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DESIGN EVOLUTION USING THE ARTISAN-PATRON MODEL: THE CASE OF AUTOMOBILE EVOLUTION

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ABSTRACT

This paper uses the Artisan-Patron (AP) model to create a transparent framework to analyze how environmental variables such as fuel price, price of steel, and CAFÉ legislation affected the evolution of the automobile (namely horsepower and weight). The analysis and results demonstrates the utility of the AP model as a frame for complex multi-epoch adaptive design problems.

1. INTRODUCTION

This paper uses the Artisan-Patron (AP) model to structure a hypothesized relationship between automotive design parameters, the corporate average fuel economy (CAFÉ) government standard, consumer preferences, fuel price, and the cost of raw materials in the automotive industry. The focus is to demonstrate how the AP model can make the triggers of product adaptation transparent and how the model can be used to forecast the implications of governmental policy upon the design of consumer products.

When government policy is of concern, the automotive product planner’s key question is: How will potential changes in governmental policy influence design decisions and ultimately the commercial performance of future designs. From the policy planner’s point of view, the key question is: What policy can be put in place to reduce the negative externalities that are of main concern without putting the manufacturers out of business. One can see immediately that a gaming relationship develops, where the product planner must balance the costs of not meeting policy guidelines with the need to provide economic return for the firm. As modeling this gaming relationship is relatively rare during social planning and policy development (Simon 1996), a secondary focus of this paper is to show how this might be done analytically through the methods proposed.

The next section gives a selective historical perspective of the automotive industry focusing on the aspects that were deemed relevant to building the aforementioned model. Section 3 gives a brief review of the AP model. Section 4 describes the mathematical formulation and solution technique. Section 5 presents the results and the paper concludes with a section that summarizes the paper and suggests some future extensions.

2. THE AUTOMOTIVE INDUSTRY

The history of the automotive industry is very rich and complex indeed, but for the aim of this paper there are four important historical areas that must be reviewed: automotive government policy regarding vehicle fuel economy, automotive engine technology, the cost of manufacturing automobiles, and the operating costs associated with owning an automobile.

2.1. Governmental Policy

The oil embargo of 1973-1974 tripled the price of crude oil and forced the United States to develop ways to reduce its dependence on foreign oil. As the average new car fleet’s fuel economy dropped from 14.8 miles per gallon (mpg) to 12.9 mpg between the years 1967 and 1974; and with the increasing popularity of the automobile year after year; the automotive industry became an obvious target. The Corporate Average Fuel Economy (CAFÉ) standard, which began in 1978, called for a

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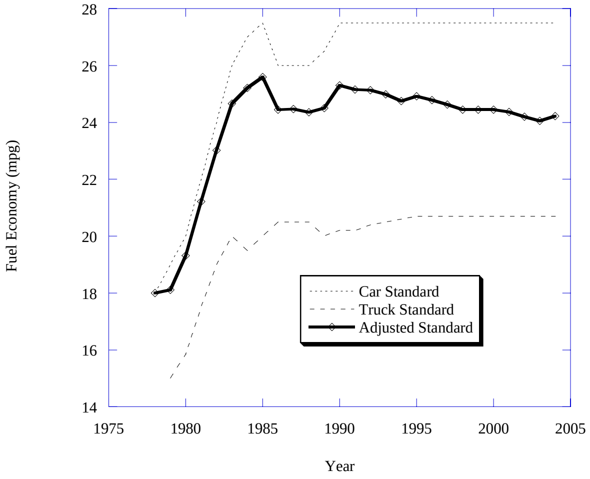
doubling in the new car fleet fuel economy by the year 1985 (27.5 mpg for cars). The yearly progression of the CAFÉ standards for both passenger cars and trucks is shown by Fig. 1. These two standards are combined into a sales-weighted adjusted standard by multiplying the yearly car/truck share by the respective standard. As half of all automobiles sold in 2004 were trucks, the adjusted standard lies in the middle.

Figure 1: Fuel Economy Standards for Passenger Cars and Trucks Model Years 1978-2004[1]



The CAFÉ policy penalty formula, which is multiplied by the total sales of the manufacturer, has remained unchanged since its inception in 1978 and is calculated as follows[2]:

$$c_t^{CAFE} = max\left[0, \rho\left(z_{CAFE,t} - z_{FE,t}\right)\right]$$

where ρ is the penalty ($55) per mpg below standard; $z_{CAFE,t}$ is the sales-weighted adjusted fuel economy standard for the manufacturer's product line mix at time t; and $z_{FE,t}$ is the sales-weighted fleet fuel economy. c_t^{CAFE} The average fuel economy has decreased only slightly since reaching its peak shortly after the enactment of the CAFÉ policy in the early 1980s, which gives support to the assertion that the policy was successful. However, one could also argue that the CAFÉ policy's influence decreased from one year to the next as the average new vehicle fuel economy was at a 15 year low in 2002: 20.91 miles/gallon (mpg). This may be a result of two (likely interacting) phenomena: (1) consumers' willingness-to-pay for competing attributes (such as acceleration or options that add weight) outpaced the influence of the CAFE penalty upon the automotive manufacture; and (2), the real costs of adhering to the CAFÉ standard are decreasing from year-to-year as a result of the penalty (ρ) not keeping pace with inflation.

