Forthcoming in Transportation Research Part D: Transport and Environment

The Inconvenient Truth about Improving Vehicle Fuel Efficiency: A Multi-Attributes Analysis of the Technology Efficient Frontier of the US Automobile Industry

Chialin Chen
Queen's School of Business
Queen's University
Kingston, Ontario K7L 3N6, Canada

Jun Zhang
Department of Economics
Queen's University
Kingston, Ontario K7L 3N6, Canada

Abstract

Vehicle fuel efficiency has taken on more economic and environmental significance due to the rise in gasoline prices in 2007/2008. We examine adoption of fuel efficiency technologies by the US automobile industry between 1985 and 2002 and consider the environmental implications. The technology efficient frontier between vehicle weight and fuel efficiency of the US automobile fleet did not move outward significantly for an extended period in the 1980s and 1990s indicating a lack of company- or industry-wide adoption of new fuel efficiency technologies. While the firm with inferior technology capability did push its efficient frontier outward to close the technology gap, the two leading firms' efficient frontiers first showed signs of possible regression in the early 1990s, and did not move outward significantly until the mid 1990s. Several managerial and policy options are examined for improving vehicle fuel efficiency.

Keywords: Vehicle fuel economy; Multi-attributes analysis; Technology adoption

1. Introduction

Higher gasoline prices have significantly increased transportation costs for consumers and industries from 2007. One result has been a move to purchase more fuel-efficient vehicles. From the environmental perspective, transportation is the main emitter of carbon dioxide (US Energy Information Administration, 2006). Given the economic and environmental implications of enhancing of vehicle fuel economy, the design of fuel-efficient vehicles has been a focus of private strategies and public policies. Since the oil crisis in the 1970s, the US government has enforced the Corporate Average Fuel Economy (CAFE) Standards requiring automobiles in the US market to achieve a certain level of average fuel economy every year. Failing to meet CAFE will result in severe financial penalty (US National Highway Traffic Safety Administration, 2007). In response to the economic and regulatory pressures, the three US domestic automakers, General Motors, Ford, and Chrysler, successfully introduced a number of small, highly fuel efficient vehicles such as Geo Metro, Ford Festiva and Escort, and Chrysler Neo in the 1980s and 1990s. Despite this, US automakers' efforts in designing fuel-efficient vehicles have been challenged.

One factor that limits automakers' ability to produce fuel-efficient vehicles is the trade-off between vehicle weight and fuel efficiency. From the perspective of multi-attributes analysis, the data points given in Figure 1 form a Pareto technology efficient frontier, the locus of design solutions is the combinations of vehicle weight and fuel efficiency as two major attributes, along which the improvement in one attribute cannot be obtained without compromising the other (Keeney and Raiffa, 1993). Due to the tradeoff between vehicle weight and fuel efficiency, weight reduction through material substitution has been the predominant strategy used to develop fuel efficient motor vehicles since the 1970s (Field and Clark, 1997). Figure 2, shows different design options as combinations of multiple attributes given an existing Pareto efficient frontier. Points on the frontier show non-inferior solutions where at least one attribute is properly addressed. Points inside the frontier are inferior or dominated solutions. The points outside the frontier are technologically infeasible. The frontier can be pushed out with technology advancement. This framework of multi-attributes analysis is consistent with that used in Dodson (1985),which suggests that technology can be described by multiple parameters and the state of the art in a technologically homogeneous domain is represented by a tradeoff function.

Given an existing efficient frontier, automakers have two options for improving a vehicle's fuel efficiency. First, they can try to move along the efficient frontier toward the lower right corner to develop more fuel efficient but smaller vehicles; e.g., material substitution through the use of lighter materials such as plastics and alumina has long been used to this end (Field and Clark, 1997). Alternatively, automakers can try to push the frontier out by adopting new technologies; e.g. Decicco and Ross (1996) analyze the benefits of multipoint fuel injection, multi-valves per cylinder, variable valve control, and continuously variable transmission. The different design practices have their advantages and disadvantages. While moving along an existing efficient frontier is generally considered a more economical option, pushing the efficient frontier outward, which often requires a series of technology innovations/adoptions over time, can lead to potential win-win solutions that address multiple performance attributes simultaneously (de Neufville, 1990). Here we seek to understand the patterns of technology changes and adoptions in the US domestic automobile industry used for improving vehicle fuel efficiency.

2. Data

In 1985, the US Environmental Protection Agency (EPA) started to use a systematic approach to test fuel efficiencies of options for new vehicle models sold. Test data are available from a number of sources. Here we use that covering the most popular option of each vehicle model listed in the automotive yearbooks by Gillis (1985 – 2002). The source provides annual industry-wide data covering the weight and fuel efficiency of all vehicle models, introduced by the "Big Three" US domestic automakers, General Motors, Ford, and Chrysler between 1985 and 2002 - Figures 3 to 5. While 1985 was when US EPA testing started, 2002 when the automakers started to aggressively pursue technology options to the internal combustion engines including gas-hybrid electric engines and fuel cells. The CAFE standards reached their highest levels in 1985 and were not further tightened for two decades or so. Therefore, the automotive design decisions of the industry were relatively free of regulatory pressure during the study period.

3. Results

To test the different possible movements of the efficient frontier, we use dichotomous shift variables (Bates and Watts, 2007). As can be seen in Figures 3 to 5, the efficient frontiers of the industry appear to be convex. The hyperbolic function, which is used to model the convex efficient frontier of an individual automaker in Chen and Zhang (2007), is used to test aggregate data for the industry. Historically, conic functions have been widely used to model Pareto efficient frontiers in engineering design and production analysis (Li et al., 1998; Arocena and Price, 2002). Theoretically, Luban (2001) analyzes the situation where multiple products are distributed along a hyperbolic surface to form a Pareto frontier along which all Nash products are rationally indifferent to each other. We first set 1985 as the base year. For each subsequent year, we test whether the efficient frontier is significantly different from that in the base year. Let *W* and *Y* denote the vehicle weight and fuel efficiency. The hyperbolic function used is

$$Y^2 = \alpha(W-\beta)^2 + \gamma + \lambda \times Z_j + \varepsilon\,, \qquad (1)$$

where Z_j is the dummy variable with $Z_j = 0$ for the base year and $Z_j = 1$ for subsequent year.

