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# New Approach to Modeling Large-Scale Transitions to Alternative Fuels and Vehicles

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**A large-scale transition to alternative fuels and vehicles is 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 game to simulate transitions to alternative fuels and vehicles was developed to explore the potential of this approach. Preliminary results of the game play suggest a possible counterintuitive dynamic: high energy prices can discourage the wide-scale adoption of alternative fuel vehicles because increased fuel costs reduce consumers' ability to pay for more costly alternative vehicle technologies.**

A major transition to alternative fuels and vehicles must be undertaken if greenhouse gas emissions and oil dependence are to be drastically reduced. New fuels including electricity, hydrogen, and biofuels as well as their corresponding drivetrains will have to achieve mass market acceptance and capacity. The light-duty vehicle segment has been petroleum fueled from almost the beginning of the 20th century. A massive inertia of infrastructure and ingrained habits surrounding conventional internal combustion drivetrains must be overcome; an industrial transformation on this scale has never before been attempted.

The scope and complexity of such a transition requires new modeling approaches (Figure 1). Models such as MARKAL, Transitional Alternative Fuels and Vehicles (TAFV), and HyTrans have been used in prior analyses but are limited by their initial assumption sets; the outputs of these models are deterministic extrapolations of the inputted assumptions (1–3). These approaches lack the ability to consider market interaction and dynamics. In the real world, competitive strategies are used in business-based decision making. Understanding these strategies is important for developing effective policies that support the transition.

To explore these transitions in a dynamic context, the authors have developed a simulation game. Simulation games have been used to explore problems that feature high degrees of uncertainty, most notably by the military (i.e., war games). The game simulates a three-

sided market of vehicle producers, fuel producers, and consumers. Working in an energy and policy scenario, players make decisions about how to manage their businesses and vehicle purchases. The game provides insight into possible dynamics and outcomes that diverge unpredictably from the input assumptions, unlike in numerical models.

## TRANSITION CHALLENGE

A large-scale alternative fuel transition presents many challenges. Many systems that are complex in their own right 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, fuel producers, and consumers all must 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. Even if the producers are fully coordinated, the release still will fail if the consumer is unable or unwilling to support the product at the planned production level.

In Figure 2, two scenarios illustrate the coordination factors involved in a successful vehicle technology release. Consumer high demand works out well for producers if they coordinate production outputs at low or high volumes (Figure 2a); however, if one producer goes low while the other goes high, the more ambitious producer is penalized because low production by the complementing producer limits the sales potential of the high-volume producer. With consumer low demand, the release is successful for the producers only if they both predict low sales volumes (Figure 2b). If they both prepare for high volume, they will be disappointed by the market size; similar problems will arise if they split their output levels between high and low.

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

## NEW VEHICLE TECHNOLOGIES

For a new vehicle technology (e.g., hydrogen fuel cell or plug-in hybrid electric), many 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.