Recently, more than ever before, the CAFÉ policy has become the target of much criticism from many different advocate groups. In addition, several policy makers claim the policy is short-sighted as it focuses on gasoline solutions rather than supporting the construction of infrastructures that would support alternative fuels (Levin 2003). The Union of Concerned Scientists agrees with this view, but they go further to suggest that alternative technology to reduce fuel consumption would be a major source of job creation and economic growth (Friedman and Mackenzie 2004). Increasing fuel economy (making travel less expensive), however, would likely increase the cost of managing traffic congestion as a result of the increased use of automobiles (Stempeck 2005). In spite of the savings at the pump, the majority of the expense incurred by the manufacturers would most likely get passed on to consumers, according to the Congressional Budget Office[3]. The auto manufactures, on the other hand, argue that making the CAFÉ policy more stringent would create problems with vehicle safety citing a 2001 National Academy of Sciences study, which stated that improvements to efficiency by making vehicles lighter caused between 1,300 and 2,600 more auto fatalities than would have occurred with out the CAFÉ regulation[4].

Other ways to reduce national fuel consumption have been considered such as increase the price of gasoline through taxation, which should have a direct influence on the preference for vehicles with better fuel economy and thereby induce the automotive industry to conform by producing higher-performing vehicles. This proposal was deemed politically unrealistic by a study conducted by the Congressional Budget Office, however, because lawmakers have not been able to garner enough support to increase taxes to fund highway and transit projects that would cost a fifth as much to the consumer as the proposed 46 cent increase that it would take to reduce fuel consumption.

2.2. Engine Technology

Of the American cars built in the year 1900, 1681 were steam powered, 1575 were electrics, and 936 were spark ignition (SI) engines (Nevins 1954). Due to the performance shortcomings of the steam and electric engines[5], the SI engine, in spite of its own shortcomings[6], steadily became the power plant architecture of choice. The SI engine continued to evolve technologically through the first half of the century, albeit very slowly compared to the years following the oil embargo.

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[1] Automotive Fuel Economy Program, Twenty-Third Annual Report to the Congress. U.S. Federal Register, Vol. 64, No. 82, Friday April 29, 1999, pp. 23149-23161

[2] http://www.nhtsa.gov/cars/rules/CAFE/index.htm

[3] http://www.cbo.gov/ftpdocs/49xx/doc4917/12-24-03_CAFE.pdf

[4] Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, (2002) Transportation Research Board, National Academy of Sciences. (http://www.nap.edu/books/0309076013/html/)

[5] The steam engine required a large amount of time to build initial pressure and required frequent stops for water filling. Electric cars were quiet, but were very expensive, had limited range, and were slow.

[6] While the SI engine started promptly, and had a operating radius that was 3x that of the electric and 4x that of steam; it was very loud.

Amann (1986) reasoned that powertrain efficiency is the main indicator of fuel economy (disregarding weight). Powertrain efficiency can then be broken down into driveline efficiency and engine brake thermal efficiency. Improving driveline efficiency is achieved by improving the working relationship between the motor, motor controller, and the transmission. Electronic fuel injection control technology allows precise control of air-fuel ratio. This technology was incorporated into production vehicles beginning in 1978 and continues to evolve by improving volumetric efficiency, which is the actual amount of air the engine ingests compared to the theoretical maximum. Advances in fuel/air mixture technology came with the collective innovations in fuel/air mix control methods (electronic carburetor, single-, and multi-point injection) and control technology (computer algorithms and sensing technology).

Alternatively, there are four ways to increase engine brake thermal efficiency: (1) increase indicated efficiency, (2) reduce mechanical friction, (3) reduce pumping losses, and (4) increase indicated power. Increasing indicated thermal efficiency is traditionally done by increasing compression ratio. Reducing mechanical friction is done through design improvements to piston, rod, rings, valve train, bearing clearances, and oils. Pumping losses can be minimized by increasing the efficiency of oil and coolant pumps. Lastly, indicated power can be maximized by improving breathing (increasing the number of valves per cylinder) or by power boosting (turbocharging).

One can see that there were many different modes for improving the performance of the SI engine and powertrain. The evolution of the SI engine essentially influenced the cost of providing horsepower. This is discussed further in Section 4.1.3.

2.3. Cost of Ownership and Raw Materials

There are many aspects of an automobile that affect its cost of ownership, but the factor that traditionally receives the attention and is often in the mind of the consumer during the purchase decision is the cost of fuel consumption. In a recent survey conducted by *Ward's Dealer Business*[7], 33% of dealers surveyed said that "fuel efficiency outweighed brand, styling, performance, safety and roominess as a consumer buying consideration." Further, "82% of dealers say their customers are more interested in fuel-efficiency and fuel-efficient vehicles than they were a year ago", and "the majority (52%) say they're having a harder time selling SUV's/trucks than a year ago, despite hefty incentives on many of the larger domestics." Although fuel prices reached record levels in 2004, they are still lower than the prices of the late 70's in real terms (See Fig. 2a). Needless to say, consumers are drifting towards more fuel-efficient vehicles as the price of gasoline rises further and further away from the inflation-adjusted lowest gas prices of 1998.

Alternatively, except for a small jump in the late 70's, the adjusted price of steel has steadily decreased to nearly half of its record set in 1978 (See Fig. 2b). The price of steel is an important indicator of vehicle cost as, arguably, between 75-90% of the vehicles total weight comes from steel components[8]. We use this detail later on in the paper.