Three statistical exercises are performed. First, aggregate industry data are used to test the temporal movements in the industry's efficient frontier. Second, we test the movements of the efficient frontier of the firm with the best technology level in the industry during each year. Third, we use each individual company's data to test the movements of its efficient frontier. To identify the firm with the best technology level in the second test, a nonlinear regression is run with dummy variables based on the hyperbolic function:

$$Y^2 = \alpha(W-\beta)^2 + \gamma_1 D_1 + \gamma_2 D_2 + \gamma_3 D_3 + \varepsilon\,, \qquad (2)$$

where, D_i (i = 1, 2, and 3) are the dummy variables. For firm *k*'s efficient frontier, we set $D_k = 1$ and $D_i = 0\ \forall i \neq k$, where *k* = 1, 2, and 3 are the indexes of the three automakers. We then run a nonlinear regression to identify the firm with the highest coefficient value of the dummy variable as the firm with the best technology level in each data year.

Tables 1 to 3 report the *t*-values relating the three sets of tests. Bolded numbers indicate results that are statistically significant with 5% significance level; a bold positive value suggests a significant outward movement of the efficient frontier. For example, the efficient frontier in 1992 is not significantly different from that in 1985 based on the aggregate industry data (Table 1) and the efficient frontier of the best firm in 1995 represents a significant improvement from that in 1987 (Table 2). The three domestic automakers are referred to as Firms 1, 2, and 3 to keep confidentiality. Tables 4 to 6 present results based on data for each of the three automakers. Here we see, by examining the parameters in bold, that the fuel efficiency technology of Firm 1 significantly improved between 1985 and 1987 (Table 4) and that the fuel-efficient technology of Firm 3 was not significantly improved between 1992 and 1996.

4. Analysis of Results

The results presented in Tables 1 and 2, despite slight differences by year, show that between 1985 and the mid 1990s the efficient frontier of the US domestic automobile industry did not move outward either at the aggregate industry data or for firms with the best technology levels. There are signs of possible regression at the industry level, although this is not statistically significant. Furthermore, while the efficient frontier based on the aggregate industry data moved outward significantly between 1995 and 1999 compared to 1985, the efficient frontier based on the firm with the best technology level in each data year did not, however, move out significantly from the 1985 level until 2000 – Table 2. One explanation is that the average improvements by the industry between 1995 and 1999 was driven by firms with inferior technologies catching up with those with the best technology, and the real improvement in fuel efficiency technologies did not occur until later.

From Table 4, we see that Firm 1 consistently achieved significant improvements in fuel efficiency technology between 1987 and 2002 over the 1985 level. In Tables 5 and 6, however, it is clear that the efficient frontiers of Firms 2 and 3 did not significantly move out until 2000 and 1996, respectively. Additionally, if 1988 is set as the base year, the efficient frontier of Firm 3 did not move significantly until 2002 – Table 6. Indeed, the efficient frontiers of both Firms 2 and 3 frequently show signs of technology regression between 1986 and 1994, and the inward movement of Firm 2's technology frontier statistically significant in 1991 compared to1988 and 1990 (Table 5).

It is tempting to conclude that Firm 1 spent significant efforts to improve/adopt fuel efficiency technologies during most of the period, whilst Firms 2 and 3 failed to do so. However, when the results are combined the data in Table 3 identifying firms with the best technology levels, we find that Firm 1 never led the industry in adopting fuel efficiency technologies until 1999. Firms 2 and 3 frequently alternated their roles as the leading firms. Aggregate data is used to obtain a set of common parameter values based on the hyperbolic function in equation 1 without the dummy variable, and then the changes in the constant term of each firm's efficient frontier is observed. A relatively high value of the constant term indicates an outward position of an efficient frontier. Figure 6 shows the rescaled technology levels of the three firms relative to the constant term in 1985 (Firm 2 then had the best technology level) normalized to zero. Firm 3 seems to have made more consistent efforts to push out its efficient frontier to close the technology gap between itself and the two leading firms whose technology levels were relatively stable until 1995, before it improved.

Our calculations show that the technology efficient frontier of the US automobile industry did not move out for an extended period in the 1980s and 1990s suggesting that some of the fuel efficiency technologies that were already available were either not adopted or only adopted in some vehicle models. For example, variable valve timing, which can achieve significant improvements in fuel efficiency (Decicoo and Ross, 1996) was known since the 1970s, and was adopted by some non-US manufacturers such as Honda, Nissan, and BMW in the 1980s and 1990s, but not by US manufactures until the late 1990s, and then only in a few models. The small-scale adoption of a new technology is seldom enough to significantly push the technology efficient frontier in any industry.[1]

[1] According to Ross and Wenzel (2002), and Zachariadis (2008), enhanced safety and emissions control features only have marginal effects on vehicle mass and fuel economy. Sprei et al. (2008) also raise the possibility of

The multi-attributes analysis shows most new vehicles in the 1980s and 1990s can only be viewed as the non-inferior, as opposed to win-win, solutions; highly fuel efficient vehicles introduced during this period were mostly light-weight, small cars at the lower right end of an existing technology efficient frontier with the other end of the curve occupied by SUVs and pickup trucks. Although most automakers did constantly improve the fuel efficiencies of some individual vehicles by making them smaller and lighter, the overall tradeoff between vehicle weight and fuel efficiency did not seem to improve during most of the period. While the average CAFE performance of the US industry as a whole did increase from 27.6 mpg to 29.0 mpg between 1985 and 2002 (US National Highway Traffic Safety Administration, 2007),[2] this was much smaller than most of the predictions (e.g. Greene and Duleep,1993; Decicco and Ross, 1996).[3]

5. Conclusion

The analyses shows that the technology efficient frontier of the US automobile industry did not improve significantly for an extended period in the 1980s and 1990s, indicating a lack of systematic adoption of new fuel efficiency technologies. While the firm with inferior technology capability did push its efficient frontier outward to close the technology gap, the two leading manufacturers' efficient frontiers first showed signs of regression in the early 1990s, and were not pushed out significantly until the late 1990s. As a result, the industry might have missed an opportunity to reduce the economic and environmental impacts.

---

automakers diverting technology gains into non-fuel saving features based on data collected in the Swedish market.

