A NEW APPROACH TO MODELING LARGE-SCALE ALTERNATIVE FUEL AND VEHICLE TRANSITIONS

by

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Abstract

A large-scale transition to alternative fuels and vehicles will be challenging. New modeling approaches are necessary to supplement existing models, such as MARKAL. One promising approach is simulation gaming. Simulation gaming has been used extensively in many fields, most conspicuously in military applications, to provide insights into the dynamics of uncertain processes. A large-scale alternative fuel and vehicle transition themed game was developed to explore the potential of this approach. Preliminary results of game play suggest a possible counter-intuitive dynamic: high energy prices can discourage wide scale adoption of alternative fueled vehicles due to the fact that increased fuel costs reduce consumers' ability to pay for more costly alternative vehicle technologies.

Introduction

A major transition to alternative fuels and vehicles must be undertaken if we are to drastically reduce GHG emissions and oil dependence. New fuels including electricity, hydrogen, and biofuels will have to achieve mass-market acceptance and capacity along with their corresponding drivetrains. The LDV segment has been petroleum fueled from practically the beginning of the 20th century. A massive inertia of infrastructure and ingrained habit surrounding conventional internal combustion drivetrains must be overcome; an industrial transformation on a scale that has never before been attempted.

[FIGURE 1]

The scope and complexity of the transition objectives (Figure 1) requires new modeling approaches. Models like MARKAL, TAFV and HyTrans *(1–3)* have been used in prior analyses, but are limited by their initial assumption sets; the output of these models is a deterministic extrapolation of their input assumptions. What these approaches lack is the ability to consider market interaction and dynamics. In the real world we see competitive strategies in business-based decision-making. Understanding these decision-making strategies is important for developing effective policies that support the transition.

To explore these transitions within a dynamic context we have developed a simulation game. Simulation games have been used for exploring problems that feature high degrees of uncertainty, most notably by the military (i.e. “war games”). Our game simulates a three-sided market of vehicle producers, fuel producers, and consumers. Working within an energy and policy scenario, players make decisions about how to manage their businesses and vehicle purchases. The game provides insights into possible dynamics and outcomes that diverge unpredictably from the input assumptions, unlike in numerical models.

Transition Challenge

The challenges of a large-scale alternative fuel transition are many. A number of systems that are complex in their own rights must be synchronized for an effective transition to occur. The transition as a whole will only be as effective as its weakest link. At the core of the system is the vehicle and fuel market itself.

Vehicle producers (VP), fuel producers (FP), and consumers must all be ready to support a new vehicle technology at a common level. A large commitment by either vehicle producers or fuel producers to a technology that is not supported by the complementary producer is doomed. But even if the producers are fully coordinated, the release will still fail if the consumer is unable or unwilling to support the product at the planned production level.

In Figure 2 a pair of scenarios are shown that illustrate the coordination factors involved in a successful vehicle technology release. The consumer *high demand* scenario works out well for the producers if they coordinate their production outputs at either *low* or *high* volumes. But if one producer goes *low* while the other goes *high* the more ambitious producer is penalized, as the low production by the complementing producer limits the sales potential of the high volume producer.

In the consumer *low demand* scenario the release is only successful for the producers if they both predict low sales volumes. If they both prepare for high volume , they will be disappointed by the market size, and similar problems will arise if they split their outputs levels between high and low.

[FIGURE 2]

The optimizing decision, in terms of risk, for this set is for low volume production by both vehicle and fuel producers, as only high volume choices lead to risk. For an alternative vehicle technology to have high impact there must be some coordinating mechanism that pushes all of the parties into the high volume category, otherwise the prospect of a large and costly failure will deadlock the producers into low risk strategies.

New Vehicle Technologies: Many Ways to Fail, Only One to Succeed

For a new vehicle technology, such as hydrogen fuel cell vehicles or plug-in electric hybrids, a number of factors must be coordinated to align in a supportive and reinforcing pattern (Figure 3). Failure of the technology could come from any number of directions.

Firstly, the technology must be genuinely market mature before it is launched. A new technology cannot be perceived as shoddy or dangerous. Internal combustion engine (ICE) vehicles have been perfected over more than a century. New vehicle technologies will be competing with a high standard in terms of cost, durability, and safety. If the new technology cannot achieve a safety and reliability level on a similar scale to the ICE it will not be adopted, given that the ICE is still an option.

Not only must the new technology be comparable to the ICE on a maturity level, it must make economic sense to consumers. Consumers will pay more for an alternative vehicle if they feel the feature set is worth the additional money. That feature set will include likely savings from increased fuel efficiency and perhaps tax incentives, but it may also include other important features whose values cannot be directly enumerated. Part of what people consider when they buy a new car is the statement the vehicle makes about them*(4, 5)*. Part of the success of the Toyota Prius, for example, is explained by the fact that like an SUV or a sports car it is a vehicle that makes a statement about the driver *(6, 7)*. Consumers will pay a premium for the right sorts of statements whether it be sneakers or cars. However, when hybrid drives are quietly folded into a conventional car line as an option, like on the Honda Civic, the statement is buried.

Next, the fuel for the new vehicle must be available in an adequate supply. There must be enough refueling stations that the buyer feels assured that their will be fuel where he wants it, and at a fair price*(8)*. Buyers will not adopt a vehicle that will be difficult or expensive to refuel.