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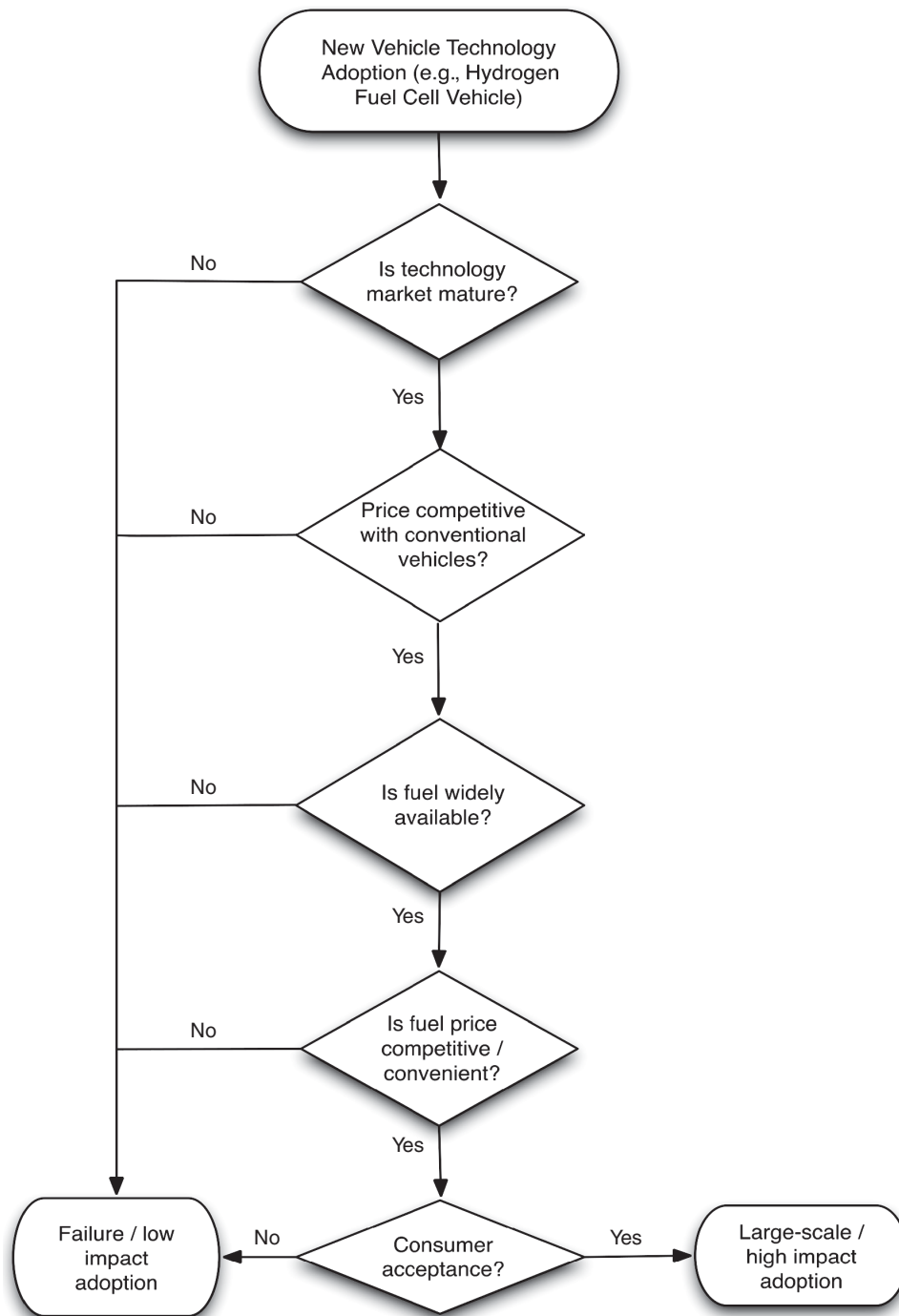


FIGURE 3 New technology adoption.

First, 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 scale similar 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 believe the feature set is worth the additional money. The feature set will include likely savings from increased fuel efficiency and perhaps tax incentives and 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). The

success of the Toyota Prius, for example, is partly because the vehicle—like an SUV or a sports car—makes a statement about the driver (6, 7). Consumers will pay a premium for the right sorts of statements, whether it means buying sneakers or cars. However, when hybrid drives are quietly folded into a conventional car line as an option (e.g., Honda Civic), the statement is buried.

Next, the supply of fuel for the new vehicle must be adequate. Refueling stations must be located such that buyers feel certain that fuel will be available where they want it and at a fair price (8). Buyers will not adopt a vehicle that will be difficult or expensive to refuel.

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

## LITERATURE REVIEW

Simulation gaming as a tool for strategic planning has its roots in military applications. Fighting war is inherently chaotic and uncertain. Strategists discovered that prestaging expected conflicts could reveal important information about how an actual conflict might play out. The competitive nature of games encourages players to make thoughtful decisions because it gives them a chance to demonstrate their abilities and gain status. Ideas tested in a competitive framework can be more robust than those developed that use insular processes (10–12).

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

No games specifically about alternative fuel and vehicle transitions were known when this project began; however, many energy-related games were. For example, *PowerPlay* explores the relationships between the appliance market, electricity producers, and energy efficiency programs (15). One of the primary revelations of *PowerPlay* is that subsidies for energy-efficient appliances actually can cause poor consumers to subsidize the purchases of wealthy consumers in a functional example of how policy can have unintended consequences.

INFRASTRATEGO, developed in the Netherlands in the mid-1990s to explore electricity deregulation, is a large game designed for 40 to 50 players (16). It was designed to reveal strategic patterns that might occur in the implementation of the *Electriciteitswet* (Electricity Act) of 1998, which liberalized the electricity market in the Netherlands. The conventional wisdom of the 1990s 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.