[2] A firm may improve its fleet average fuel economy through changing the marketing mix without significant improvement in fuel efficiency technologies, see Chen and Zhang (2007).

[3] Brink and Wee (2001) also show that the increase in vehicle weight was a major reason for the car-fleet specific fuel consumption no longer showing a decrease after 1990 in the Netherlands.

Acknowledgements: This research is supported in part by Natural Science and Engineering Research Council Canada (Grant Number: RGPIN/249675-2007).

References

Arocena, P. and Price, C.W. (2002), Generating Efficiency: Economic and Environmental Regulation of Public and Private Electricity Generators in Spain, *International Journal of Industrial Organization* 20, 41-69.

Bates, D.M. and Watts, D.G. (2007), *Nonlinear Regression Analysis and Its Applications*, Wiley-Interscience: New York.

Brink, R.M.M.V.D. and Wee, B.V. (2001), Why Has Car-Fleet Specific Fuel Consumption Not Shown Any Decrease Since 1990? Quantitative Analysis of Dutch Passenger Car-Fleet Specific Fuel Consumption, *Transportation Research D* 6, 75-93.

Chen, C. and Zhang, J (2007), Why Not a 40-MPG SUV? Designing Fuel Efficient Motor Vehicles with Technology Constraints between Vehicle Weight and Fuel Efficiency, Working Paper, Queen's School of Business, Queen's University.

de Neufville, R. (1990), *Applied Systems Analysis*, McGraw-Hill, New York.

Decicco, J.M. and Ross, M. (1996), Recent Advances in Automotive Technology and the Cost-Effectiveness of Fuel Economy Improvement, *Transportation Research D* 2, 79-96.

Dodson, E.N. (1985), Measurement of State of the Art and Technological Advance, *Technological Forecasting and Social Change* 27, 129-146.

Field, F.R. and Clark, J.P. (1997), A Practical Road to Lightweight Cars, *Technology Review* 100, 28-35.

Gillis, J. (1985 – 2002), *The Used Car Book*, Harper Collins, New York.

Greene, D.L. and Duleep, K.G. (1993), Costs and Benefits of Automotive Fuel Economy Improvement: A Partial Analysis, *Transportation Research A* 27, 217-235.

Keeney, R.L. and Raiffa, H. (1993), *Decisions with Multiple Objectives*, Cambridge University Press, Cambridge.

Li, Y, Fadel, G.M., and Wiecek, M.M. (1998), Approximating Pareto Curves Using the Hyper-Ellipse, in Proceedings of 7th AIAA/USAF/NASA/ISSMO Multidisciplinary Analysis and Optimization Symposium, Part 3, Paper No. 98-4961, 1990-2002.

Luban, D.J. (2001), Value Pluralism and Rational Choice, Working Paper, Georgetown Law School (Paper No. 264335).

Ross, M. and Wenzel, T. (2002), *An Analysis of Traffic Deaths by Vehicle Type and Model*, American Council for and Energy-Efficient Economy (Report Number T021), Washington, DC.

Sprei, F., Karlsson, S., and Holmberg, J. (2008), Better Performance or Lower Fuel Consumption: Technological Development in the Swedish New Car Fleet 1975-2002, *Transportation Research D* 13, 75-85.

US Energy Information Administration (2006), *Emissions of Greenhouse Gases Report*, US Energy Information Administration (Report #: DOE/EIA-0573), Washington DC.

US National Highway Traffic Safety Administration (2007), *Summary of Fuel Economy Performances*, US National Highway Traffic Safety Administration, Washington DC.

Zachariadis, T. (2008), The Effect of Improved Safety on Fuel Economy of European Cars, *Transportation Research D* 13, 133-139.

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
1985	0.05	0.31	1.75	1.53	0.85	0.93	1.01	1.54	1.83	**3.36**	**3.65**	**3.41**	**3.01**	**3.53**	**3.36**	**3.30**	**6.03**
1986	-	0.27	2.00	1.72	0.86	1.02	1.11	1.70	**2.04**	**3.88**	**4.25**	**3.90**	**3.49**	**4.13**	**3.92**	**3.84**	**7.11**
1987	-	-	1.92	1.59	0.66	0.84	0.89	1.54	1.86	**3.91**	**4.42**	**3.93**	**3.85**	**4.56**	**4.47**	**3.98**	**7.81**
1988	-	-	-	-0.55	-1.39	-0.57	-0.45	-0.64	0.23	**2.23**	**2.48**	**2.35**	**2.41**	**3.01**	**3.00**	**2.34**	**6.10**
1989	-	-	-	-	-1.03	-0.30	-0.19	-0.14	0.62	**2.77**	**3.30**	**2.87**	**3.00**	**3.80**	**3.76**	**3.15**	**7.79**
1990	-	-	-	-	-	0.22	0.30	0.86	1.20	**3.22**	**4.00**	**3.27**	**3.42**	**4.30**	**4.19**	**3.87**	**8.75**
1991	-	-	-	-	-	-	0.05	0.27	0.72	**2.29**	**2.48**	**2.39**	**2.18**	**2.64**	**2.50**	**2.33**	**4.98**
1992	-	-	-	-	-	-	-	0.20	0.65	**2.23**	**2.44**	**2.33**	**2.09**	**2.55**	**2.41**	**2.30**	**4.91**
1993	-	-	-	-	-	-	-	-	0.65	**2.96**	**3.68**	**3.06**	**3.11**	**3.99**	**3.89**	**3.46**	**8.54**
1994	-	-	-	-	-	-	-	-	-	1.91	**2.23**	**2.05**	**2.07**	**2.64**	**2.62**	**2.10**	**5.64**
1995	-	-	-	-	-	-	-	-	-	-	0.32	0.27	0.54	1.15	1.09	0.57	**4.82**
1996	-	-	-	-	-	-	-	-	-	-	-	-0.04	0.19	0.86	0.81	0.20	**5.29**
1997	-	-	-	-	-	-	-	-	-	-	-	-	0.28	0.85	0.79	0.31	**4.41**
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	0.59	0.51	0.07	**4.56**
1999	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.07	-0.58	**4.46**
2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.50	**4.24**
2001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**5.51**

Notes: (i) Base years are in the first column. (ii) Bolded *t*-values indicate statistically significant at 5% significance level.

