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Determinants of New-Car Fuel Efficiency

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The determinants of new-car fuel efficiency during the period 1976-1981 are examined statistically with cross-sectional data on new automobiles. A significant improvement in overall fuel economy is found during this period. Most of the increased fuel economy from 1976 through 1979 is because of weight reduction, but from 1979 through 1981 the improvement came about primarily because of additional measures. Variables such as domestic versus foreign manufacturer, horsepower, and performance are not statistically related to fuel economy during this period.

In 1973 the price of gasoline increased sharply as a result of the Arab oil embargo, which prompted a shift in automobile demand toward more fuel-efficient cars. The Energy Policy and Conservation Act, passed by Congress in 1975, mandates incremental fuel economy increases until 1985, at which time average fleet fuel consumption of each manufacturer must be at least 27.5 mpg. The interest in fuel efficiency shown by Congress, automobile consumers, and automobile producers encourages the examination of the recent history of fuel-efficiency improvements in the automobile fleet.

In a Mellon Institute report, Shackson and Leach (1) document several ways in which vehicles can be made more fuel efficient. Downsizing reduces vehicle weight, thus improving fuel efficiency, but fuel efficiency also can be improved by more efficient engines, tires with less rolling resistance, improved aerodynamics, and other means that do not affect vehicle weight. Shackson and Leach forecast that fuel consumption relative to weight of new automobiles will diminish significantly in the future as a result of these measures. Their forecast is depicted graphically in Figure 1, which shows the relationship of fuel consumption to curb weight expected in future years. The downward rotation of the line depicts fuel economy improvements caused by measures other than weight reduction, whereas movement along a line results entirely from reducing vehicle weight. Figure 1 shows the expectation that future fuel economy will be achieved by further weight reduction and by complementary measures. Automobile manufacturers have now had a few years' experience in attempting to improve fuel efficiency. By quantifying the effectiveness of the recent history of fuel economy efforts, the reasonableness of the Mellon and other forecasts can perhaps be judged.

THREE HYPOTHESES

The interest in fuel-efficiency trends in this study can be stated in terms of three hypotheses:

1. Recent improvements in fuel economy are due almost entirely to vehicle weight reduction,
2. The rush to reduce vehicle weight has had secondary punitive effects on fuel economy, and
3. Weight-reduction efforts have been complemented by other fuel-efficiency efforts.

These alternative hypotheses are depicted graphically in Figures 2-4. The sample mean curb weight and corresponding gasoline consumption for the 1976 and the 1981 model years are shown in Figures 2-4.

In Figure 2 the relationship between gasoline consumption and curb weight estimated with 1976 new-car data corresponds closely to the same relationship estimated with 1981 data, even though 1981 cars are lighter and more fuel efficient. In this case the improvement in fuel efficiency is due to weight reduction, as stated in hypothesis 1. In Figure 3 the relationship of fuel consumption to curb weight estimated with 1981 new-car data lies above the 1976 relationship. In Figure 3 weight reduction has improved fuel economy, but the improvement efforts have been offset partly by secondary punitive effects. For example, in an effort to make small cars more appealing, manufacturers have offered them with more options such as air conditioners, which diminish fuel economy. Figure 4 shows the hypothesis that weight-reduction efforts have been complemented by other fuel economy efforts. The mean curb weight and corresponding fuel consumption in 1981 (and in 1976) are the same in Figures 2-4. However, the downward shift in the relationship of fuel consumption to weight depicts the effect of fuel economy improvements in addition to weight reduction.

During the sample period of 1976 through 1981, the fuel efficiency of new cars has indeed improved. The objective here is to define statistically the reasons for this improvement, specifically, the extent to which fuel efficiency is due to weight