[FIGURE 3]

Finally, after the issues of technology maturity, cost, and fuel availability are resolved, you must have a vehicle that the consumer will accept. Conventional ICE vehicles are inexpensive, easily refueled, have a long range, and are familiar. It is generally expected that conventional ICEs will be less costly than alternative vehicles *(9)*. Alternative vehicles will have to at least match the expectations that consumers have for a conventional vehicle, or they will not adopt it.

Literature Review

Simulation gaming as a tool for strategic planning has its roots in military applications. War-fighting is inherently chaotic and uncertain. Strategists discovered that pre-staging expected conflicts could reveal important information on how an actual conflict might play out. The competitive nature of the games encourages thoughtful decision-making by the players, as it is a chance to demonstrate their abilities and gain status. Ideas tested in a competitive framework can be more robust than those developed using insular processes *(10–12)*.

The use of simulation games for non-military applications began in the 1950's. Clark Abt, an early pioneer, argues that the games are a powerful tool for strategic introspection because they integrate a variety of intelligences: intellectual, emotional, and physical*(13)*. Many simulation games have been developed to explore infrastructure related questions. *Games in a World of Infrastructures (14)* covers games on a wide variety of topics including telecom, electricity deregulation, water management, and construction.

There were no known specific games about alternative fuel and vehicle transitions when we began this project. There are, however, a number of energy related games. *PowerPlay (15)*, for one, explores the relationship between the appliance market, electricity producers, and energy efficiency programs. One of *PowerPlay's* primary revelations was that subsidies for energy efficiency appliances can actually cause poor consumers to end up subsidizing the purchases of wealthy consumers: a functional example of how policy can often have unintended consequences.

Infrastratego *(16)* was developed in the Netherlands in the mid-1990's to explore electricity deregulation. It is a large game, designed for 40-50 players. It was designed to reveal strategic patterns that might occur in the implementation of the *Electriceitswet* (Electricity Act) of 1998, which liberalized the electricity market in the Netherlands. The conventional wisdom of the 1990's was that opening electricity markets to greater competition was the next evolutionary step for the industry*(17)*. The Infrastratego analysis accurately forecasted many problems that emerged in the actual transition.

UTILITIES 21 is almost identical to Infrastratego in theme(18). It is a large game, designed for 20-60 players and a two-day play session. Players take on the roles of electricity retailers, generators and consumers within a dynamic electricity market. The macromodel for UTILITIES 21 was based on the FOSSIL 2 model (19) used for the US national energy plans by the DOE from 1978-1996. Like Infrastratego, UTILITIES 21 based analyses found that electricity market deregulation was ripe for exploitation.

Research Questions and Objectives

To explore the potential value of serious games as a tool for improving alternative fuel and vehicle transition policies we designed and built a game. The game was designed with the following questions and objectives in mind:

Research questions:

- *Is it possible to design a serious game to model alternative fuel/vehicle transition?*
- *How can we model the behavior, decisions and interactions of different players in the market (consumers, vehicle manufacturers, fuel producers)?*
- *What sorts of insights can the system offer about the automotive vehicle and fuel market transitions?*
- *What sorts of insights can the system offer about specific policies such as the 2025 CAFE standard or economic trends such as increasing oil prices?*

Objectives:

- *Design a system that models vehicle and fuel markets within configurable policy and energy scenarios.*
- *Implement it in browser-based software.*
- *Design a game interface that allows a streamlined access to the model*
- *Make the overall model "pluggable" -- configurable to support multiple assumptions about drivetrain technologies, fuel costs, regulatory policies and other system factors with minimal modifications.*
- *Run the game multiple times with human players.*
- *Analyze play results to see what can be learned from the system, and the types of data that it generates (what might it be possible to learn).*

The Game Design

The game, named Autopia, is a three-sided market simulation composed of vehicle producers, fuel producers, and consumers. Game play takes place over the course of ten turns, each of which representing a four year period. Each turn begins with a model computation phase that calculates the state of the game based on the input from the last turn's player input. Elements like fuel prices, fleet attrition, and consumer income are generated in that phase.

A play flow can be seen in Figure 4. Money in the game enters from the consumer players' income. With this income they must buy all of their fuel and vehicles. Fuel purchases of the four game fuels: gas, diesel, electricity and hydrogen, are immediately deducted from the consumer's funds. FP players seek to correctly guess the demand for fuels on the current turn and in the future. The consumer player has no control over this function. This is intended to represent the fact that fuel purchase patterns are generally habit-based and do not change unless necessitated *(8)*. To allow a consumer player to manipulate the fuel purchases of his millions of simulated consumers would have been unrealistic.

Fuel purchase entails a calculation of fuel usage. Fuel usage is calculated as a function of VMT, vehicle age, and drivetrain type. Average VMT for a vehicle is a declining function of its age*(20)*. New vehicles are assumed to travel 15000 miles/year, (24,000 km) while the oldest vehicles travel less than 3000 miles/year (5000 km) . Fuel usage for plug-in hybrid electric vehicles must be calculated for electricity and its other fuel. Consumers transact money for fuel with the fuel producers. Fuel prices are set using an algorithm that considers consumer demand, producer capacity, and an energy price scenario *(21)*.