Table 1. Test Results (*t*-values) of the Efficient Frontiers with Industry Aggregate Data

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
1985	-0.53	-0.14	0.45	0.37	0.06	0.21	0.12	0.07	0.58	1.74	1.95	1.58	1.91	1.82	**2.26**	**2.49**	**4.04**
1986	-	0.65	1.12	0.85	0.71	0.55	0.54	0.87	1.17	**2.05**	**2.64**	**2.22**	**2.58**	**2.34**	**1.96**	**2.17**	**4.88**
1987	-	-	0.95	0.48	0.25	0.47	0.33	0.33	1.07	**1.97**	**2.56**	**2.36**	**2.65**	**2.16**	**2.21**	**2.47**	**5.11**
1988	-	-	-	-0.32	-0.51	-0.29	-0.27	-0.48	0.17	1.05	1.35	1.32	1.61	1.51	1.52	1.81	**4.00**
1989	-	-	-	-	-0.35	0.03	-0.06	-0.27	0.39	1.39	1.74	1.49	1.79	1.66	1.94	**2.19**	**4.19**
1990	-	-	-	-	-	0.06	-0.02	0.03	0.46	1.54	**2.04**	1.52	1.90	**2.12**	**2.79**	**3.12**	**5.08**
1991	-	-	-	-	-	-	-0.08	-0.06	0.35	1.07	1.27	1.32	1.46	1.35	0.98	1.17	**2.94**
1992	-	-	-	-	-	-	-	0.03	0.44	1.07	1.33	1.34	1.48	1.32	1.03	1.22	**3.02**
1993	-	-	-	-	-	-	-	-	0.51	1.64	**2.17**	1.65	**2.03**	**1.97**	**2.26**	**2.57**	**5.11**
1994	-	-	-	-	-	-	-	-	-	1.02	1.23	1.24	1.45	1.51	1.21	1.50	**3.61**
1995	-	-	-	-	-	-	-	-	-	-	0.16	0.13	0.37	1.05	0.93	1.40	**3.45**
1996	-	-	-	-	-	-	-	-	-	-	-	0.16	0.36	0.87	0.77	1.25	**3.57**
1997	-	-	-	-	-	-	-	-	-	-	-	-	0.17	0.79	0.60	0.98	**2.67**
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	0.68	0.49	0.94	**2.90**
1999	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.19	0.29	**2.26**
2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.66	**2.70**
2001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**2.12**

Notes: (i) Base years are in the first column (ii) Bolded *t*-values indicate statistically significant at 5% significance level.

Table 2. Test Results (*t*-values) of the Efficient Frontiers with the Best Technology Data

Year	Leading Firm	Year	Leading Firm
1985	Firm 2	1994	Firm 3
1986	Firm 3	1995	Firm 2
1987	Firm 3	1996	Firm 3
1988	Firm 3	1997	Firm 3
1989	Firm 2	1998	Firm 3
1990	Firm 2	1999	Firm 1
1991	Firm 3	2000	Firm 2
1992	Firm 3	2001	Firm 2
1993	Firm 2	2002	Firm 3

Table 3. Firms with the Best Technologies: 1985 – 2002

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
1985	1.51	**2.03**	**3.19**	**3.57**	**2.83**	**3.86**	**3.18**	**2.91**	**2.31**	**3.55**	**3.58**	**3.27**	**2.68**	**3.43**	**3.34**	**3.77**	**4.83**
1986	-	0.00	1.27	1.54	0.88	**2.04**	1.42	1.14	0.76	**2.21**	**2.28**	**2.11**	1.70	**2.42**	**2.22**	**2.59**	**3.59**
1987	-	-	1.64	**2.08**	1.10	**2.72**	1.88	1.88	1.23	**3.53**	**3.58**	**3.11**	**2.29**	**3.36**	**3.23**	**3.88**	**5.48**
1988	-	-	-	0.38	-0.17	0.97	0.27	0.35	-0.10	**1.98**	**2.09**	1.86	1.36	**2.38**	**2.07**	**2.51**	**3.96**
1989	-	-	-	-	-0.69	0.50	-0.21	-0.01	-0.51	1.83	1.95	1.68	1.14	**2.30**	1.92	**2.40**	**4.17**
1990	-	-	-	-	-	0.70	0.03	0.52	-0.03	**2.19**	**2.32**	1.82	1.17	**2.05**	1.76	**2.39**	**4.09**
1991	-	-	-	-	-	-	-0.76	0.03	-0.45	**2.38**	**2.47**	**2.16**	1.48	**2.70**	**2.48**	**3.24**	**4.67**
1992	-	-	-	-	-	-	-	0.61	0.06	**2.68**	**2.74**	**2.38**	1.66	**2.78**	**2.61**	**3.34**	**4.76**
1993	-	-	-	-	-	-	-	-	-0.64	1.91	**2.04**	1.66	1.06	**2.41**	**1.98**	**2.52**	**4.36**
1994	-	-	-	-	-	-	-	-	-	**2.43**	**2.53**	**2.14**	1.52	**2.84**	**2.51**	**3.07**	**4.67**
1995	-	-	-	-	-	-	-	-	-	-	0.29	0.09	-0.19	1.29	0.65	1.19	**3.24**
1996	-	-	-	-	-	-	-	-	-	-	-	-0.15	-0.36	1.06	0.40	0.83	**2.86**
1997	-	-	-	-	-	-	-	-	-	-	-	-	-0.21	1.16	0.54	0.91	**2.76**
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	1.22	0.66	0.92	**2.49**
1999	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.76	-0.64	1.31
2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.24	**2.32**
2001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**2.38**

Notes: (i) Base years are in the first column (ii) Bolded *t*-values indicate statistically significant at 5% significance level.