Figure 2a:
Real vs. Adjusted Average Price of Fuel[9]

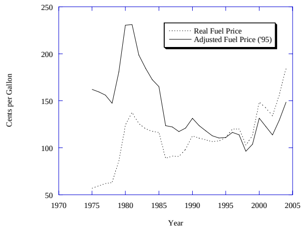
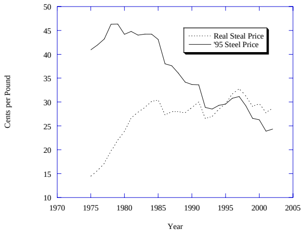


Figure 2b:
Real vs. Adjusted Average Yearly Price of Steel[10]



3. ARTISAN-PATRON MODEL

Wissmann and Yassine (2005) presented the Artisan-Patron (AP) model, which structures several kinds of information: (1) the information needed to aid the Artisan in adapting its artifacts to the changing environment (consumer taste, government policy, cost of raw materials, etc.); (2) the design information that results from the adaptation; (3) the veritable product performance; and (4) the consumer response that serves as feedback for the next adaptive iteration. The model is based on the notion that artifacts are rarely forged based upon a design that does not evolve as a consequence of a changing environment (Simon 1996, Petroski 1992, 2003). Furthermore, the AP model is intended to be a framework for the information that influences artifact change, which helps artisans manage complexity and make better decisions in highly competitive markets. The authors showed how design can be viewed as a multi-epoch effort to adapt artifacts, which is performed by an Artisan who strives to maximize his reward. The reward is determined by Patrons, who place a value upon the artisan's artifact and choose to purchase based on how that value relates to price. If value is greater than price, the Patron will be induced to make the transaction. The Artisan then uses the Patron's response as feedback to help improve the artifact's future design.

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[7] *Ward's Dealer Business* (2004). High Fuel Prices Show Effects in Showrooms. Sept. 1, p. 9.

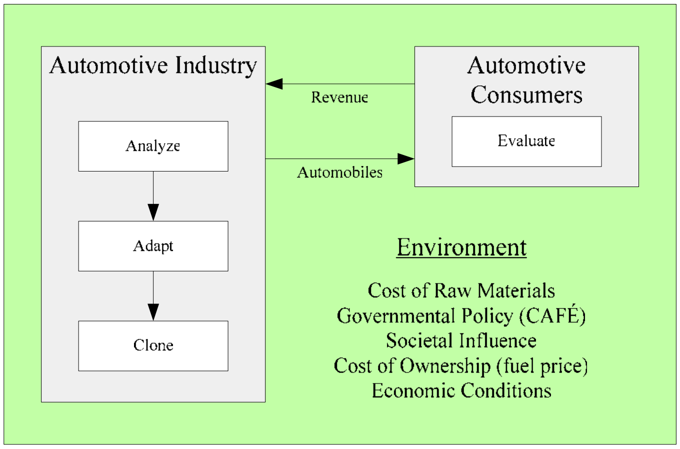
[8] See Tbl. A1 in Appendix.

[9] History: Gasoline Prices: Bureau of LaborStatistics (BLS) survey prices: 1919-1979 leaded regular; 1980-1981: unleaded regular; 1982-1994: Energy Information Administration (EIA) data extrapolated using BLS survey data; 1995-current: EIA Survey. Real (inflation adjusted prices) price data is deflated by the Consumer Price Index, source BLS, where year 1995 = 1. Forecast 2004-2005: Gasoline prices, current Short-Term Energy Outlook (STEO). Forecasted Consumer Price Index, Global Insight.

[10] http://minerals.usgs.gov/minerals/pubs/of01-006/ironandsteel.pdf

Figure 3 shows the relationship between the automotive industry and consumers through the lens of the AP model, as well as what environmental factors are considered by the current study. Although the designs were indeed replicated, the analysis discussed in the next sections assumes that the automobiles were manufactured as designed (no variance was introduced while executing the cloning task).

Figure 3: The Automotive System using the AP Model



4. MODEL FORMULATION

Although several simplifying assumptions must be made, the evolution and adaptation of the aggregate automotive design (in terms of horsepower and weight) as a result of several environmental factors such as the CAFÉ policy and price of gasoline, can be modeled using the AP model. The aspect that makes this possible is that the automobile's power plant has been dominated by a single architecture—the spark ignition (SI) engine. Although there are many different designs of SI engines and the automobile has had many architectural changes throughout its many subsystems, the data suggests that vehicle aggregate horsepower (x_1) and weight (x_2) can be used to predict both aggregate fuel economy and the time it takes to accelerate the vehicle from rest to 60 miles/hr (mph). As weight negatively influences both fuel economy and acceleration time, an attribute had to be found that would "keep weight in". This was done by finding a relation between vehicle weight and safety. All other ideas for "keeping weight in", such as additional styling, features and/or options, introduced other confounding attributes. Therefore, we assume that there are three critical-to-value attributes (CVAs) upon which the automotive consumer bases his/her purchase decision, which can be explained by hoarsepower and weight: fuel economy (*fe*), 0-60 mph acceleration time (*at*), and a measure of safety which is related to the fatality rate in two-car crashes (*sf*). The present work further assumes that the design parameter setting decisions were influenced by only a few environmental variables: price of steel, price of fuel at the pump, unemployment rate, CAFÉ policy, and inflation.

Simplifying assumptions were also made regarding market structure, namely that entire automotive industry can be represented by six manufacturers who compete with homogeneous products. This level of aggregation was thought appropriate because the interest was in understanding how the automotive industry as a whole reacted to changes in the environment versus the reactions of a single player. Many of the "orthodox" economic theory assumptions, such as unbounded rationality, profit maximization, and the notion of equilibrium (transient) where also posited.

4.1. The Analysis Task

During the analysis task, the Artisan attempts to discern how other entities, called Patrons, determine their reward structure for the Artisan's artifacts and how relevant environmental factors will affect design decisions. The next sections describe the value model used, the critical to value attributes posited, and what factors influence vehicle cost.