The next stage of the game is the vehicle auction. Vehicle producers design and build vehicles for the auction in the prior turn with the goal of a successful consumer reception. The vehicle building process flow is shown in Figure 5. Often this means they will copy cars that have been successful in the past, just as real manufacturers do. Vehicle producer players develop vehicles and invest in R&D, which improves selected aspects of their technology portfolios and thus improves their vehicle offerings. One of the key decisions in the VPs game is to select the technologies she thinks are most promising. Consumers and VPs negotiate prices on the vehicles. The consumer is seeking to meet a replacement vehicle quota for his drivers.

[FIGURE 4]

[FIGURE 5]

After fuel and vehicles are purchased the players are scored on their performance. VP and FP players are scored based on their market success based on their bank balances. Consumers players are scored based on two criteria: 1) supplying the desired amount of vehicles to their drivers, and 2) how much the drivers *like* the vehicles that have been purchased for them. This is calculated using a utility function with unique coefficients for each consumer player group *(21)*.

GAME PLAY HISTORY

Autopia, and a simplified variant called Autobahn, were played about twelve times between December 2010 and December 2011. Most of the game instances were unique in their scenarios and feature sets as the game evolved, so inter-game statistical comparisons are not appropriate. In general, simulation games are not a useful tool for generating point estimates of real world parameters. Their strength is in developing insights into the operational dynamics of the complex system.

Game History

[TABLE 1]

[FIGURE 6]

Game play yields narrative data about prospective market reactions to various scenarios, as well as detailed quantitative data on player decisions. The narrative data is taken in a post-game debriefing session in which the players explain what their strategies were and how they responded to various events in the game. These debriefing sessions are an important part of the methodology; they are where the insights from the gaming session are revealed. The recorded game data serves as a further complement to the players' impressions. In a repeated game format, in which multiple player groups run the same game or the same group plays a sequence of related scenarios this data can be used to analyze the actual similarities and differences between the play sessions.

Analysis of Game Results

The modeling objective in Autopia was to try to capture the critical dynamic interactions and decisions of the market. In building and running the Autopia models, we observed several recurring patterns of player behavior. These observations cannot be quantitatively validated, as a statistically significant trial was not attempted; they are instead examples of observations that are possible within the system. They indicate what can be learned using Autopia as part of a rigorous exploratory process*(22)*.

FINDINGS

High Fuel Prices Can Mean Low AFV Penetration

It is generally assumed that people will want high mpg vehicles when faced with high fuel prices, and indeed it has been empirically observed in recent years*(23)*. But that does not necessarily mean consumers will choose to buy alternative fueled vehicles (AFVs). Gasoline powered economy conventionally fueled vehicles (CFVs) now in production can achieve highway fuel efficiencies of over 40 mpg, which is a substantial improvement for most buyers*(24, 25)*.

When fuel prices are high, $5-$12/gge, ($1.25 - $3/lge) Autopia consumers have less money to spend on vehicles. The high-income groups incorporate more AFVs (hybrids and plug-ins) into their fleets as the additional cost of the AFV is a much smaller percentage of the cost of an expensive vehicle than of an economy vehicle. The much larger lower income consumer groups however turn to high economy gasoline CFVs, because they don't have the extra funds to buy large numbers of AFVs: high fuel prices have depleted their budgets. When they do buy AFVs they tend to go for inexpensive gas HEVs (standard hybrids) as those are the most affordable entry point.

How realistic is this response? A $1 increase in gasoline prices (gge), for example, would mean an additional $600/year fuel expenditure in order to maintain a constant VMT of 12000 miles/year (19000 km) for a vehicle that gets 20 mpg (8.5 kpl). That might not seem like a lot of money, and for some it would not be a factor. However it is important to understand that the Autopia consumer works off of a vehicle and fuel budget and not a household budget. There is no credit in Autopia, nor is there a disposable income budget. A dollar spent by the consumer to buy fuel is a dollar of potential revenue lost to the vehicle producers. Given that an Autopia turn is a simulated four years, the consumer has $2400 less to spend per vehicle: *about the price difference between a conventional gas vehicle and a hybrid gas vehicle.*

In high fuel price scenarios the trend that invariably arises is the bifurcation of the vehicle market. The high end of the market, the top 30%, gets AFVs that span the range from standard hybrids to full battery electrics. Though AFVs, these vehicles are typically not very efficient. The VPs design them with high style and performance to appeal in the high-end market, and these features cost mpg. The advanced technology serves to keep the VPs CAFE mpg up, so as to minimize penalties and allows them to offer more attractive features on the car while still meeting the minimum mpg requirement for the game. For example, if there is a 10 mpg (4.25 kpl) minimum rule in a game, a gas HEV can carry more style and performance than a CFV; the added efficiency of the HEV is translated into features rather than mpg.

The bottom 70% of the market in high fuel price scenarios, in contrast, struggles to hold on to its vehicles. A large market develops for cheap CFVs with low scores on style and performance. These drivers cannot afford the luxury of a long-range view of the value of AFVs. Consequently, if fuel prices continue their increases, drivers get into even worse financial shape; they lose some of their cars and switch to alternative modes. The higher-end consumers, who have invested in AFVs, are less vulnerable to fuel price increases and volatility because they buy less fuel (i.e. higher average fleet mpg), and because they can choose to moderate their style and performance desires in AFVs to get increased mpg, should they need to do it.