Almost identical to INFRASTRATEGO in theme, UTILITIES 21 is a large game designed for 20 to 60 players and a 2-day play session (18). Players take on the roles of electricity retailers, generators, and consumers in a dynamic electricity market. The macromodel for UTILITIES 21 was based on the FOSSIL 2 model used for U.S. national energy plans by the U.S. Department of Energy from

1978 to 1996 (19). As with INFRASTRATEGO, analyses based on UTILITIES 21 find that electricity market deregulation was ripe for exploitation.

## RESEARCH PLAN

To explore the potential value of serious games as a tool for improving the policies for a transition to alternative fuels and vehicles, the authors designed and built a game. This game was designed with the following questions and objectives in mind.

### Questions

- Is it possible to design a serious game to model the transition to alternative fuels and alternative vehicles?
- How can the behaviors, decisions, and interactions of different players in the market (i.e., consumers, vehicle manufacturers, and fuel producers) be modeled?
- What sorts of insights can the system offer about transitions in the automotive vehicle and fuel markets?
- What sorts of insights can the system offer about specific policies [e.g., the 2025 Corporate Average Fuel Economy (CAFE) standard] or economic trends (e.g., increasing oil prices)?

### Objectives

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

## THE GAME OF AUTOPIA

### Design

Autopia is a three-sided market simulation composed of players who are vehicle producers, fuel producers, and consumers. Game play takes place over the course of 10 turns, each of which represents a 4-year period. Each turn begins with a model computation phase that calculates the state of the game according to player input from the last turn. Elements such as fuel prices, fleet attrition, and consumer income are generated in that phase.

The game play flow is illustrated in Figure 4. Money enters the game from the consumer players' income, and consumers must buy all of their fuel and vehicles with this income. Fuel purchases of the four game fuels (gas, diesel, electricity, and hydrogen) are immediately deducted from the consumers' funds. Fuel producer players seek to correctly guess the demand for fuels on the current turn and in the future, and the consumer player has no control over this function. This situation is intended to represent fuel purchase patterns that are