4.1.1. Value Model

The value of any proposed product is calculated by (Cook 1997): (1) translating all continuous critical-to-value attributes responses into value coefficients $v(z_1)$, $v(z_2)$, $v(z_3)$,…, $v(g_j)$; and (2) multiplying those coefficients by the baseline value of the product, V_0 , as shown by Eq. (1).

$$V_{New} = V_0\, v(z_1)\, v(z_2)\, v(z_3)\dots v(z_a) \qquad (1)$$

V_{New} is the price at which the probability of consumer purchase goes to zero. V_0 is the value of the baseline vehicle, which for this study is the average vehicle of 1995 (car and truck). The value at the cartel point can be calculated using $V_0 = \bar{p}_0\left(\frac{\eta_0 + 1}{\eta_0}\right)$,

Where η_0 is the price elasticity of demand[11], and $\bar{p}_0$ is the average price at the reference point. The general form for the value coefficient is

$$v_{a,t} = \left[\frac{(z_{a,I} - z_{a,C})^2 - (z_{a,I} - \hat{z}_a)^2}{(z_{a,I} - z_{a,C})^2 - (z_{a,I} - z_{a,0})^2}\right]^{\gamma} \qquad (2)$$

where $z_{a,I}$ is the ideal attribute setting where the consumer is unwilling to pay for further improvement, $z_{a,C}$ is the critical setting where the consumer is unwilling to purchase the product even if all other attributes are at an ideal setting, $z_{a,0}$ is the attribute setting of the baseline product, and $\hat{z}_a$ is the forecasted attribute performance of a particular design.

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[11] Products with high elasticities ($\eta > 1$) are often called luxuries, whereas those with small elasticities ($\eta < 1$) are called necessities. Donndelinger and Cook (1997) determined that η was approximately unity for automobiles. We determined that a value of $\eta = 1.2$ gave better results at the baseline year.

4.1.2. Critical-to-Value Attributes and Design Variables

There are possibly thousands of critical-to-value (CVA) attributes to the automotive consumer, which can be broken down into several levels depending on their specificity. The high level attributes might be accessibility, comfort, aesthetics, handling dynamics, externalities, packaging, powertrain, quality, and safety. The second level attributes of externalities might be fuel economy/emissions (FE/E), vehicle life cycle, and general; whereas the third level of fuel economy/emissions may be specified as city fuel economy, highway fuel economy, CO_2, NO_x, and so on.

As the focus of this paper to investigate how governmental policy affects automobile design, fuel economy is an obvious attribute to include in the study, but it can not be the only attribute studied. Designing an automobile, just as designing any product, is an act of satisficing and therefore the attributes that will be affected as design parameters change must also be included in the study. As shown later in section 4.2.1, there are two design variables that can be used to successfully forecast fuel economy: horsepower and weight. Changing the weight and horsepower, however, also influences the acceleration and top speed performance of the automobile. For all three attributes, more horsepower and less weight improve performance. We chose to use the time to accelerate to 60 mph from rest as the representative attribute for all acceleration. As top speed is a very rarely experienced attribute (i.e. its $\gamma \approx 0$), we assumed it is not a CVA.

The amount of horsepower that an engine can produce is limited by the increasing cost of providing it (technological constraints). Weight, however, is not “kept-in” in the same manner as cost decreases with weight. As weight is not something directly experienced by the consumers as in the case of laptop computers, mp3 players, or cell phones for example; weight cannot be a CVA. Therefore, there must be at least one CVA that explains why weight might be desired. After much consideration, it was decided that fatality rate in two car collisions would be an excellent way to make the connection. Indeed, a 1998 report issued by the Insurance Institute for Highway Safety[12] provides clear evidence that automobile weight is related to fatality rates in two car collisions.

Table 1 summaries the parameter assumptions for the aforementioned CVA value curves (Eq. 2).

Table 1: Value Curve Parameters for the CVAs[13]

Attribute	***Baseline***	***Ideal***	***Critical***	γ
fe(mpg)	21.9	$\beta_{4,t}$	0.5	$\beta_{5,t}$
at(sec.)[14]	11.3	1.5	40	0.17
sf (deaths per mil. vehicles)	47	0	150	$\beta_{6,t}$

4.1.3. Vehicle Cost Model

Total variable cost is decomposed into two components: cost as a function of overall automobile weight and cost associated with delivering a given level of engine horsepower. The cost as a function of weight is based on the assumption that the vast majority of the automobile are constructed from steel and that the assembled vehicle cost can be modeled as a multiple of the yearly price of steel. The multiples used within our model give results that are consistent with a comparative study conducted by the Argonne National Laboratory (Vyas et al. 2000). The variable cost of an automobile as a function of weight is assumed to adhere to the following relationship: $\hat{c}_t^{weight} = \beta_{3,t} x_{2,t}$.

The general form for the cost function associated with providing horsepower comes from previously published results that studied the wholesale price of engines as a function engine power (Michalek et al. 2004). Changes in engine technology within the framework of this paper are captured by the cost of delivering horsepower. Two points about the cost of delivering technology are clear: first, pace of innovation follows an S-curve form; and second, there are discontinuous jumps when the underlying architecture is changed (usually the cost goes up). The assumptions that are fed into the current model regarding engine cost are summarized within Tbl. A3 in the Appendix. The formula used to capture the cost of providing horsepower is $\hat{c}_t^{engine} = \beta_{1,t} e^{\beta_{2,t} x_{1,t}}$.

Total variable cost is therefore: $\hat{c}_t^V = \hat{c}_t^{weight} + \hat{c}_t^{engine}$.

4.2. The Adaptation Task

With all the analysis complete, the Artisan is now has all the information that is needed to make trade-off decisions in his design. During the adaptation task, the Artisan must first link design parameters to CVAs, and second, satisfice between patron value, the cost incurred to produce the artifact, and other constraints imposed by the environment.