So the counter-intuitive effect is actually straightforward economics: people will not adopt more efficient technology if they cannot afford it, and high fuel prices can make AFVs unaffordable for many of the consumer players by sapping their financial reserves. On the high end of the market consumers can justify buying AFVs either because they increase the feature level of the car or because they can rationalize the added initial expense with the expectation of future cost savings due to the increased efficiency of the vehicles.

Feature Gap

It is safe to assume that AFVs will always be more expensive than CFVs. The reason for this in HEV/PHEVs is that the electric drive system is added to a conventional gasoline or diesel drivetrain that is capable, on its own, of driving the vehicle. Batteries, especially large batteries, are costly, with prices projected to be $150-$325/kwh in the year 2030*(9)*. This translates to a battery cost from $3750-$8125 for an economy class BEV, like a Nissan Leaf, with an 80-100 mile range (25 kWh battery), which may need to be replaced in the vehicle’s operating life. In contrast, the fuel tank of a CFV is a small contributor to the cost of the vehicle and is unlikely to need replacement. Hydrogen fuel cell vehicles include a motive battery that is typically comparable in size to that of standard HEV. It is possible that HFCVs might achieve cost parity with a CFV because a hydrogen fuel cell stack is much simpler than an ICE, but there are still important technology and refueling network challenges to be overcome for HFCVs

Given that the duplicating the feature set of a CFV in an AFV will cost significantly more money, the *feature gap* is the distance between feature comparable AFVs and CFVs. For instance, for the price of Chevy Volt ($40,000), a PHEV 40, there exist a number of attractive options from prestige brands. The Volt compares, functionally, to the Chevy Cruze Eco, an entry level small-midsize sedan, at about half the price *(26)* How many Cruze buyers are going to be willing to pay an extra $20,000 for a vehicle whose only benefit is improved gasoline mileage (albeit substantially) for short range driving? Likewise, how many buyers in the entry-level luxury market are going to be willing to trade substantial style and performance premiums for increased mpg if they must drive a far more modest economy-trimmed vehicle?

Toyota's Prius offers a market-based approach to dealing with the feature gap. The Prius is only offered as a hybrid. There is no directly comparable vehicle in the Toyota line. Furthermore, Toyota has designed the vehicle to provide a specific driving experience. The vehicle is stylistically distinctive inside and out. Buyers appreciate the fuel economy and the opportunity to drive a high profile vehicle at a relatively modest price*(27)*. The Prius closes the feature gap by by offering a unique driving experience that appeals to a particular market niche*(28)*.

A policy approach to closing the feature gap is to simply set rules on the technologies that are permitted in new vehicles. For example, if there were a regulation that said that all gasoline or diesel vehicles had to be hybrids, there would be no feature gap between hybrids and CFVs (hybrids would become the de facto CFV). Such a rule would, in effect, regulate certain engine configurations out of existence: closing the feature gap by eliminating options.

Conclusion

The long-range future of the vehicle and fuel markets is an open question. Multiple historical, environmental, social, and technological factors will play a role in the outcome. The standard forecasting tools do not work under these conditions. As an alternative approach, we have built a simulation game through which the dynamic relationships in the vehicle and fuel market can be explored in a controlled, observable setting.

The work described here is only a beginning. Much of it is the construction of the models and metaphors that underpin the game. A number of games were played, in various formats. The games demonstrate the data the system can generate. The general trends from the games are analyzed. The trends illuminate many of the challenges that we can expect to face as the transportation system adapts to an unknown future. We believe further pursuit of this methodology can yield important insights in how to best manage this uncertainty.

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Figures:

Tables:

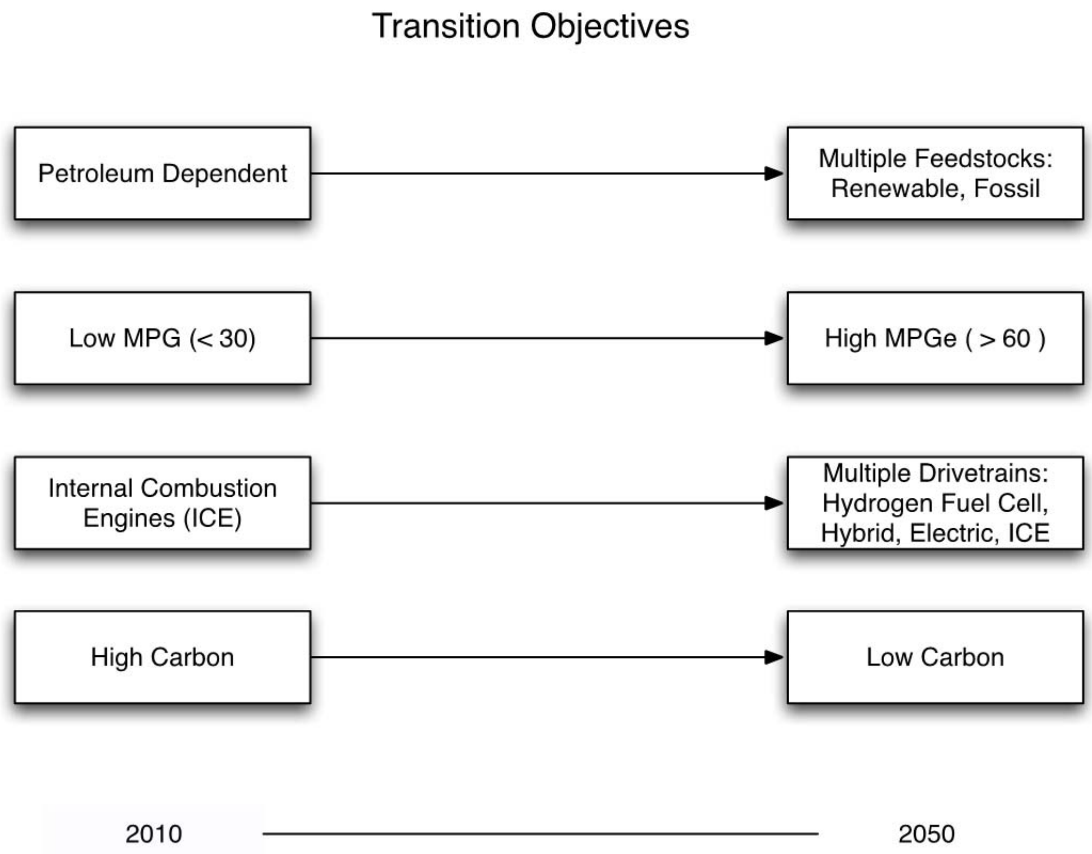

Figure 1: A transition has multiple objectives

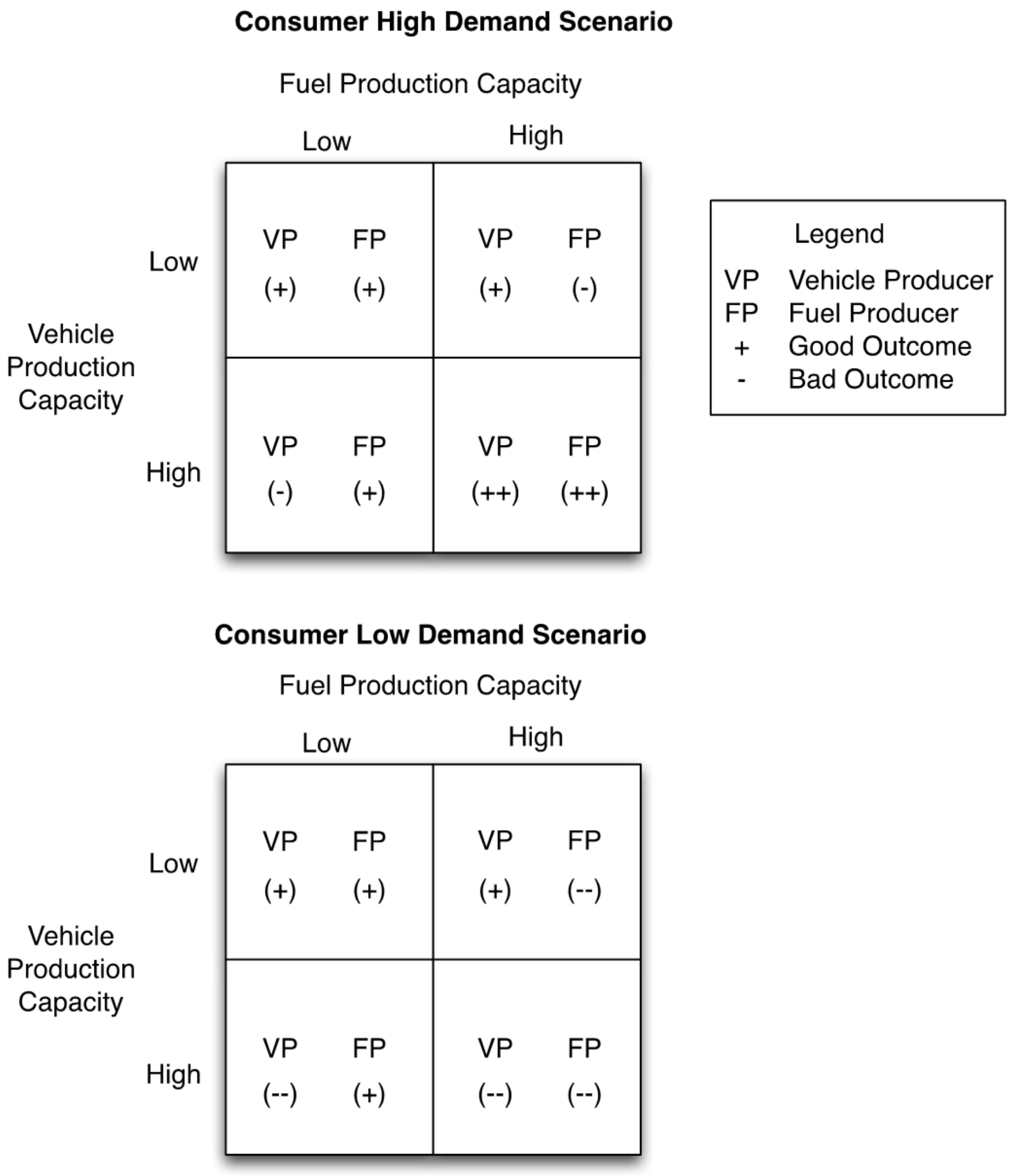

