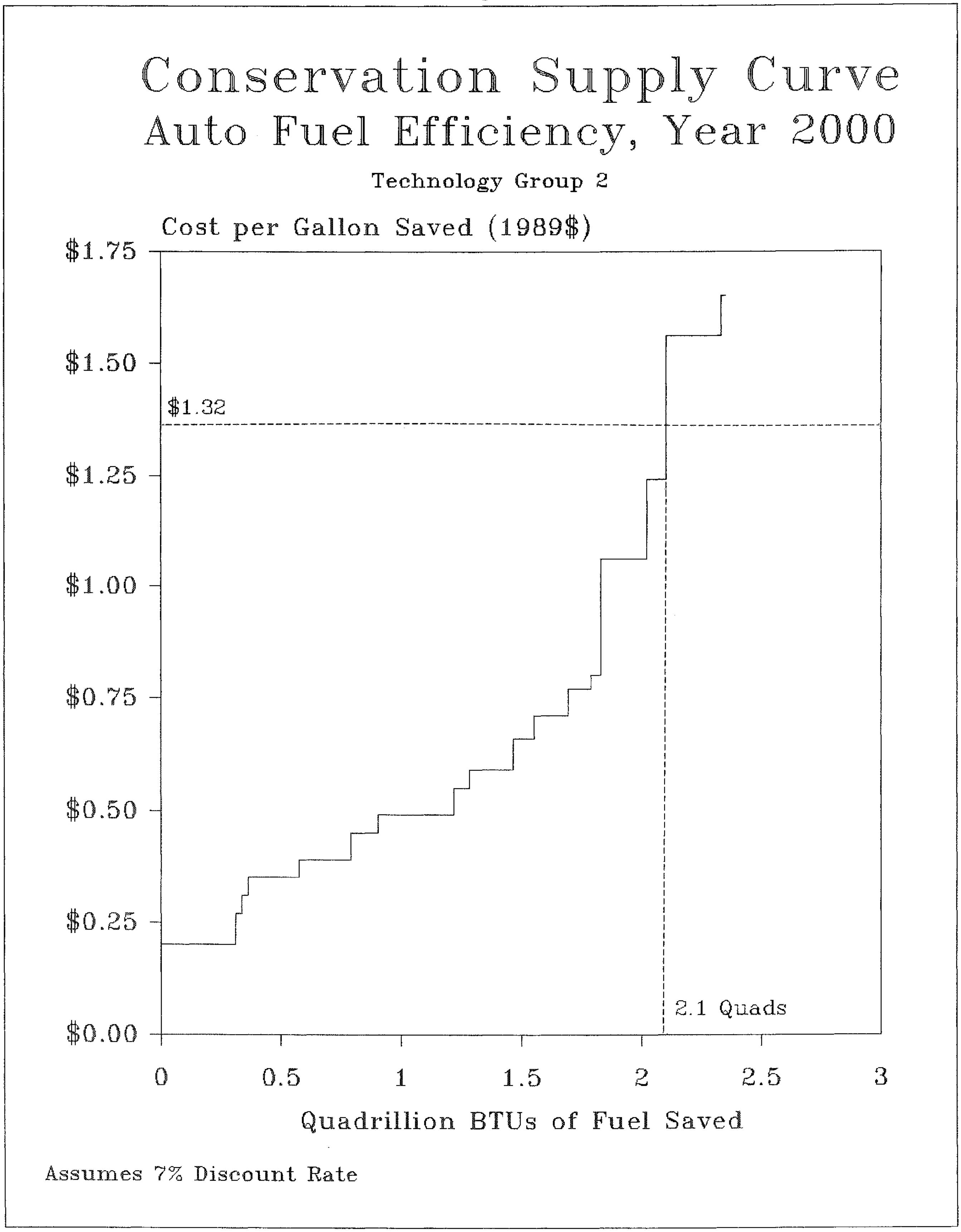
Conservation Supply Curve
Auto Fuel Efficiency, Year 2000
Technology Group 2
Cost per Gallon Saved (1989$)
$1.75
$1.50
$1.32
$1.25
$1.00
$0.75
$0.50
$0.25
$0.00
2.1 Quads
0
0.5
1
1.5
2
2.5
3
Quadrillion BTUs of Fuel Saved
Assumes 7% Discount Rate