In this section, we describe the methods used to achieve the transfer functions, we describe the single-epoch design model, and the demand, price, and profit models.

4.2.1. Transfer Functions

Transfer Functions are created to link design variables (**x**) to product performance attributes (**z**). Although sophisticated analytical tools, such as ADVISOR (Markel et al. 2002), have been shown to be quite adept engineering models for use in the automotive industry when alternative engine architectures

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[12] Insurance Institute for Highway Safety (1998). New Study of Relationships between Vehicle Weight and Occupant Death Rates Helps Put in Perspective Issue of Crash Compatibility. Highway Loss Data Institute. (http://www.hwysafety.org/news_releases/1998/pr021098.htm).

[13] β's are discussed thoroughly in Tbl. A3 in the Appendix

[14] McConville and Cook (1996).

needed to be considered, two simple regression models from historical data proved to be adequate for forecasting fuel economy (*fe*) and 0-60 acceleration time (*at*) from horsepower (x_1) and weight (x_2). The data used came from an annual published report by the Environmental Protection Agency[15] (EPA) that summarizes key industry-wide automobile performance measures. The transfer functions are $\hat{z}_{fe,t} = \alpha_{fe,1} + \alpha_{fe,2} x_{1,t} + \alpha_{fe,3} x_{1,t}$ and $\hat{z}_{at,t} = \alpha_{at,1} + \alpha_{at,2} x_{1,t} + \alpha_{at,3} x_{1,t}$ for fuel economy and 0-60 acceleration time respectively. The transfer functions are assumed to remain valid so long as the SI engine is the dominant architecture, which is the case over the time period under analysis.

The model used to link weight to fatality rate comes from a report produced by the *Insurance Institute for Highway Safety* that links automobile weight to passenger fatality rates in two car collisions (*sf*).[16] The aggregation of car, truck and van data yielded the following transfer function: $\hat{z}_{sf,t} = \alpha_{sf,1} + \alpha_{sf,2} x_{2,t} + \alpha_{sf,3} x_{2,t}^2$. The numeric values for the α parameters and R^2 values for all three engineering models are reported in Tbl. A2 in the Appendix.

4.2.2. The Single-Epoch Design Model

With each passing year, the automotive industry was forced to assess how it should modify its design in response to its changing environment. There are at least two factors that limit its ability to produce what might be thought of as an optimal design—bounded rationality and technological limits. The automotive industry knew its environment was changing to be sure, but it was unable to know exactly how with certainty, so the vehicle designers needed to make predictions using hard won knowledge and how indicators that may signal changes in the future—feedback *and* feedforward. Actually, even if they knew exactly what the optimum design should be, costs are always too high to provide that optimum, and therefore tradeoffs were made.

Figure 4 shows the posited automotive industry's yearly design adaptation model. The boxes with bold boarders designate the dynamic factors considered within this study that forced the automotive industry to adapt year after year.

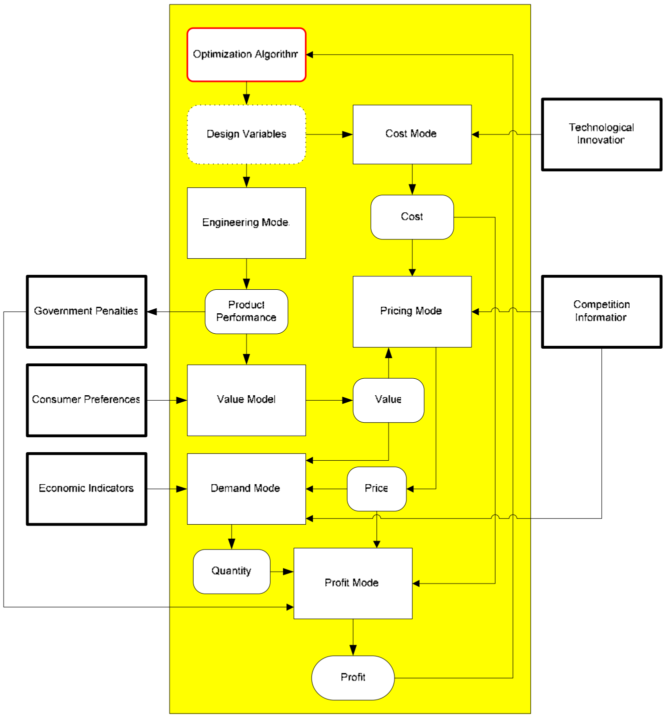

Figure 4: Single-Epoch Design Model

4.2.3. Demand Model

The S-model demand function is used here as it is exact in the limit of small departures in price, value and demand. The fundamental assumption of the S-model is that the demand for a product *i* is an analytic function of the values and prices of the *N* competing products that make up a market segment. Cook (1997) offered Eq. 3 as a hyper-plane approximation to the actual demand surface for a single competitor *i* among *N* total competitors in the market.

$$D_i = K\left[V_i - p_i - N^{-1}\sum_{j\neq i}\left(V_j - p_j\right)\right] \tag{3}$$

The constant K is the negative slope of the demand curve for the market segment of interest and is defined mathematically by the phenomenological measures of total market demand, $D_{T,0}$; elasticity of demand, η_t; and average price, $\bar{p}_0$; at the reference state as follows:

$$K_t = \frac{\eta_t D_{T,0}}{\bar{p}_0} \tag{4}$$

As we are interested in the aggregate demand of the entire automobile market, Eq. 3 can be simplified to $D_{T,t} = K_t\left(\bar{V}_t - \bar{p}_t\right)$, where $\bar{V}_t$ and $\bar{p}_t$ are the estimated average value and price of the products for each time period *t*.