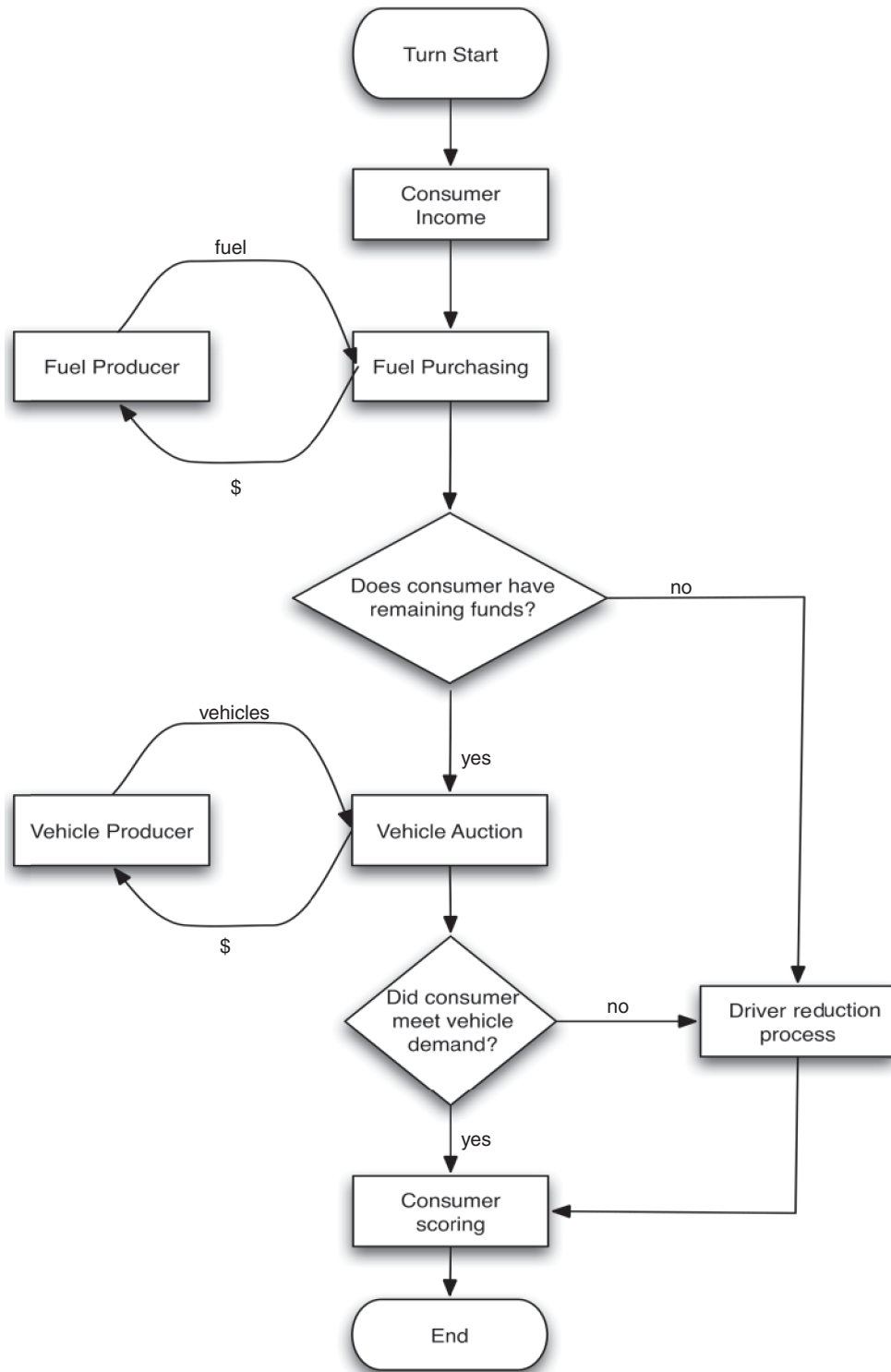


FIGURE 4 Game play flow (consumer perspective).

generally habit-based and do not change unless necessitated (8). To allow a consumer player to manipulate the fuel purchases of millions of simulated consumers would have been unrealistic.

Fuel purchase requires a calculation of fuel usage, which is a function of vehicle miles traveled (VMT), vehicle age, and drivetrain type. Average VMT for a vehicle is a declining function of its age (20). It is assumed that new vehicles travel 15,000 mi (24,000 km) per year and the oldest vehicles travel less than 3,000 mi (5,000 km) per year. Fuel usage for plug-in hybrid electric vehicles (PHEVs) must be calculated for electricity and their other fuel. Consumers exchange money for fuel with the fuel producers. Fuel prices are set with 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, seeking a positive reception from consumers, design vehicles for the market (Figure 5). Producers often copy cars that have been successful just as real manufacturers do. Vehicle producer players develop vehicles and invest in research and development, which improves selected aspects of their technology portfolios and thus

improves their vehicle offerings. One of the key decisions in the vehicle producer players' game is to select the technologies they think are most promising. The consumer and vehicle producer players negotiate vehicle prices; the consumer players seek to meet replacement vehicle quotas for their drivers. To accompany the flow presented in Figure 5, the final production cost ( $C$ ) formula and the final formula for miles per gallon are

$$C = m \times (d + 500 \times (s + p))$$

$$M = b - 0.4s - 1.0p$$

where

- $m$  = multiplier,
- $d$  = drivetrain base cost,
- $p$  = performance score,
- $s$  = style score,
- $M$  = production miles per gallon, and
- $b$  = base drivetrain miles per gallon.