Figure 2: Product Release Demand Scenarios

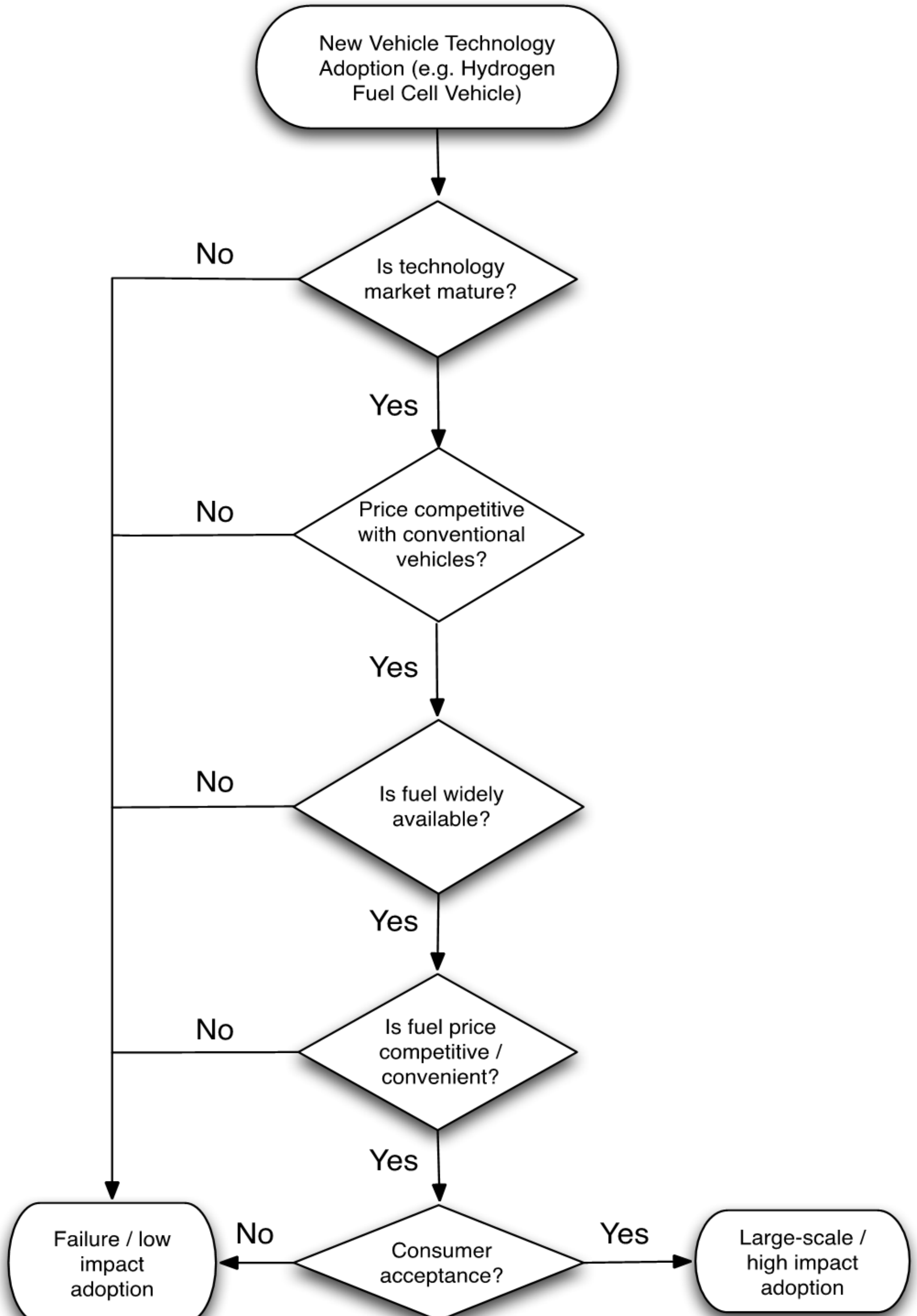