Table 3

CONSERVATION SUPPLY CURVE, AUTO FUEL EFFICIENCY

TECHNOLOGY GROUP 1

SAVINGS IN 2010

	TECHNOLOGY	CONSUM COST ($)	ANNUAL COST ($)	INDIVID NEW CAR MPG INCR (%)	MARKET SHARE INCR (%)	NEW CAR FLT MPG INCR (%)	INDIVID NEW CAR MPG INCR (MPG)	NEW CAR FLT MPG INCREASE (MPG)	ACTUAL NEW CAR FLT MPG (MPG)	EPA-RATED NEW CAR FLT MPG (MPG)	COST CNSRV FUEL TECH N ($/GALLON)	AVG COST CNSRV FUEL TECH 1..N ($/GALLON)	ACTUAL FLEET MPG (MPG)	2010 ENERGY SAVINGS (QUAD BTU)
	BASE, 1987 MPG								19.8	28.3			19.8	
1	RCF	15	2.06	1.5	37	0.56	0.30	0.11	19.9	28.4	0.23	0.23	19.9	0.069
2	OHC	74	10.14	6.0	69	4.14	1.19	0.82	20.7	29.6	0.30	0.29	20.7	0.498
3	IVC	80	10.96	6.0	75	4.50	1.24	0.93	21.7	31.0	0.33	0.31	21.6	0.518
4	FWD	150	20.55	10.0	23	2.30	2.17	0.50	22.2	31.7	0.38	0.32	22.1	0.259
5	4V	105	14.39	6.8	100	6.80	1.51	1.51	23.7	33.8	0.42	0.36	23.6	0.718
6	ACCESS	29	3.97	1.7	80	1.36	0.40	0.32	24.0	34.3	0.47	0.37	23.9	0.142
7	AERO	80	10.96	4.6	85	3.91	1.10	0.94	24.9	35.6	0.50	0.39	24.8	0.393
8	TRANS	39	5.34	2.2	75	1.65	0.55	0.41	25.3	36.2	0.52	0.39	25.2	0.163
9	MPFI	67	9.18	3.5	56	1.96	0.89	0.50	25.8	36.9	0.57	0.41	25.7	0.190
10	ADV FRIC	80	10.96	4.0	80	3.20	1.03	0.83	26.7	38.1	0.62	0.42	26.5	0.301
11	CVT	100	13.70	4.7	45	2.12	1.25	0.56	27.2	38.9	0.67	0.44	27.0	0.195
12	LUB/TIRE	22	3.01	1.0	100	1.00	0.27	0.27	27.5	39.3	0.70	0.45	27.3	0.091
13	5AOD	150	20.55	4.7	40	1.88	1.29	0.52	28.0	40.0	1.03	0.47	27.8	0.169
14	WT RED	250	34.25	6.6	85	5.61	1.95	1.57	29.6	42.3	1.30	0.57	29.3	0.477
15	TIRES II	20	2.74	0.5	100	0.50	0.15	0.15	29.7	42.5	1.38	0.57	29.4	0.042
														4.225