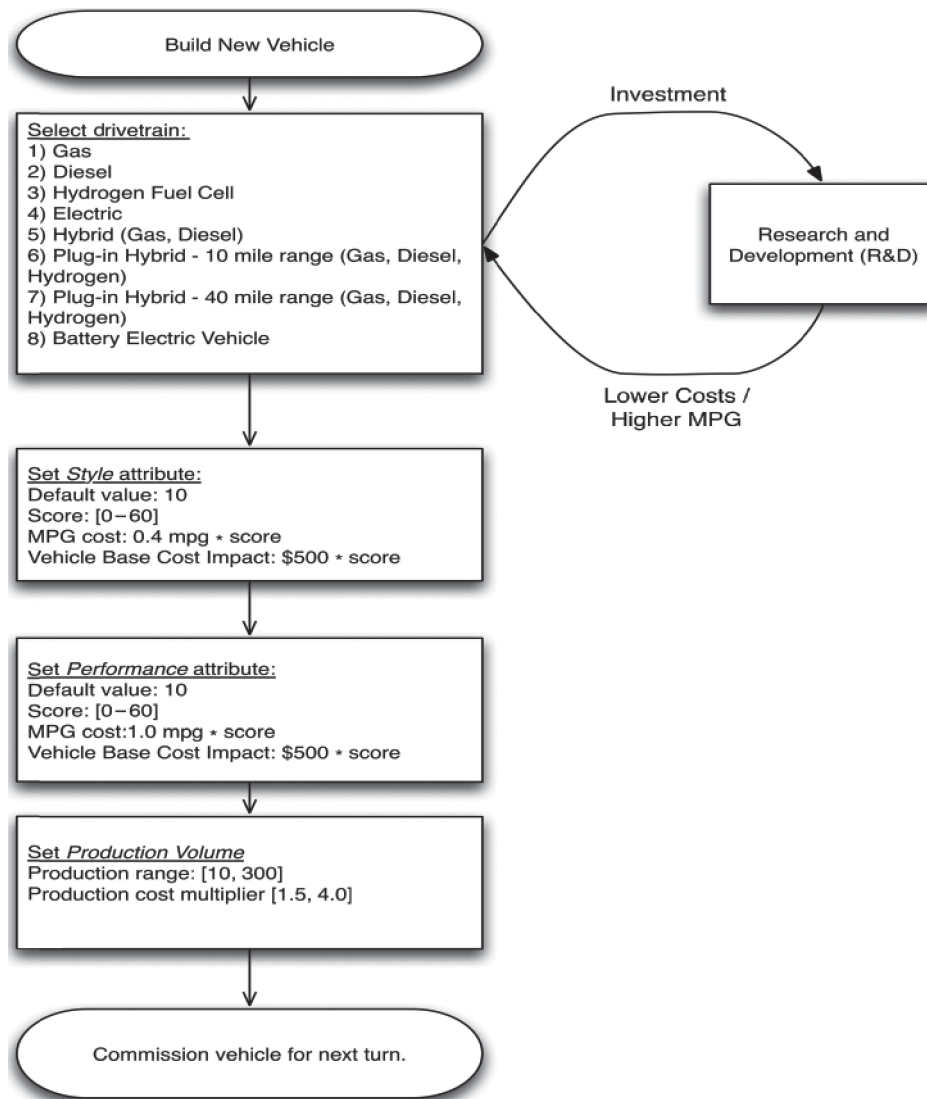


FIGURE 5 Vehicle build process flow.

TABLE 1 Game Record: Autopia and Autobahn (22)

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 UCD
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, initialization of too many HEVs in the beginning
13	Autobahn 2	Autobahn	11/9/11	Training Game 2, AEO 2011 high fuel price scenario, initialization better
14	Autobahn 3	Autobahn	11/22/11	AEO 2011 with a volatility factor, three-player game

NOTE: GUI = graphical user interface; UCD = University of California, Davis; AEO 2011 = Annual Energy Outlook 2011.

After purchasing fuels and vehicles, the players are scored on their performance. Vehicle producer and fuel producer players are scored on the basis of their market success, as reflected in their bank balances. Consumer players are scored according to two criteria: whether they have supplied the desired quantity of vehicles to their drivers and how much the drivers like the vehicles that have been purchased for them. These criteria are calculated by using a utility function with unique coefficients for each consumer player group (21).

**Play History**

Autopia and an abbreviated variant called Autobahn were played about 12 times between December 2010 and December 2011 (Table 1) (22). Most game instances were unique in their scenarios and feature sets as the game evolved, so between-game statistical comparisons

are not appropriate. In general, simulation games are not useful tools for generating point estimates of real-world parameters; their strength is in developing insights into the operational dynamics of a complex system.