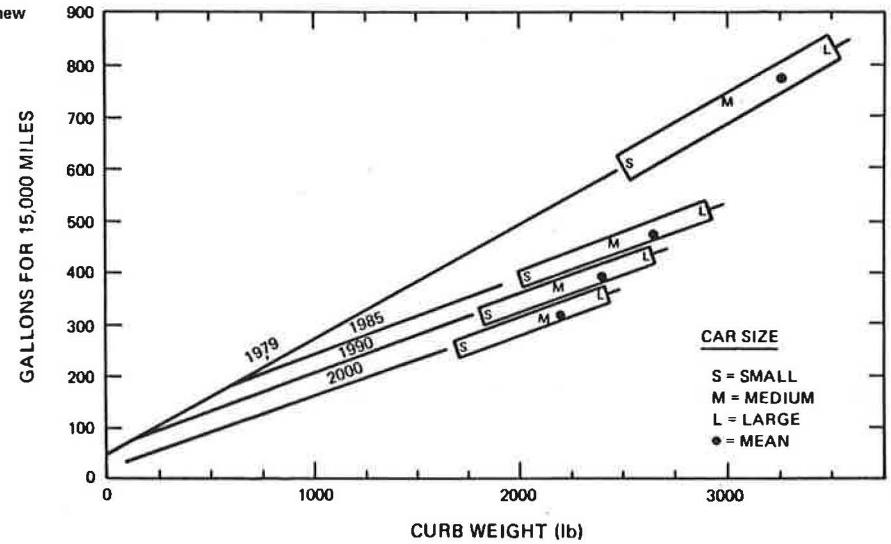


Figure 1. Mellon forecast of fuel consumption by new automobile fleet.

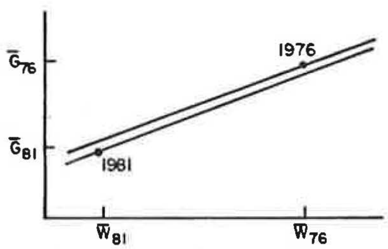


Figure 2. Hypothesis 1.

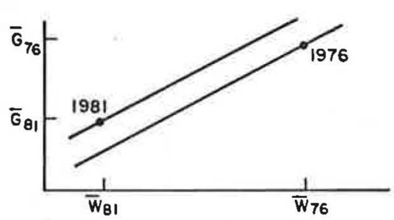


Figure 3. Hypothesis 2.

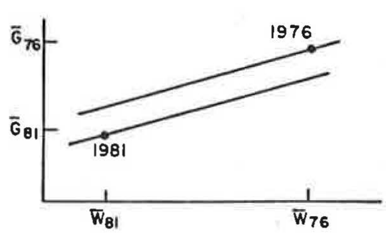


Figure 4. Hypothesis 3.

reduction versus other measures. It will be determined whether performance or horsepower changes have contributed to fuel economy improvements and also whether foreign cars are more fuel efficient than domestic cars. Whether large cars or small cars have shown major improvement in fuel economy will be examined.

STATISTICAL ANALYSIS: A SIMPLE LINEAR MODEL

This statistical analysis is based on annual samples from 1976 through 1981 of new cars appearing on the U.S. market. Some fuel-efficiency analyses have considered the market share of various car classes. Instead, an unweighted sample of new cars is used here because the interest in this study is in the effectiveness of the automobile producers' efforts to improve fuel efficiency. Extensive and successful efforts by producers to improve efficiency could be mitigated by a shift in demand toward high-consumption vehicles such as vans or light trucks. Alternatively, average fleet fuel efficiency could increase dramatically as a result of a demand shift toward efficient cars, even if automobile producers made no attempt to improve fuel efficiency.

The sample of new cars in this study included each make and model listed in the 1976 to 1981 editions of Consumer Reports. If two cars were virtual twins or a car had more than one engine choice, one car was sampled. Data were also obtained from Consumer Reports on automobile curb weight, horsepower, transmission type, and whether the producer was domestic or foreign. Mile-per-gallon estimates for city driving were obtained from the annual Gas Mileage Guide published by the U.S. Department of Energy and the U.S. Environmental Protection Agency (EPA) (EPA's city mpg estimates were used because composite city-highway estimates are not available for each year from 1976 to 1981). The annual sample size, as shown in Table 1, varied from 38 to 53 automobiles, which is the maximum number of observations obtained from the sources just mentioned after the sample had been adjusted for twins and multiple engine types. Although the sample included five classes of automobiles (subcompact, compact, intermediate, full size, and luxury), it is weighted toward small cars. In 1981 there were only four or five luxury cars on the market but more than 20 subcompacts.