Table 4. Test Results (*t*-values) of the Efficient Frontiers for Firm 1

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
1985	-0.74	-1.40	0.63	0.37	0.06	-1.23	-0.23	0.07	0.14	1.74	1.42	1.34	1.06	1.80	**2.26**	**2.49**	**3.75**
1986	-	-1.88	1.58	1.16	1.38	-0.70	0.61	1.05	0.87	**2.33**	**2.21**	**2.00**	1.61	**2.87**	**3.34**	**3.53**	**5.10**
1987	-	-	**2.18**	1.79	**2.97**	0.92	1.52	1.93	1.54	**2.79**	**2.88**	**2.59**	**2.48**	**3.87**	**4.06**	**4.21**	**5.91**
1988	-	-	-	-0.30	-0.79	**-2.14**	-1.01	-0.69	-0.48	1.14	0.81	0.74	0.67	1.26	1.70	**1.98**	**3.25**
1989	-	-	-	-	-0.35	-1.71	-0.67	-0.27	-0.14	1.39	1.13	1.03	0.94	1.51	1.94	**2.19**	**3.37**
1990	-	-	-	-	-	**-1.99**	-0.34	0.03	0.08	1.54	1.44	1.23	1.10	**2.30**	**2.79**	**3.12**	**5.05**
1991	-	-	-	-	-	-	1.18	1.52	1.26	**2.67**	**2.65**	**2.40**	**2.06**	**3.20**	**3.68**	**3.87**	**5.38**
1992	-	-	-	-	-	-	-	0.35	0.37	1.86	1.65	1.51	1.19	1.88	**2.39**	**2.61**	**3.78**
1993	-	-	-	-	-	-	-	-	0.08	1.64	1.51	1.29	0.97	1.71	**2.26**	**2.57**	**4.06**
1994	-	-	-	-	-	-	-	-	-	1.34	1.20	1.03	0.75	1.30	1.78	**2.03**	**3.18**
1995	-	-	-	-	-	-	-	-	-	-	-0.02	-0.26	0.02	0.56	0.93	1.40	**3.07**
1996	-	-	-	-	-	-	-	-	-	-	-	-0.21	-0.16	0.44	0.92	1.36	**3.04**
1997	-	-	-	-	-	-	-	-	-	-	-	-	0.18	0.77	1.21	1.63	**3.25**
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	0.68	1.12	1.61	**3.60**
1999	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.62	1.30	**4.13**
2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.66	**3.10**
2001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**2.31**

Notes: (i) Base years are in the first column. (ii) Bolded *t*-values indicate statistically significant at 5% significance level.

Table 5. Test Results (*t*-values) of the Efficient Frontiers for Firm 2

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
1985	-0.33	0.23	0.79	0.63	0.17	0.36	0.36	0.44	0.87	1.54	**2.01**	1.79	**2.08**	**2.11**	**2.02**	1.43	**3.99**
1986	-	0.65	1.12	1.12	0.51	0.55	0.54	0.90	1.17	**1.96**	**2.64**	**2.22**	**2.58**	**2.65**	**2.52**	**2.04**	**4.88**
1987	-	-	0.95	0.48	-0.20	0.47	0.33	0.17	1.07	**2.00**	**2.56**	**2.36**	**2.65**	**2.69**	**2.69**	1.65	**5.11**
1988	-	-	-	-0.58	-1.18	-0.29	-0.27	-0.88	0.17	0.98	1.35	1.32	1.61	1.55	1.59	0.60	**4.00**
1989	-	-	-	-	-0.83	0.06	-0.01	-0.38	0.61	1.50	**2.17**	1.89	**2.24**	**2.25**	**2.22**	1.22	**5.63**
1990	-	-	-	-	-	0.39	0.31	0.46	1.04	1.92	**2.73**	**2.24**	**2.63**	**2.68**	**2.59**	1.86	**6.20**
1991	-	-	-	-	-	-	-0.08	-0.28	0.35	1.02	1.27	1.32	1.46	1.45	1.49	0.80	**2.94**
1992	-	-	-	-	-	-	-	-0.13	0.44	1.07	1.33	1.34	1.48	1.47	1.50	0.86	**3.02**
1993	-	-	-	-	-	-	-	-	0.92	**1.97**	**2.85**	**2.31**	**2.73**	**2.82**	**2.73**	1.78	**6.21**
1994	-	-	-	-	-	-	-	-	-	0.86	1.23	1.24	1.45	1.43	1.47	0.60	**3.61**
1995	-	-	-	-	-	-	-	-	-	-	0.33	0.45	0.64	0.59	0.66	-0.27	**3.18**
1996	-	-	-	-	-	-	-	-	-	-	-	0.16	0.36	0.26	0.37	-0.81	**3.57**
1997	-	-	-	-	-	-	-	-	-	-	-	-	0.17	0.10	0.18	-0.67	**2.67**
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.10	-0.01	-0.95	**2.90**
1999	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.09	-0.93	**3.35**
2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.94	**2.94**
2001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**4.56**

Notes: (i) Base years are in the first column (ii) Bolded *t*-values indicate statistically significant at 5% significance level.