**Narrative Data**

Game play yields narrative data about prospective market reactions to various scenarios as well as detailed quantitative data about player decisions; sample data from a game are presented in Figure 6. The narrative data are taken in a postgame 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 process because insights from the gaming session are revealed. The recorded game data serve as a further complement

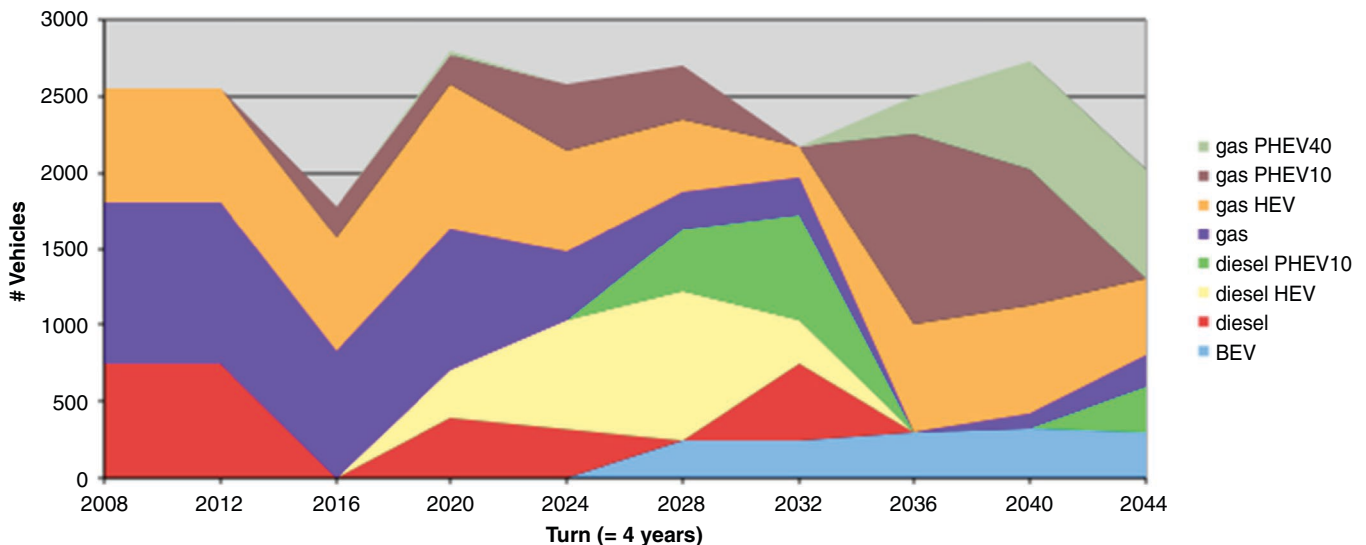


FIGURE 6 Drivetrain sales chart (sample plot) (BEV = battery electric vehicle).



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—these data can be used to analyze similarities and differences between play sessions.

## Analysis of Results

The modeling objective in Autopia is to capture the critical dynamic interactions and decisions of the market. Several recurring patterns of player behavior were observed while building and running the Autopia models. These observations cannot be quantitatively validated because a statistically significant trial was not attempted; instead, they are examples of observations that are possible within the system and indicate what can be learned by using Autopia as part of a rigorous exploratory process (23).

## FINDINGS

### High Fuel Prices, Low AFV Penetration

In general, people faced with high fuel prices are assumed to want vehicles with high fuel efficiency, and indeed, this trend has been observed empirically in recent years (24). However, this trend does not necessarily mean that consumers will choose to buy alternative fuel vehicles (AFVs). Economy gasoline-powered conventionally fueled vehicles (CFVs) now in production can achieve highway fuel efficiencies of more than 40 mpg, which is a substantial improvement for most buyers (25, 26).

When fuel prices are high [\$5 to \$12/gasoline gallon equivalent (GGE) (\$1.25 to \$3/gasoline liter equivalent)] Autopia consumers have less money to spend on vehicles. The high-income groups incorporate more AFVs (HEVs and PHEVs) into their fleets because the additional cost of the AFV is a much smaller percentage of the cost of an expensive vehicle than of an economy vehicle. However, the much larger lower-income consumer groups turn to gasoline-powered CFVs with high fuel efficiency because they do not have the extra funds to buy large quantities of AFVs; high fuel prices have depleted their budgets. When they do buy AFVs, they tend to choose the less expensive gasoline-powered HEVs (standard hybrids), which have 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 in fuel expenses to maintain a constant VMT of 12,000 mi (19,000 km) per year for a vehicle with a fuel efficiency of 20 mpg (8.5 km/L). That amount might not seem like a lot, and it would not be a factor for some consumers. However, it is important to understand that the Autopia consumer plays with a vehicle and fuel budget, not a household budget. In Autopia, consumers do not have credit or disposable income budgets. One dollar spent by the consumer on fuel is \$1 of potential revenue lost to the vehicle producers. Given that one Autopia turn simulates 4 years, a consumer has \$2,400 less to spend per vehicle—about the difference between a gasoline-powered CFV and a gasoline-powered HEV.