It is postulated first that fuel efficiency of an automobile is primarily a function of its curb weight. Fuel efficiency may be indicated by miles per gallon or required fuel to travel, say, 15,000 miles. Fuel consumption to travel 15,000 miles is used because the relationship between fuel consumption and weight is more likely to be linear than the relationship between miles per gallon and weight (2, p. 40). A simple linear cross-section regression estimate between fuel consumption of the ith car in year t (G_{it}) and its curb weight (W_{it}) was obtained for each year from 1976 to 1981 and for the composite period. The results are given in Table 1. The weight coefficients are positive and significant, as expected. The coefficient for the composite period of 0.232 indicates that an automobile weight reduction of, say, 100 lb reduces fuel consumption for a

Table 1. Regression estimates of gasoline consumption and curb weight of new vehicles.

Year	Intercept	Weight Coefficient		R^2	SE	Sample Size	Gasoline Consumption		Weight	
		Tons	t-Value				Gallons	SD	Pounds	SD
Composite	77.2	0.232	38.38	0.845	86.9	238				
1976	201.5	0.203	15.72	0.843	92.3	48	864.8	230.6	3,270.5	1,044.1
1977	77.7	0.236	22.81	0.911	71.6	53	805.2	237.3	3,088.3	961.4
1978	18.2	0.254	13.66	0.813	109.9	45	797.3	251.0	3,063.8	890.1
1979	98.1	0.231	16.76	0.859	71.3	48	776.4	188.2	2,933.3	754.3
1980	93.1	0.221	11.92	0.785	82.9	41	719.5	176.4	2,833.4	706.8
1981	61.2	0.215	18.73	0.907	47.5	38	646.3	153.5	2,723.2	680.3

Table 2. Regression estimates of expanded model of gasoline consumption.

Year	Intercept	Weight Coefficient		Ratio of Horsepower to Weight		Dummy Producer Variable		Dummy Transmission Variable		R^2	SE
		Tons	t-Value	Ratio	t-Value	Coefficient	t-Value	Coefficient	t-Value		
Composite	55.57	0.232	37.05	753.09	0.59	-11.35	-0.85	4.34	0.30	0.843	87.18
1976	115.24	0.204	13.73	2,006.69	0.63	-2.25	0.07	21.01	0.47	0.831	-94.94
1977	159.64	0.231	21.41	-782.88	0.28	-26.44	-0.94	-43.46	-1.50	0.908	-72.08
1978	67.47	0.253	12.59	-857.29	0.26	-7.06	0.15	-19.72	-0.43	0.795	113.56
1979	144.48	0.227	14.93	-299.8	0.10	-1.70	0.06	-29.24	-0.90	0.850	72.89
1980	286.36	0.210	11.26	-3,349.76	0.91	-64.74	-2.05	-31.16	-0.99	0.791	80.63
1981	-37.39	0.223	17.67	1,660.65	0.73	5.81	0.27	33.67	1.66	0.908	46.65

Notes: The dummy producer variable is 1 for domestic, zero for foreign. The dummy transmission variable is zero for automatic, 1 for manual. R^2 is the coefficient of determination adjusted for degrees of freedom. SE is the standard error of the regression equation.

trip of 15,000 miles by 23.2 gal. Overall, this simple model has a high degree of explanatory power and the weight coefficients appear stable and are highly significant.

The last four columns in Table 1 give the sample mean gasoline consumption, its standard deviation, the sample mean curb weight, and its standard deviation on an annual basis. The average weight of new cars declined consistently throughout the period and, as expected, so did fuel consumption. The standard deviations of these variables also have diminished over time. New cars are becoming more fuel efficient over time, and they also are becoming more homogeneous in terms of weight. This observed decrease in variability of new-car weight over the sample period supports the Mellon forecast shown in Figure 1.

The mean gasoline consumption of a 1976 automobile was 864.8 gal, which declined to 776.4 gal in 1979 and 646.3 gal in 1981. This improvement in fuel economy is the result of both weight reduction and other measures, the relative importance of which is determined in the next section.

MULTIVARIATE STATISTICAL ANALYSIS

A simple linear model was postulated to determine the statistical credibility of a model based only on curb weight. Other variables were examined to see whether the statistical explanation of fuel efficiency could be improved by considering a more completely specified model. Because gasoline consumption may be influenced by engine horsepower, this variable was added and the model was reestimated. The horsepower coefficients are insignificant for each year and for the composite period. For this reason and because performance (horsepower divided by weight) may be a more appropriate variable, these results are not reported in detail. [The ratio of horsepower to weight is often used as a measure of automobile acceleration, which in turn is sometimes taken as a performance measure, according to a report in September 1976 by the Federal Task Force on Motor Vehicle Goals Beyond 1980.]