Figure 3: New Technology Adoption

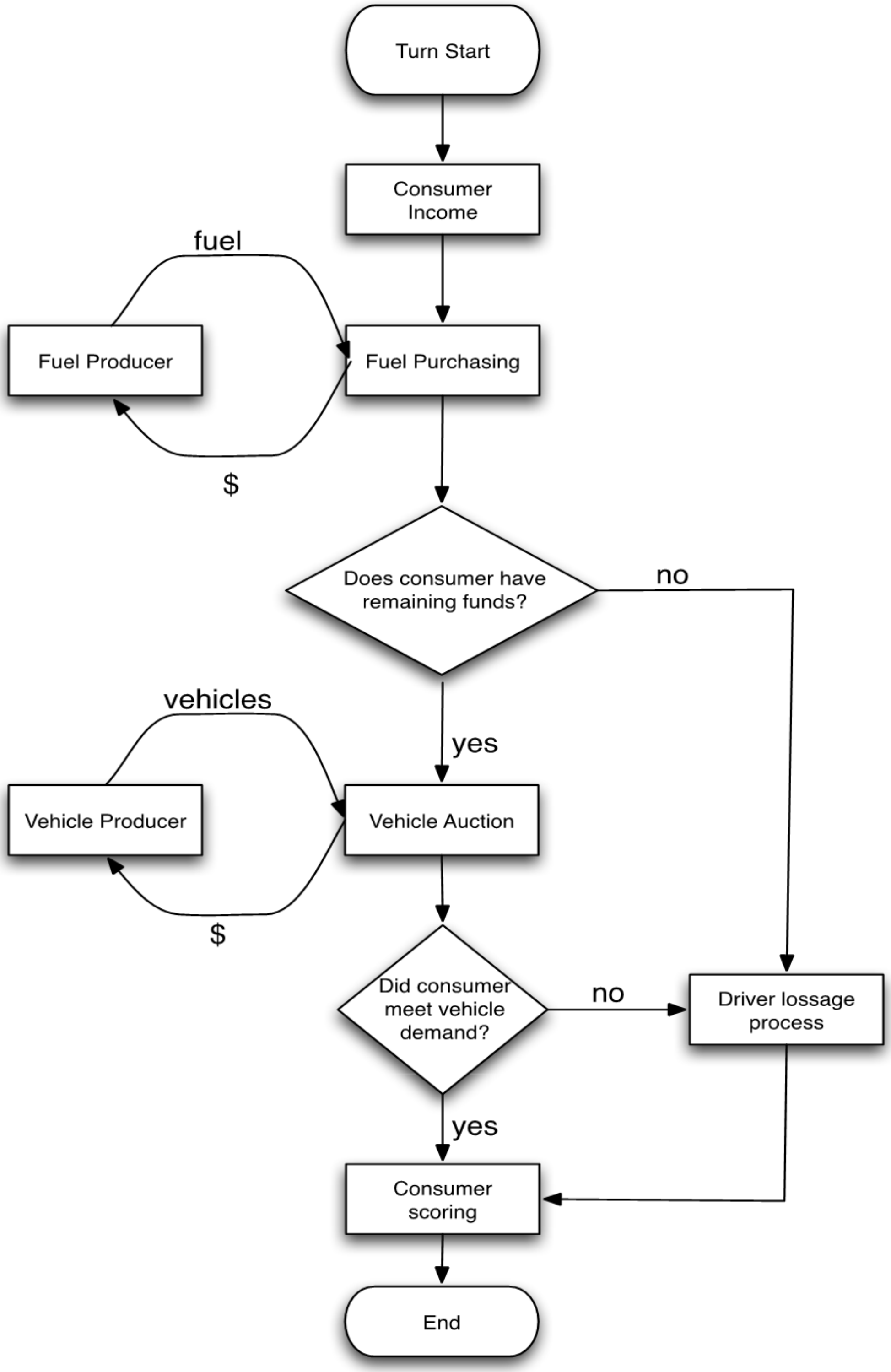

Figure 4: Game Play Flow (Consumer Perspective)