Table 6. Test Results (*t*-values) of the Efficient Frontiers for Firm 3

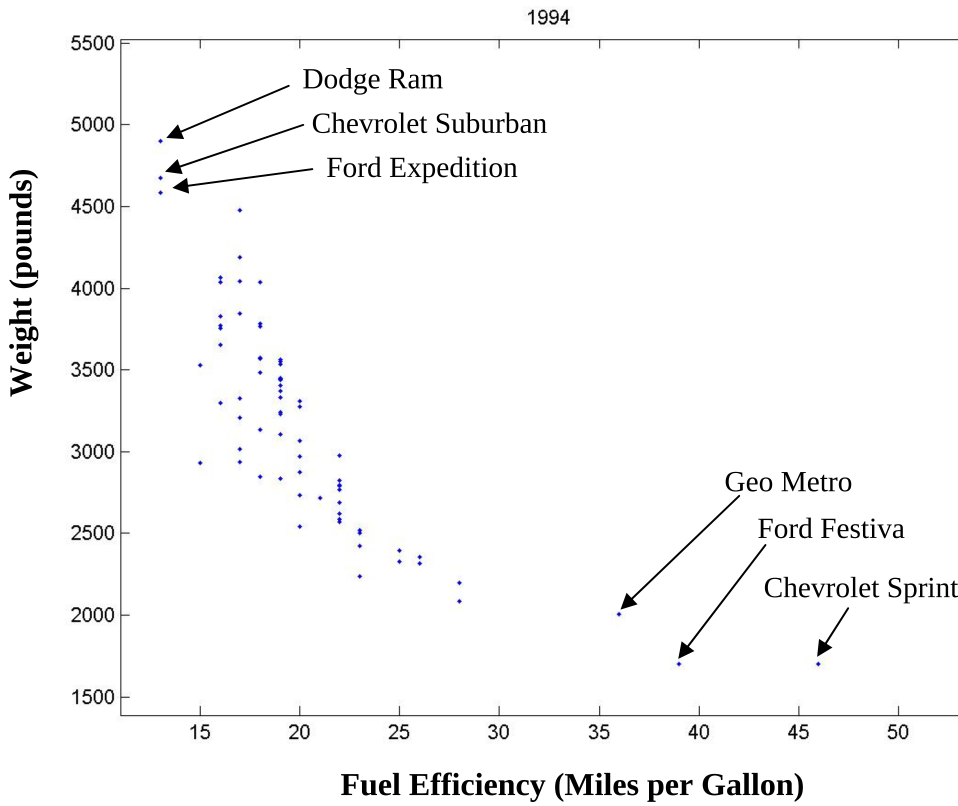
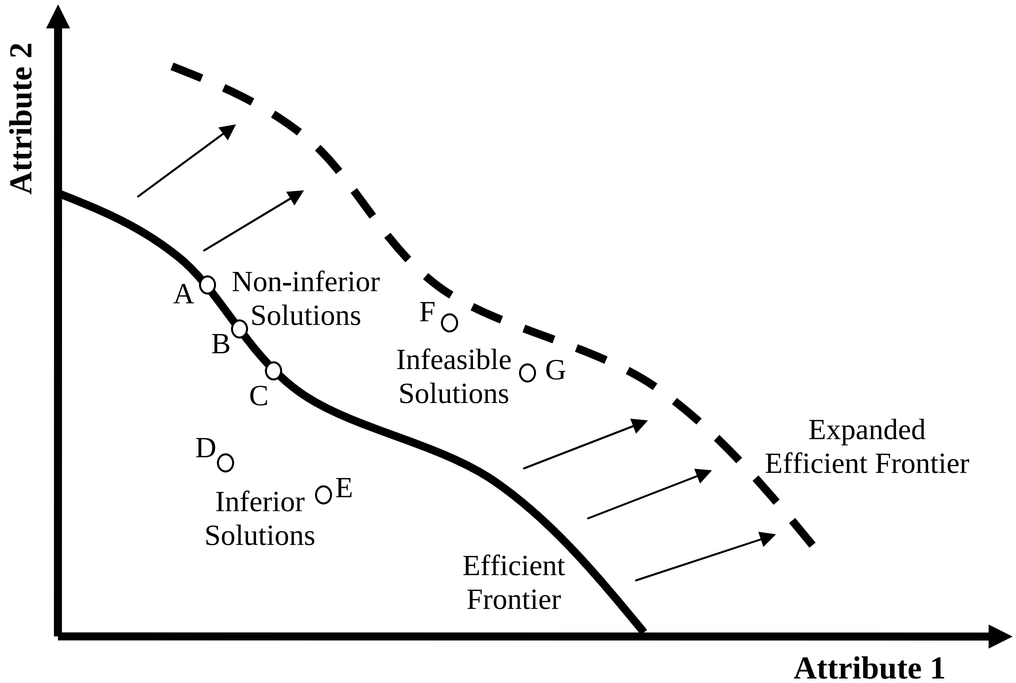
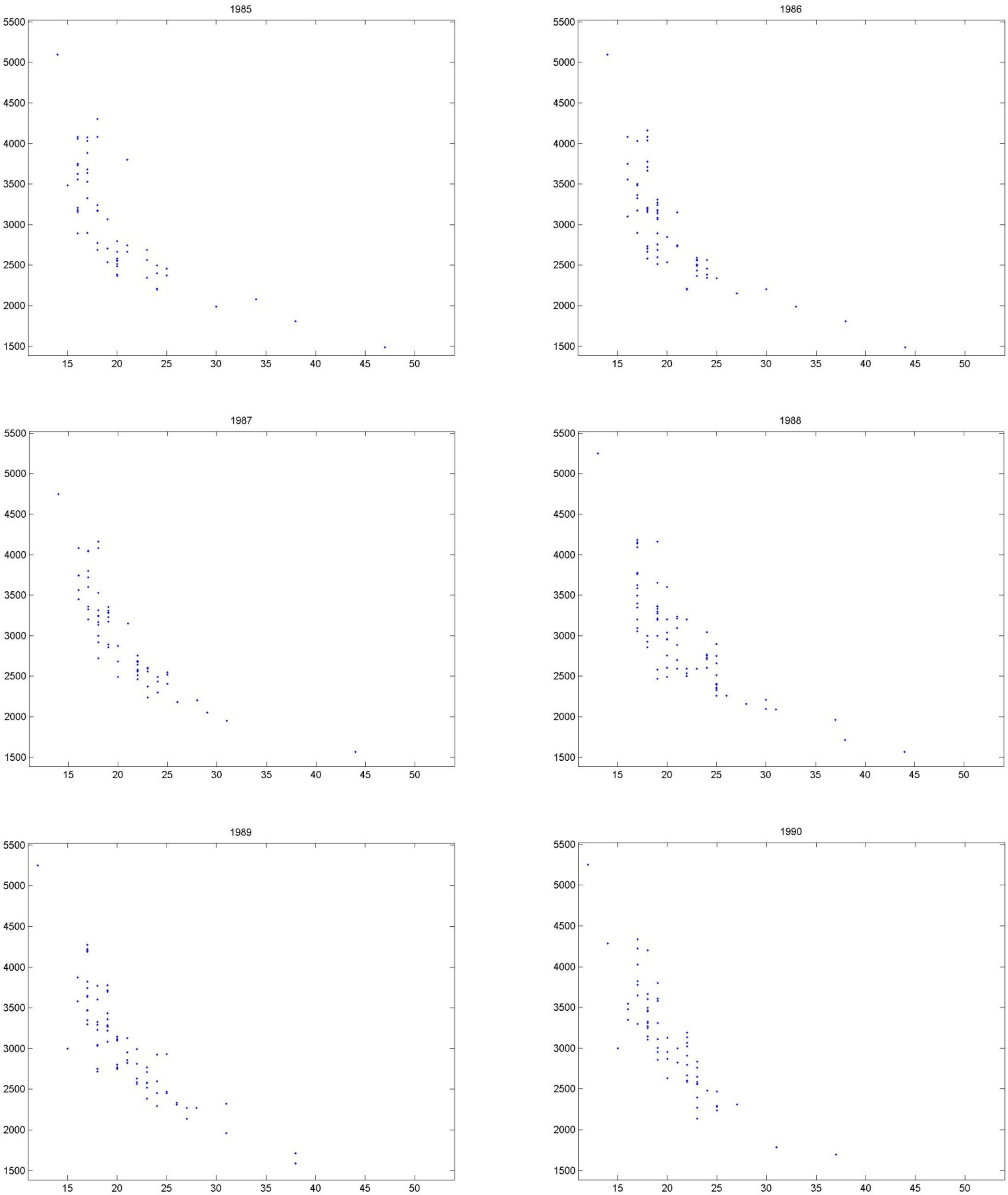