Performance is a measure of acceleration capability and it is considered a statistical determinant of fuel consumption. EPA mileage data indicate that cars with three- or four-speed manual transmissions obtain an improvement of about 1 to 3 mpg over those cars with automatic transmissions. A dummy transmission variable was set equal to zero for cars with an automatic transmission and equal to 1 for those with a manual transmission. Foreign-made cars have the reputation of being more fuel efficient than domestic cars. Although the superior fuel efficiency of foreign cars is partly because of their light weight and partly because of their use of manual transmissions, tests were done to determine whether foreign cars are more fuel efficient when the model is adjusted for weight and type of transmission. A second dummy variable was introduced to denote whether the manufacturer was domestic or foreign. Fuel consumption may have been influenced by other variables, such as radial tires, but data limitations restricted our model to the foregoing variables. Regression estimates of this expanded model for each year and the composite period are given in Table 2.

A comparison of Tables 1 and 2 shows that the weight coefficients are not affected much by additional variables, and they continue to be the most significant determinant of fuel consumption. In contrast, the performance indicator and the transmission variable are insignificant in each year. The synergistic effect between weight and horsepower suggested by Gray and von Hippel (3, p. 58) apparently has not been operative during this period. If the synergistic effect means that smaller cars will use lower-performing engines (whose performance is defined as the ratio of horsepower to weight), this synergistic effect has not contributed to improved fuel economy. However, this effect may be interpreted as lighter cars using smaller engines (with perhaps equal performance), the performance of which may remain constant. Automobiles and their engines have become smaller over the last 6 years, but the ratio of horsepower to weight is statistically unrelated to fuel economy.

The coefficient for the producer dummy is negative in each year except 1981, but it is only significant in 1980. Foreign cars tend to be compacts or subcompacts; hence, there is a high inverse correlation between weight and the producer dummy variable. As a consequence of multicollinearity, the regression coefficients and their standard errors become unreliable. This, plus the failure of the producer dummy to be significant during several years, means that the hypothesis cannot be rejected that domestic and foreign cars are equal with respect to weight-adjusted fuel efficiency.

The coefficients of determination in Table 2 have been adjusted for degrees of freedom so they can be compared with those in Table 1. For 4 of the 6 years and the composite period, the explanatory power of the expanded model is lower than that of the simple model. Thus, it may be concluded that the main statistical determinant of gasoline consumption of a new automobile is its curb weight and that this variable by itself explains most of the variation in fuel consumption.

RELATIVE IMPORTANCE OF WEIGHT REDUCTION

A close statistical association between curb weight and fuel consumption has been shown, but it has not been possible to demonstrate the significance of additional variables. The importance of other variables can be demonstrated as a composite but not individually by identifying changes in the relationship between fuel consumption and weight. The simple model is used for this analysis because the expanded model has no additional explanatory power.

If the simple model were statistically stable over the sample period, fuel-efficiency efforts other than weight reduction would apparently be random and probably unimportant. This possibility is hypothesis 1, which is shown in Figure 2. Alternatively, perhaps the statistical results in Table 1 contain significantly different intercepts or slopes or both or the coefficients contain time trends. If the slope or intercept coefficients diminished in size over the period, non-weight-reduction fuel economy efforts would have been complementary. This possibility is our third hypothesis and is shown in Figure 4. Furthermore, in the event of an unstable relationship between fuel consumption and weight, the nature of the instability is important. If fuel economy efforts other than weight reduction were concentrated in large cars, the regression line would rotate clockwise and the intercept would be unstable. Alternatively, an unstable intercept but constant slope implies that the relationship between fuel consumption and weight of all cars has changed about equally. A conventional statistical analysis is now employed to determine the statistical stability of the slopes and intercepts in Table 1 and to determine the presence of any time trends.

An analysis-of-variance (ANOVA) test was used to determine whether the individual regression estimates in Table 1 could be interpreted as being drawn from the same sample. The estimated F-statistic is 4.376, which is significant at the 1 percent level. The regression estimates for the individual years are significantly different, which implies that some type of fuel economy effort in addition to weight reduction has been important during this period.