Figure 3

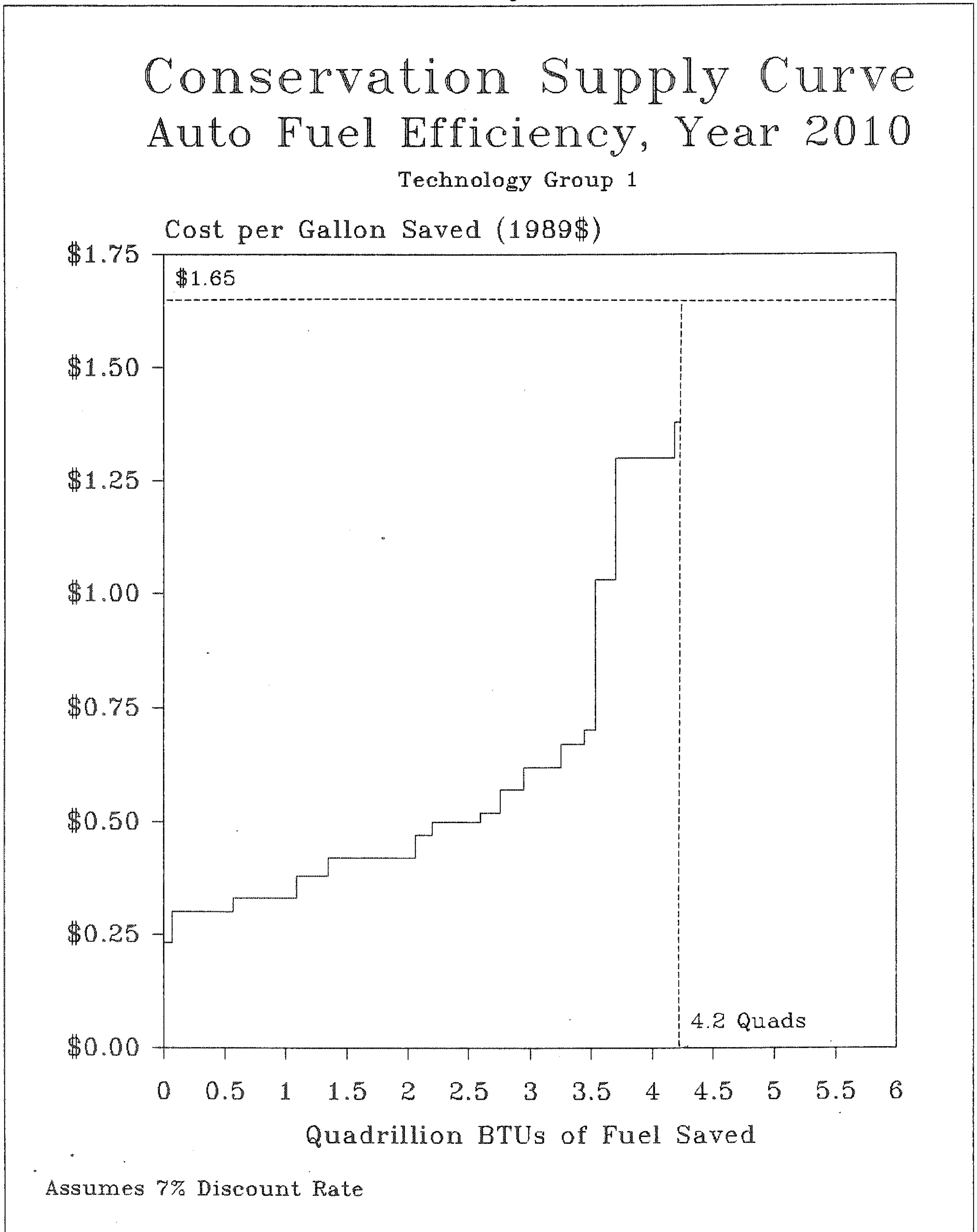
Conservation Supply Curve
Auto Fuel Efficiency, Year 2010
Technology Group 1
Cost per Gallon Saved (1989$)
$1.75
$1.65
$1.50
$1.25
$1.00
$0.75
$0.50
$0.25
$0.00
4.2 Quads
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Quadrillion BTUs of Fuel Saved
Assumes 7% Discount Rate