Figure 1. Vehicle Weights and Fuel Efficiencies: All U.S. Domestic Vehicles (1994)



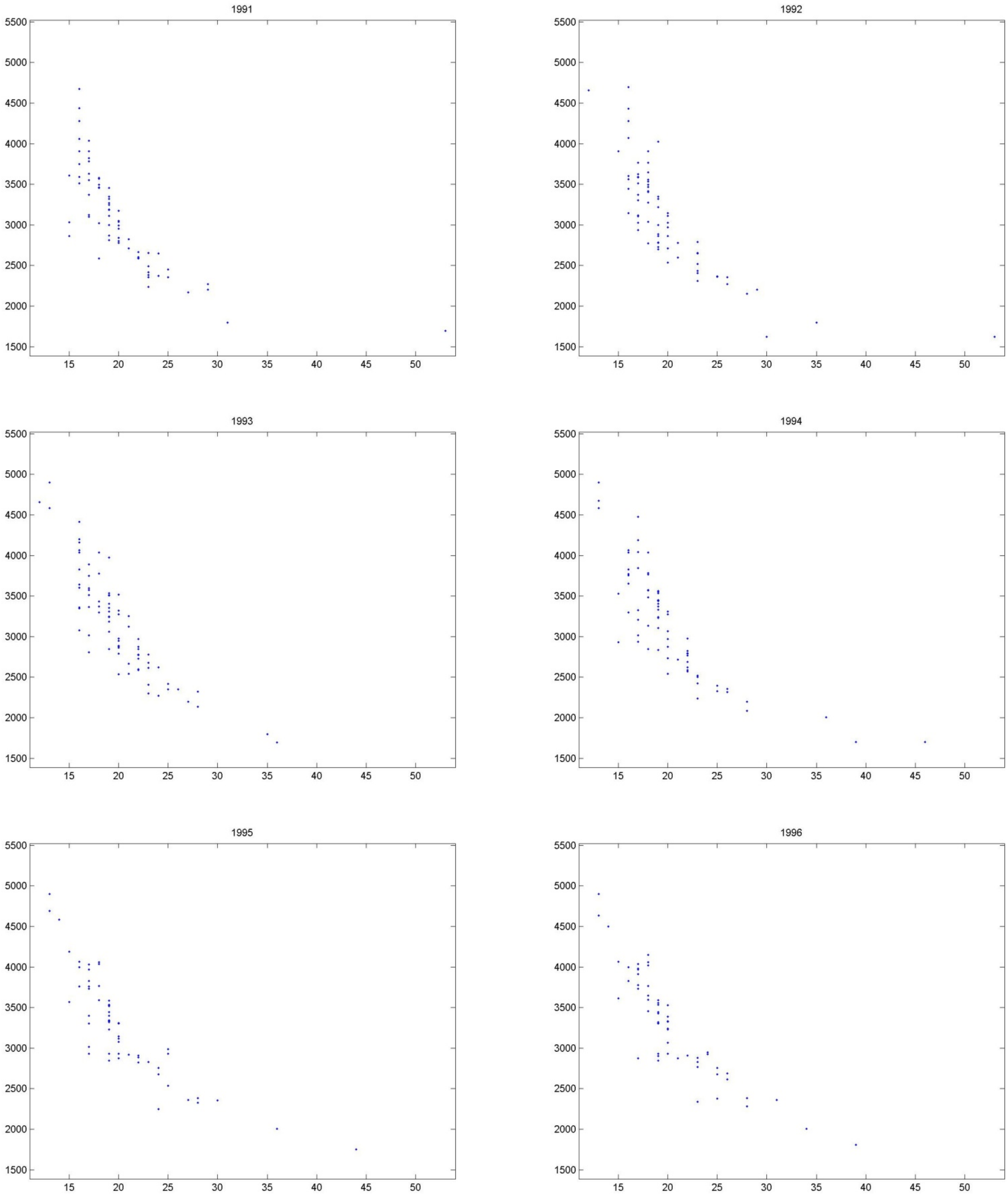
Source: de Neufville (1990)