Further ANOVA tests were conducted to determine whether the intercepts or slopes were statistically different. Testing for the equality of slopes produced an F-value of 1.875, which is significant at the 10 percent level but not at the 5 percent level. With a similar test, it was found that the intercepts in the simple models were significantly different at the 1 percent level. [The Biomedical Computer Programs used do not contain a procedure to test equality of intercepts directly. Therefore an intercept dummy variable was added for each year from 1976 to 1981 and tests were made to see whether the extra sum of squares caused by regression was significantly larger than without the dummy variables. This ANOVA test is described by Draper and Smith (4, pp. 67-69).] This result allows the rejection of the first hypothesis, that fuel economy improvement efforts have been due entirely to weight reduction. The relative stability of the slope coefficients and instability of the intercepts implies that the relationship between gasoline consumption and weight has shifted rather than rotated. The composite influence of fuel economy efforts has apparently been approximately uniform across car classes rather than concentrated on small or large cars.

Although differences in intercepts do not necessarily imply a time trend, a significant positive or negative time trend would allow the determination of whether non-weight-reduction fuel-efficiency efforts have been complementary or punitive. Therefore the simple model was rerun and a time trend in which the intercept decreases by equal increments each year but the slopes remain uniform was allowed for. The estimated regression equation is

$$G_{it} = 129.20 + 0.227W_{it} - 14.865t \qquad R^2 = 0.857 \qquad (1)$$
$$(38.164) \quad (-4.821)$$

where the time-trend coefficient is negative and highly significant. Since 1976, cars from each successive model year have required, on the average, about 15 fewer gallons to travel 15,000 miles. This improved efficiency is in addition to that achieved through weight reduction. The significant negative time trend confirms hypothesis 3, that fuel economy efforts other than weight reduction have been complementary (see Figure 4).

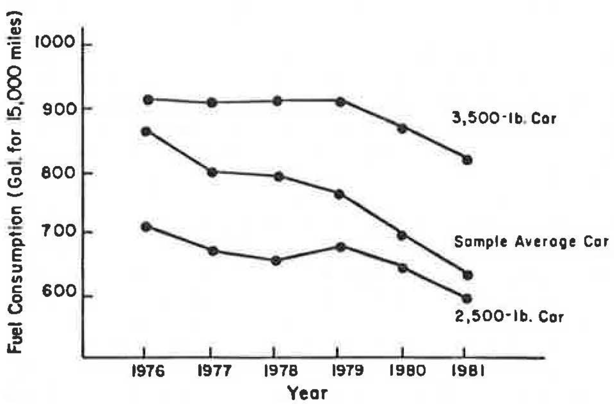
The specification of Equation 1 presumes a linear decrease in gasoline consumption in addition to the weight reduction effect. The nature of this trend is depicted graphically by assuming a car of given weight and using the regression results in Table 1 to estimate its fuel efficiency. The estimated gasoline consumption of a relatively large car of 3,500 lb and a small car of 2,500 lb is shown in Figure 5. The sample mean car weight and its corresponding fuel consumption (obtained from Table 1) are also shown in Figure 5 to illustrate the influence of all measures on average fuel consumption.

Fuel-consumption figures for a constant-weight car are compared with the sample mean fuel-consumption estimates that reflect the composite influence of weight reduction and all other measures of fuel economy. Overall, required gasoline consumption decreased from 864.8 gal in 1976 to 776.4 gal in 1979, a difference of 88 gal. During this time the improved fuel economy of a 3,500-lb car was only 12 gal. The major improvement in fuel economy achieved during the period 1976-1979 is therefore a consequence of weight reduction. From 1979 to 1981 an average new car required 130 fewer gallons to travel 15,000 miles; a 3,500-lb car required 87 fewer gallons. Most of the fuel economy achieved from 1979 to 1981 is because of measures other than weight reduction.

POSSIBLE BIAS DUE TO EPA MEASUREMENT PROCEDURE

The preceding results are based on EPA fuel-efficiency estimates, which are transformed into gasoline consumption. EPA tests are conducted with a

Figure 5. Estimated fuel consumption for 3,500-lb car, 2,500-lb car, and sample average car by year for 1976-1981.



dynomometer, so mileage estimates are simulated, not actual road mileage. EPA estimates have been criticized as being biased upward. At issue here is the nature and extent of the bias and particularly how the use of actual road mileage would have affected the regression results in Tables 1 and 2.

In an unpublished report for the U.S. Department of Energy, B. McNutt and R. Dulla in 1979 compared on-road fuel efficiency with EPA mileage for each year from 1974 to 1977. They used a linear relationship between EPA and on-road miles per gallon and concluded that on-road mileage falls short of EPA certified mileage. Although the EPA and on-road equations were different for each year, a time trend in that difference was not observed.