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[15] Hellman, K.H. and R.M. Heavenrich (2004). Light-Duty Automotive Technology and Fuel Economy Trends: 1975-2004. EPA—United States Environmental Protection Agency (Office of Transportation and Air Quality). April, EPA420-R-04-001

[16] Insurance Institute for Highway Safety (1998). New Study of Relationships between Vehicle Weight and Occupant Death Rates Helps Put in Perspective Issue of Crash Compatibility. Highway Loss Data Institute. (http://www.hwysafety.org/news_releases/1998/pr021098.htm).

4.2.4. Pricing and Profit Models

The pricing model is used to forecast the manufacture's pricing strategy to aid in cash-flow projections. This price is the seller-posted price (MSRP) and does not consider one-on-one haggling. The pricing model used here is the well known result of a Cournot game amongst homogeneous competitors in value and cost (Pashigian 1995):

$$\bar{p}_t = \frac{\bar{V}_t + N\hat{c}_t^V}{N+1}.$$

Once again, as it is the overall industry that is being considered and not a single competitor, the analysis can be made using the industry average value and cost. The number of competitors, *N*, is taken to be six for the entire time period under study.

As the profit of interest is that of the industry without fixed cost or investment, it can be formulated as

$$\Pi_t = \hat{D}_t\left(\hat{p}_t - \hat{c}_t^V - \hat{c}_t^{CAFE}\right).$$

4.2.5. Design Satisficing Technique

Bringing the historical data together with the mathematical models presented throughout Section 4, we now have a mathematical framework to model how the automotive industry chose to evolve the average automobile. This framework[17], in its entirety, links profit to the design variables and yields a discontinuous, non-linear solution space. This is shown by Figures 5a and 5b, the solution spaces for 1977 and 1995 respectively. The solution space is discontinuous due to the value-coefficient functions that force value to zero (which incidentally forces profit to zero) when a critical attribute level has been breached. Any constrained non-linear optimization technique such as genetic algorithms or even Solver in Excel can easily find the optimum solution to this system.

Figure 5a:1977 Solution Space (Before CAFE Policy)

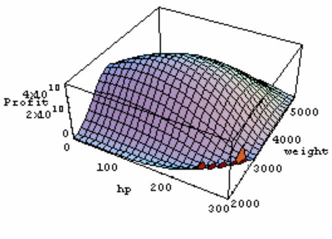
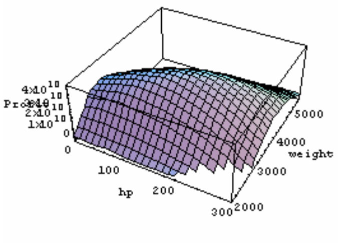


Figure 5b:1995 Solution Space (With CAFE Policy)



The complete mathematical model is as follows:

Max: $D_{T,t}\left(\hat{p}_t - \hat{c}_t^V - \hat{c}_t^{CAFE}\right)$

wrt: $\mathbf{x}_t = \left\langle x_{1,t}, x_{2,t} \right\rangle$

st: $0 \le x_{1,t} \le 400$

$$1000 \le x_{2,t} \le 6000$$

$$D_{T,t} = K_t\left(\bar{V}_t - \bar{p}_t\right)$$

$$K_t = \frac{D_{T,0}\hat{\eta}_t}{\bar{p}_0}$$

$$\bar{p}_t = \frac{\bar{V}_t + N\hat{c}_t^V}{N+1}$$

$$\bar{V}_t = v_{fe,t} v_{(0-60),t} v_{sf,t} V_0$$

$$\hat{c}_t^V = \hat{c}_t^{weight} + \hat{c}_t^{engine}$$

$$\hat{c}_t^{engine} = \beta_{1,t} e^{\beta_{2,t} x_{1,t}}$$

$$\hat{c}_t^{weight} = \beta_{3,t} x_{2,t}$$

$$v_{fe,t} = \left[\frac{\left(\beta_{4,t} - z_{fe,C}\right)^2 - \left(\beta_{4,t} - \hat{z}_{fe}\right)^2}{\left(\beta_{4,t} - z_{fe,C}\right)^2 - \left(\beta_{4,t} - z_{fe,0}\right)^2}\right]^{\beta_{5,t}}$$

$$v_{a,t} = \left[\frac{\left(z_{at,I} - z_{at,C}\right)^2 - \left(z_{at,I} - \hat{z}_{at}\right)^2}{\left(z_{at,I} - g_{at,C}\right)^2 - \left(z_{at,I} - z_{at,0}\right)^2}\right]^{\gamma_{at}}$$

$$v_{sf,t} = \left[\frac{\left(z_{sf,I} - z_{sf,C}\right)^2 - \left(z_{sf,I} - \hat{z}_{sf}\right)^2}{\left(z_{sf,I} - z_{sf,C}\right)^2 - \left(z_{sf,I} - z_{sf,0}\right)^2}\right]^{\beta_{6,t}}$$

$$\hat{z}_{fe,t} = \alpha_{fe,1} + \alpha_{fe,2} x_{1,t} + \alpha_{fe,3} x_{2,t}$$

$$\hat{z}_{at,t} = \alpha_{at,1} + \alpha_{at,2} x_{1,t} + \alpha_{at,3} x_{2,t}$$

$$\hat{z}_{sf,t} = \alpha_{sf,1} + \alpha_{sf,2} x_{2,t} + \alpha_{sf,3} x_{2,t}^2$$

$$c_t^{CAFE} = max\left[0, \beta_{7,t}\left(z_{CAFE,t} - z_{fe,t}\right)\right]$$

$$\hat{\eta}_t = \beta_{8,t}\eta_0{}^{*}$$

5. RESULTS

Although the goal was to analyze the implications of environmental variables on the evolution of the automobile, we believed that the model should not only be able to forecast the design parameters, but also give reasonable forecasts of the intermediate variables. Therefore, as the outputs were analyzed, a reflective mode of inquiry was taken, which promoted rigor and exposed several hidden assumptions, which will be discussed in turn.