Figure 2. Different Design Options with Efficient Frontiers



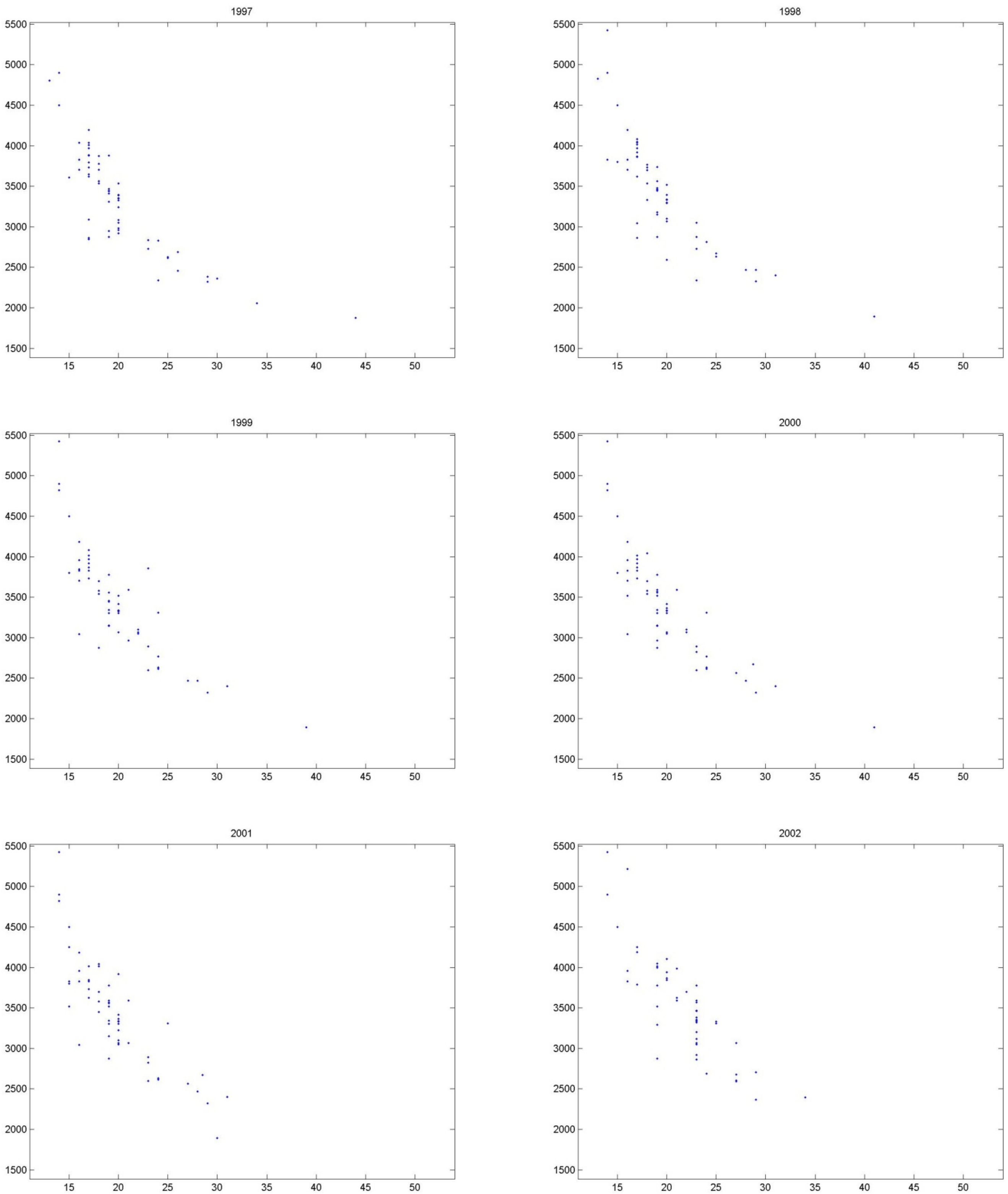
Note: The vertical and horizontal axes represent vehicle weights (lbs) and fuel efficiencies (MPG).

Figure 3. Vehicle Weight and Fuel Efficiency Data (1985-1990)



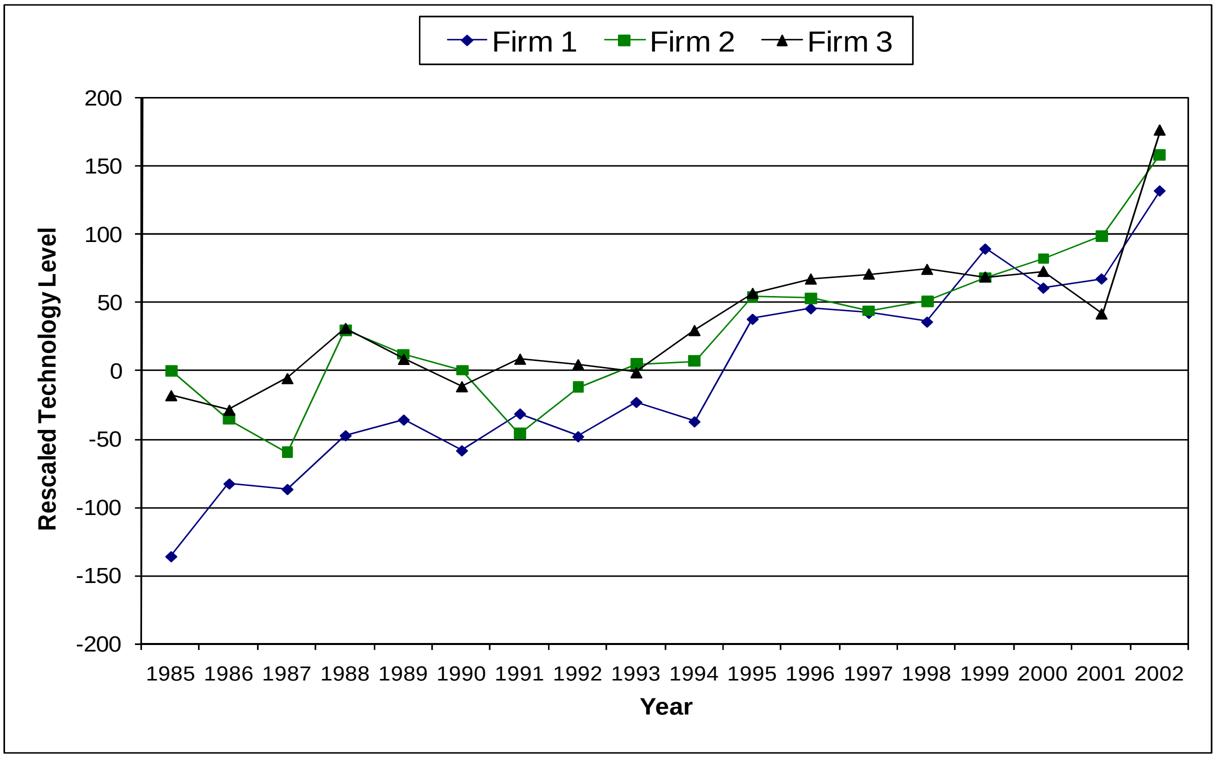
Note: The vertical and horizontal axes represent vehicle weights (lbs) and fuel efficiencies (MPG).

Figure 4. Vehicle Weight and Fuel Efficiency Data (1991-1996)



Note: The vertical and horizontal axes represent vehicle weights (lbs) and fuel efficiencies (MPG).

Figure 5. Vehicle Weight and Fuel Efficiency Data (1997-2002)



Note: All the technology levels (the constant values) are rescaled to make Firm 2's 1985 technology level equal to 0.

Figure 6. Rescaled Technology Trends Over Time