A more recent study for the Department of Energy by Energy and Environmental Analysis (5) reexamined the EPA and on-road mileage estimates and adopted a reciprocal equation in lieu of the linear relationship. Their so-called master equation for passenger cars for 1951 to 1980 is

$$MPG_{Rd} = MPG_{EPA}/(0.0237MPG_{EPA} + 0.76) \quad (2)$$

where MPG_{Rd} is on-road miles per gallon and MPG_{EPA} is EPA miles per gallon.

If Equation 1 is used to define the relationship between on-road and EPA miles per gallon during the period under consideration, it can be determined how the regression results would have looked had on-road fuel consumption been used as the dependent variable. An important property of Equation 2 is that it represents each year in the time period and it contains no time trend. Although EPA mileage estimates may be biased estimates of on-road mileage, there is no time trend in this bias. Thus the results of this paper concerning weight-adjusted fuel efficiency over time are not sensitive to the use of EPA or on-road mileage.

Equation 2 can be transformed from a mileage equation to a fuel-consumption equation by first replacing miles per gallon by miles divided by gallons and inverting to obtain

$$G_{Rd}/M = [(0.0237M/G_{EPA}) + 0.76] \div (M/G_{EPA}) \quad (3)$$

in which M is miles. Multiplying through by the denominator on the right, letting M equal 15,000, and solving for G_{Rd} gives

$$G_{Rd} = 356 + 0.76G_{EPA} \quad (4)$$

where G_{EPA} is the dependent variable in the regression model used in this paper. Equation 4 implies that the EPA estimate of gallons of gasoline necessary to travel 15,000 miles underestimates actual on-road required gallons, at least over the relevant range (less than 1,941 gal). For the purposes of this study, the important property of Equation 4 is its linearity. A graphic picture of the fuel-economy trends in Figure 5 by using on-road gallons is simply a linear transformation of those trends. In an extensive analysis of on-road versus EPA mileage estimates, Murrel (6) also concludes that the bias has been about constant since 1976. The overall conclusion that fuel-economy improvements from 1976 to 1979 are due to vehicle weight reduction and that improvements during 1980 and 1981 are due mainly to other factors is not sensitive to the use of EPA or on-road gasoline consumption. [The simple linear model used here (and reported in Table 1), which is $G_{EPA} = \hat{\alpha} + \hat{\beta}W$, can be transferred into a simple linear model with on-road gallons as the dependent variable by substituting the equation into Equation 4. The resulting equation is $G_{Rd} = 356 + 0.76\hat{\alpha} + 0.76\hat{\beta}W$, where where $\hat{\alpha}$ and $\hat{\beta}$ can be obtained from Table 1.]

CONCLUSIONS AND IMPLICATIONS

An apparently negative conclusion is that variables such as horsepower, performance, transmission type, and domestic versus foreign manufacturer are not associated significantly with gasoline consumption. Foreign manufacturers have been interested in fuel economy for several years. Their efforts apparently consist of building small cars but not cars that are more efficient on a per-pound basis than U.S. cars. American small cars are likely to be competitive with foreign-made cars, at least in terms of operating costs. The failure of the performance variable to be significant implies that fuel economy has not been attained at the expense of reduced ratios of horsepower to weight.

In addition to becoming lighter, new cars have become more homogeneous in terms of weight. A disadvantage of small cars is their lack of safety in collisions with larger cars. The trend toward more homogeneous car weights may imply an improvement in the safety of new cars.

Initially in this paper, some fuel economy projections by the Mellon Institute were noted that are the results of weight reduction and other measures. The examination of recent automobile industry efforts to achieve economy here indicates that such efforts have been successful. Furthermore, the recent trends in automotive fuel economy efforts are in the direction that the Mellon Institute forecasts for the next two decades (see Figure 1). New cars are becoming lighter and therefore more fuel efficient. The first phase of fuel-efficiency improvements was completed in 1979 and consisted primarily of weight reduction. In 1980 and 1981 a second distinct phase was observed that has been more successful than the first phase and that includes primarily fuel-efficiency improvements in addition to weight reduction. These efficiency improvements have apparently been shared about equally by all car classes.

ACKNOWLEDGMENT

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