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[17] Explanation of β's is located in Tbl. A3

[*] η_0 is assumed to be 1.2 for the base year of 1995

Figures 6a and 6b show the results of horsepower and weight forecasts, respectively. Both forecasts yield an acceptable R^2 value, which indicates a decent fit between the data.

Figure 6a: Forecasted vs. Historical Horsepower (R^2 =0.919)

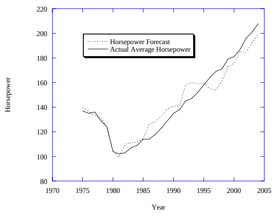
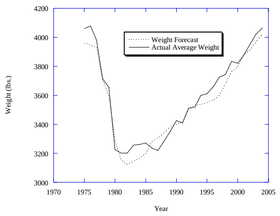


Figure 6b: Forecasted vs. Historical Weight (R^2 =0.943)



Figures 7a and 7b show the forecasted versus historical values for fuel economy and 0-60 acceleration time, respectively. The fits for fuel economy and acceleration are not as good as they were for the design parameters, but they are adequate.

Figure 7a: Forecasted vs. Historical Fuel Economy (R^2 =0.854)

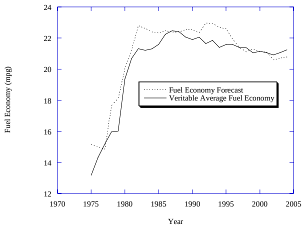
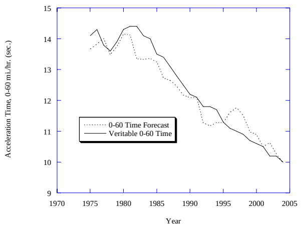


Figure 7b: Forecasted vs. Historical 0-60 Accel. time (R^2 =0.873)



Although motor vehicle fatality data is published by the National Safety Council, it is not measured in the same way as metric derived through regression, so direct comparison is difficult. Even if data was available, there would be fit problems for several reasons. First, we did not account for innovation in safety, but rather assumed that the technology was the same for all years as it was in 1995, from where the transfer function came from. Second, we did not account for legislation changes that may have influenced technology. Indeed, upon investigation, it was found that airbag legislation was introduced by the Carter presidential administration, revoked by the Regan administration, and reinstated by the first Bush administration. Lastly, as mentioned earlier, safety is not the only attribute that puts weight in vehicles (consumers may like roomier vehicles that seat more passengers).

Figures 8a and 8b show the forecasted versus historical demand and price, respectively. The fit here is not as good as the other variables, but close inspection shows that the forecasts mimic the trends. Looking at the equations for demand and price reveals that small errors in the input variables may be the cause for the disparity.

Figure 8a: Forecasted vs. Historical Demand(R^2 =0.465)

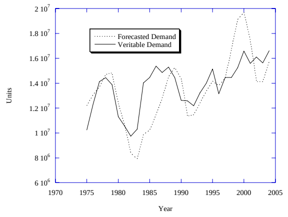
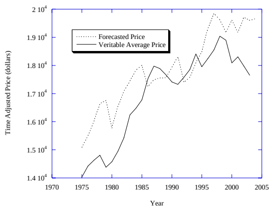
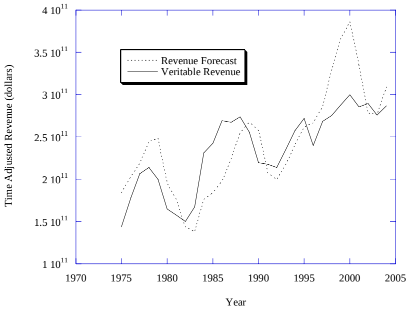


Figure 8b: Forecasted vs. Historical Price (R^2 =0.419)



Amazingly, the forecasted automotive industry revenue fits the historical data with more precision than the input variables as shown in Fig. 9. The large forecast error during the late 90's is largely due to overly optimistic demand and price forecasts.

Figure 9: Forecasted vs. Historic Automotive Industry Revenue (R^2 =0.597)



The model's forecasts of CAFÉ penalties paid to the government are severely inflated, which can be explained by the following three points: (1) automobile manufacturers receive credits for outperforming the standard that can be used to offset future penalties; (2) there are caps upon the yearly penalty that must be paid; and (3) manufacturers my petition to have the penalties waved if it can be shown that they will force them out of business.

6. DISCUSSION

The focus of this paper was to demonstrate how the AP model can be used to frame the product planning and design problem. In this paper, we used value functions of the form suggested by Cook (1997) to allow us to estimate the value automotive consumers placed on vehicles over time. This value function, along with other important data used to capture the dynamic environment enabled the use of an optimizing framework that posited a transient equilibrium. The results indicate that there is a good match between the forecasted and historical data. In the absence of clairvoyance, these results are seen as satisfactory.

The model is not perfect, however. Several gratuitous assumptions were made, the largest being that the death rate in two-car collisions is what keeps weight in the vehicle. This is obviously an egregious assumption. Nevertheless, it allowed modeling to progress. If this paper's goal was to attach or make recommendations regarding CAFÉ legislation, this would be a problem. But as the goal was simply to apply the AP model to a complex real world situation, we posited the aforementioned assumption and marched on.