Table 4

CONSERVATION SUPPLY CURVE, AUTO FUEL EFFICIENCY

TECHNOLOGY GROUP 2

SAVINGS IN 2010

TECHNOLOGY	CONSUM COST ($)	ANNUAL COST ($)	INDIVID NEW CAR MPG INCR (%)	MARKET SHARE INCR (%)	NEW CAR FLT MPG INCR (%)	INDIVID NEW CAR MPG INCR (MPG)	NEW CAR FLT MPG INCR (MPG)	ACTUAL NEW CAR FLT MPG (MPG)	EPA-RATED NEW CAR FLT MPG (MPG)	COST CONSRV FUEL TECH N ($/GALLON)	AVG COST CONSRVD FUEL TECH 1..N ($/GALLON)	ACTUAL FLEET MPG (MPG)	2010 ENERGY SAVINGS (QUAD BTU)
BASE, 1987 MPG								19.8	28.3			19.8	
1 TRANS MAN	60	8.22	8.0	75	6.00	1.58	1.19	21.0	30.0	0.18	0.18	21.0	0.704
2 RCF	15	2.06	1.5	37	0.56	0.31	0.12	21.1	30.1	0.24	0.19	21.1	0.066
3 TCLU	35	4.80	3.0	16	0.48	0.63	0.10	21.2	30.3	0.29	0.19	21.2	0.056
4 OHC	74	10.14	6.0	69	4.14	1.27	0.88	22.1	31.5	0.31	0.24	22.0	0.468
5 IVC	80	10.96	6.0	75	4.50	1.33	0.99	23.1	33.0	0.36	0.27	23.0	0.487
6 FWD	150	20.55	10.0	23	2.30	2.31	0.53	23.6	33.7	0.41	0.29	23.5	0.244
7 4V	105	14.39	6.8	100	6.80	1.61	1.61	25.2	36.0	0.45	0.33	25.1	0.675
8 ACCESS	29	3.97	1.7	80	1.36	0.43	0.34	25.6	36.5	0.50	0.34	25.4	0.133
9 AERO	80	10.96	4.6	85	3.91	1.18	1.00	26.6	37.9	0.53	0.36	26.4	0.369
10 MPFI	67	9.18	3.5	56	1.96	0.93	0.52	27.1	38.7	0.60	0.37	26.9	0.182
11 ADV FRIC	80	10.96	4.0	80	3.20	1.08	0.87	27.9	39.9	0.65	0.39	27.7	0.288
12 CVT	100	13.70	4.7	45	2.12	1.31	0.59	28.5	40.8	0.70	0.41	28.3	0.186
13 LUB/TIRE	22	3.01	1.0	100	1.00	0.29	0.29	28.8	41.2	0.73	0.41	28.6	0.087
14 IDLE OFF	250	34.25	9.0	50	4.50	2.59	1.30	30.1	43.0	0.97	0.46	29.8	0.376
15 5AOD	150	20.55	4.7	40	1.88	1.42	0.57	30.7	43.8	1.13	0.48	30.4	0.154
16 WT RED	250	34.25	6.6	85	5.61	2.03	1.72	32.4	46.3	1.42	0.57	32.0	0.436
17 TIRES II	20	2.74	0.5	100	0.50	0.16	0.16	32.6	46.5	1.51	0.57	32.2	0.039
													4.950