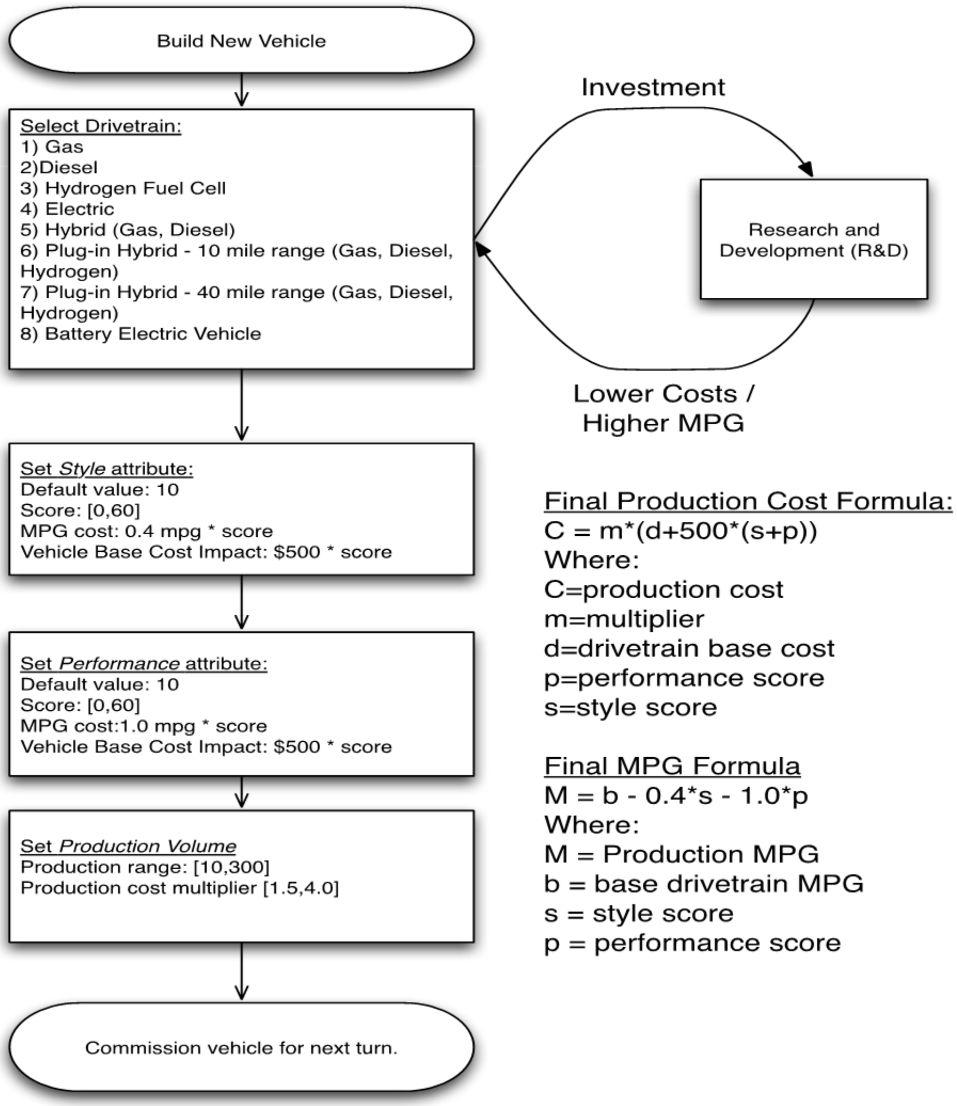

Figure 5: Vehicle Build Process Flow

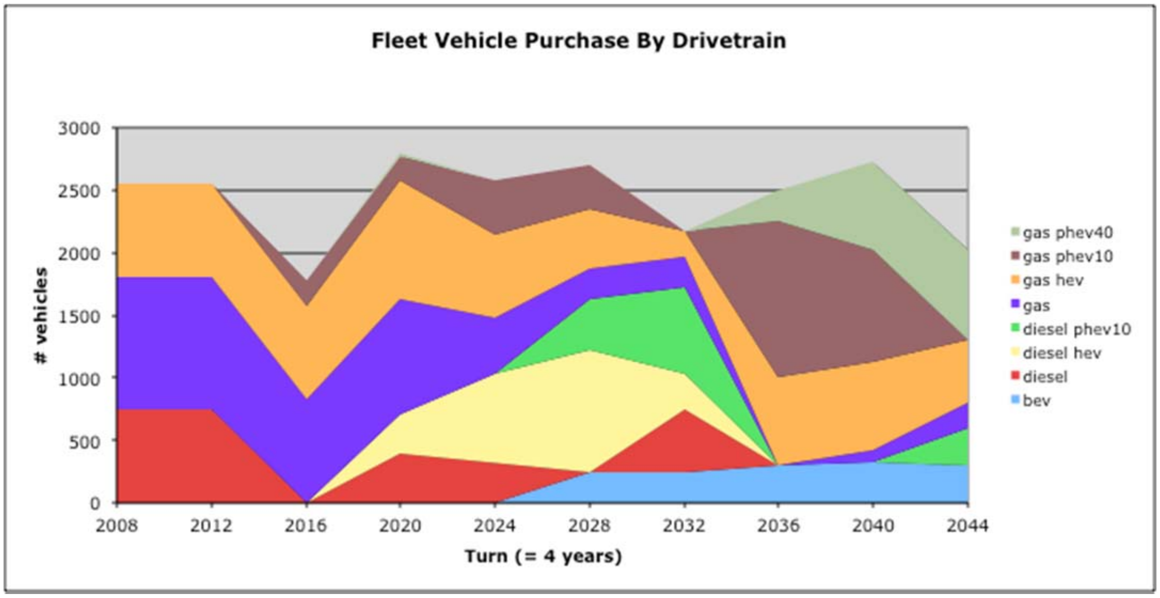

Figure 6: Drivetrain Sales Chart (sample plot)

ID	Game	Game Type	Date	Description
1-3	Play Testing 1	Autopia	12/9/10-12/20/10	Play and GUI testing.
4	Autopia Test 1	Autopia	1/6/11	First full Autopia Test
5	Conference Game Test	Autopia	1/13/11	Scenario tests for first conference game
6	Conference Game	Autopia	1/19/11	First full Autopia game with outside players.
7	Autopia Course	Autopia / Autobahn	4/5/11-6/10/11	Small games and tests as part of Autopia class taught at UC Davis.
8	Graduate School of Management – UCD	Autopia	5/12/11	Game played with Graduate School of Management students and Autopia class students.
9	CAFE Test	Autopia	6/2/11	Game to test CAFE implementation
10	Asilomar 1	Autobahn	8/29/11	Demonstration session 1 for Asilomar 2011 Transportation and Energy Conference
11	Asilomar 2	Autobahn	8/31/11	Demonstration session 2 for Asilomar 2011 Transportation and Energy Conference
12	Autobahn 1	Autobahn	11/4/11	Training game 1. AEO 2011 High fuel price scenario. Game initializes too many hevs in the beginning.
13	Autobahn 2	Autobahn	11/9/11	Training game 2. AEO 2011 High fuel price scenario. Initialization works better.
14	Autobahn 3	Autobahn	11/22/11	AEO 2011 with a volatility factor. 3 player game.

Table 1: Autopia / Autobahn Game Record