As the automotive industry is arguably in the process of active experimentation with alternative power plant architectures, using the analytic approach of the this paper to forecast the future weight and horsepower of vehicles in response to CAFÉ legislation changes would be spurious. Nevertheless, as long as the modeling assumptions did not oversimplify, the framework here might still be useful.

One can see through this model, however, that it is difficult to forecast how a change in any single factor will change industry behavior due to the "gaming" behavior of the designer. For example, if gas prices would have stayed constant and high after the OPEC embargo in 1978 it would have influenced the preference for fuel economy for sure, but it would have also influenced technological innovation (the cost for horsepower) and the consumer's maximum willingness-to-pay. Alternatively, if governmental policy would have adjusted the CAFÉ penalty to account for inflation or made the CAFÉ standard more stringent, there is evidence that this would have also influenced technological innovation, but consumer preferences would remain unchanged.

Future research should focus on how to represent and model the information that flows through the AP model to aid the Artisan in the product adaptation process. An agreed upon value functions elicitation method that can be used by designers has yet to gain wide-spread acceptance by the field. Nor has a method for selecting among design alternatives (Hazelrigg 2003).

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APPENDIX

Table A1: Weight Distribution in the Ford Taurus[18]

System/Subsystem	***Weight***	***Percentage***		***System/Subsystem***	***Weight***	***Percentage***
Body-in-White	826	25.5		Transmission	134	4.1
Hinges, locks, gauges, etc.	33	1.0		Clutch and controls	7	0.2
Body electronics	23	0.7		Final drive	110	3.4
Moldings/ornaments	30	0.9		***Total Transmission System***	251	7.7
Trim/insulation/seals	207	6.4		***Total Powertrain***	1010	31.1
Seats	107	3.3				
Glass	81	2.5		Frame	99	3.1
Radio, lighter, mirrors, etc.	21	0.7		Suspension	153	4.7
Paint/coatings	10	0.3		Steering	60	1.8
Total Body	1338	41.2		Brakes	154	4.7
				Wheels/tires/tools	181	6.6
Base engine	444	13.7		Fender shields/bumpers	90	2.8
Engine accessories	160	4.9		Chassis electronics	41	1.3
Engine electronics	38	1.2		Accessories	4	0.1
Emission controls	30	0.9		***Total Chassis***	782	24.1
Fuel storage system	24	0.7				
Exhaust system	33	1.0		Fluids	115	3.5
Catalytic converter	30	0.9				
Total Engine System	759	23.4		***Total Vehicle***	3245	100

Table A2: Attribute Forecasting Parameters

	fe	***at***	***sf***
$\alpha_{z,1}$	51.35326	12.0636	339.059
$\alpha_{z,2}$	0.107276	-0.0649	-0.13184
$\alpha_{z,3}$	-0.01292	0.002694716	1.42479×10^{-5}
R^2	0.949	0.978	0.943

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[18] Advanced Automotive Technology: Visions of a Super-Efficient Family Car (1995). Office of Technology Assessment, OTA-ETI-638: GPO stock #052-003-01440-8 (http://www.wws.princeton.edu/cgibin/byteserv.prl/~ota/disk1/1995/9514/9514.PDF)

Table A3: Time Dependent Model Parameters

	Description	Assumptions and Comments	Mathematical Formulation
$\beta_{1,t}$	Parameter of engine cost		$\beta_{1,t} = 2000(Adj.\,PriceSteel_t)$
$\beta_{2,t}$	Exponential parameter of engine cost	Technological progress was slow in the beginning, innovation was more rapid throughout the 80's and early 90's and slowed over the next decade.	$\beta_{2,t} = \begin{cases} 0.011 & 1975-1977 \\ 0.011(0.99)^{Y-1977} & 1978-1980 \\ 0.00918(1.02)^{1995-Y} & 1981-1995 \\ 0.00918(0.99)^{Y-1995} & 1996-2004 \end{cases}$
$\beta_{3,t}$	Cost of automobile raw materials per pound	Translates to 10x the real price of steel per pound in year *t*	$\beta_{3,t} = 10^* \, (Real\ Price\ of\ Steal_{\ t})$
$\beta_{4,t}$	Ideal fuel economy	Obviously more is better, but here we make the assumption that there exists a fuel economy that, on average, the consumer will not be willing to pay more even if all other attributes were ideal.	$\beta_{4,t} = \begin{cases} 26 & 1975-1981 \\ 26 * (0.995)^{Y-1989} & 1982-2004 \end{cases}$
$\beta_{5,t}$	Preference for fuel economy	The desirability of fuel economy will be related to the price of gas	$\beta_{5,t} = \frac{Adj.Fuel\,Price_t}{10}$
$\beta_{6,t}$	Preference for safety and features		$\beta_{6,t} = \begin{cases} 1.7 & 1975-1977 \\ 1.25 & 1978 \\ 1 & 1979 \\ 0.82(0.97)^{1995-Y} & 1980-1995 \\ 0.82(1.09)^{2004-Y} & 1996-2004 \end{cases}$
$\beta_{7,t}$	Time adjusted CAFÉ penalty	The CAFÉ penalty has been the same since 1978–$55/gal./vehicle.	$\beta_{7,t} = \frac{\$55}{CPI_t^{1995}}$
$\beta_{8,t}$	Multiple to account for economic fluctuation	We assume an inverse relationship between the yearly average unemployment rate (u_t) and aggregate automotive demand.[19] The 6.78 factor makes $\eta_0 = 1.2$ in 1995.	$\beta_{8,t} = \frac{6.78}{u_t}$

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[19] U.S. Department of Labor, Bureau of Labor Statistics