Figure 4

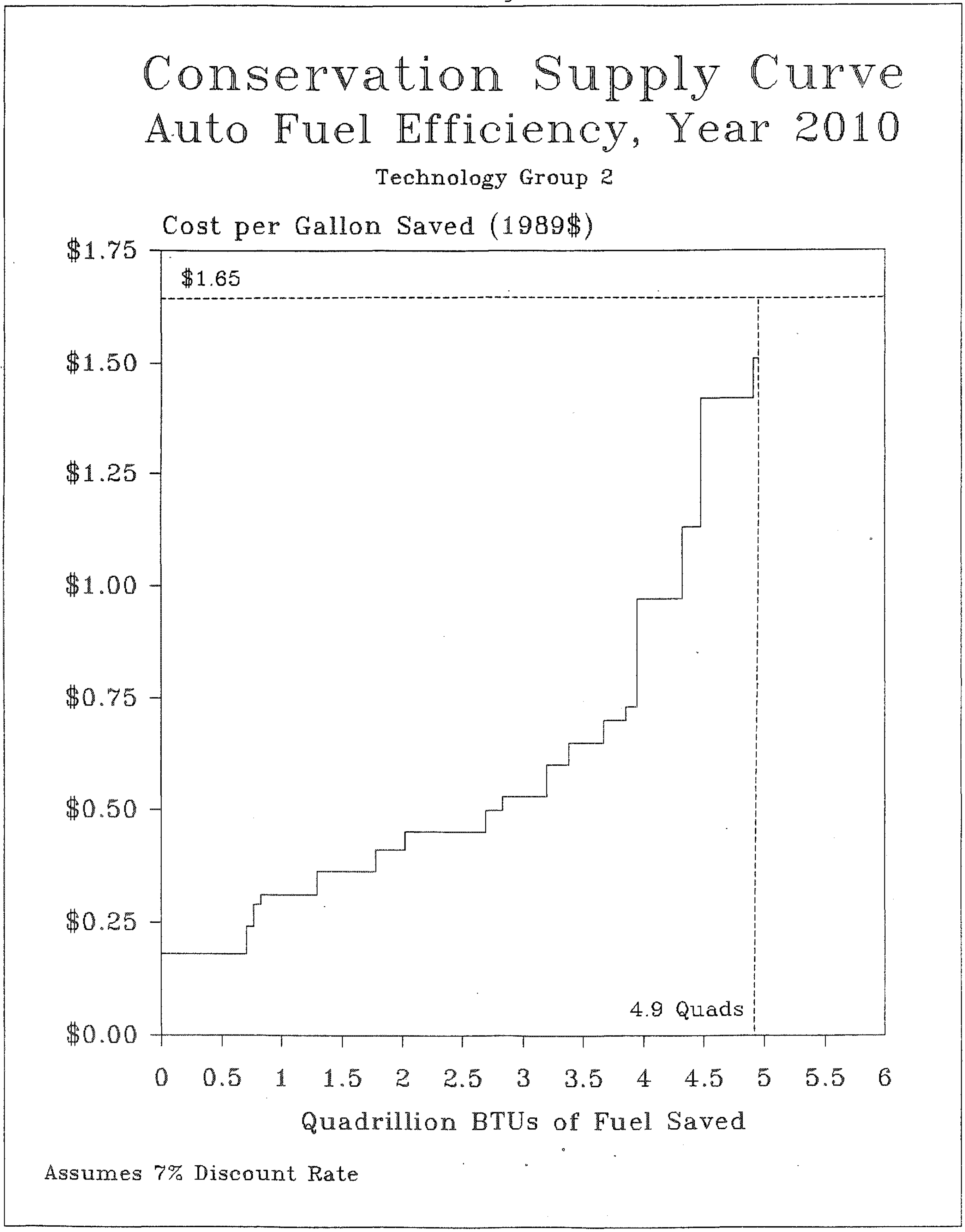
Conservation Supply Curve
Auto Fuel Efficiency, Year 2010
Technology Group 2
Cost per Gallon Saved (1989$)
$1.75
$1.65
$1.50
$1.25
$1.00
$0.75
$0.50
$0.25
$0.00
4.9 Quads
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Quadrillion BTUs of Fuel Saved
Assumes 7% Discount Rate

Table 5

PROJECTED AUTOMOBILE FLEET FUEL ECONOMIES (MPG)

	2000	2010
Frozen Efficiency Scenario		
EPA:	28.3	28.3
Actual:	21.6	19.8
Market Scenario		
EPA:	28.4	38.0
Actual:	21.8	26.6
Group 1 Cost Effective		
EPA:	34.3	42.0
Actual:	26.3	29.4
Group 2 Cost Effective		
EPA:	36.0	46.0
Actual:	27.6	32.2
Vehicle Miles of Travel	$1,675 \times 10^9$	$2,042 \times 10^9$

PROJECTED ENERGY SAVINGS (QUADS / % REDUCTION)

	2000	2010
Group 1 Cost Effective		
Relative to Froz. Eff.	1.7 / 18%	4.2 / 33%
Relative to Market	1.6 / 17%	.9 / 9%
Group 2 Cost Effective		
Relative to Froz. Eff.	2.1 / 22%	4.9 / 39%
Relative to Market	2.0 / 21%	1.7 / 18%