In high-fuel-price scenarios, the trend that invariably arises is the bifurcation of the vehicle market. The high end of the market (top 30%) gets AFVs that span the range from standard hybrids to full battery electric vehicles. Even though they are AFVs, these high-performance luxury vehicles typically are not efficient. The vehicle producers design them with high style and performance to

appeal to the high-end market, but such features cost fuel efficiency. Advanced technology keeps the vehicle producers' CAFE fuel efficiency up to minimize penalties and still meet the minimum fuel efficiency requirement for the game while allowing them to offer more attractive features on the car. For example, if a minimum rule in a game is 10 mpg (4.25 km/L), then a gasoline-powered HEV can carry more style and performance than a gasoline-powered CFV; the added efficiency of the HEV is translated into features rather than fuel efficiency.

In contrast, the bottom 70% of the market in high-fuel-price scenarios 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 AFV value. Consequently, if fuel prices continue to increase, drivers get into even worse financial shape; some lose their cars and switch to alternative modes. The high-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 fuel efficiency in the fleet) and because they can moderate their style and performance desires in AFVs to get increased fuel efficiency, should they need to.

Therefore, the counterintuitive effect actually is straightforward economics: people will not adopt more efficient technology if they cannot afford it, and high fuel prices can sap the financial reserves of many consumer players, making AFVs unaffordable. At the high end of the market, consumers can justify the added initial expense of an AFV purchase with added features or the expectation of future cost savings due to the increased fuel efficiency of the vehicle.

### Feature Gap

One can safely assume that AFVs always will be more expensive than CFVs because HEVs and PHEVs are built by adding an electric drive system to a conventional gasoline or diesel drivetrain that is capable, on its own, of driving the vehicle. Batteries—especially large ones—are costly, with prices projected to be \$150 to \$325 per kilowatt-hour in 2030 (9). This cost projection translates to a battery cost of \$3,750 to \$8,125 for a 25-kW-h battery with a range of 80 to 100 mi in an economy-class battery electric vehicle such as the Nissan Leaf, and the battery may need to be replaced during the operating life of the vehicle. In contrast, the fuel tank of a CFV represents a small portion of total vehicle cost but is unlikely to need replacement. Hydrogen fuel cell vehicles (HFCVs) typically include a motive battery that is comparable in size to that of standard HEV. HFCVs might achieve cost parity with CFVs because a hydrogen fuel cell stack is much simpler than an ICE, but HFCVs face important challenges related to the technology and refueling network that remain to be overcome.

Given that duplicating a CFV feature set in an AFV costs significantly more money, the feature gap is defined as the distance between AFVs and CFVs with comparable features. For instance, functionally, the PHEV Chevy Volt (\$40,000), which can travel 40 mi on battery power alone, is comparable to the Chevy Cruze Eco, an entry-level small-to-midsize sedan at about half the price (27). How many Cruze buyers are willing to pay \$20,000 more for a vehicle whose only benefit is improved (albeit substantially) gasoline mileage for short-range driving? Similarly, how many buyers in the entry-level luxury market are willing to trade substantial style and performance premiums for increased fuel efficiency if they must drive a far more modest economy-trim vehicle?

The Toyota Prius offers a market-based approach to dealing with the feature gap. The Prius is offered only as an HEV, and no vehicle in the Toyota line is directly comparable. Furthermore, Toyota has designed the Prius 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 (28). The Prius closes the feature gap by offering a unique driving experience that appeals to a particular market niche (29).

A policy approach to closing the feature gap is to simply set rules on permitted technologies in new vehicles. For example, if a regulation stipulated that all gasoline or diesel vehicles had to be HEVs, then the feature gap between HEVs and CFVs would disappear (in other words, HEVs would become de facto CFVs). In effect, such a rule would regulate certain engine configurations out of existence, closing the feature gap by eliminating options.

## CONCLUSIONS

The long-range future of the vehicle and fuel markets is unknown; multiple historical, environmental, social, and technological factors will play a role in its outcome. Standard forecasting tools do not work under these conditions. Simulation gaming is an alternative approach that can be used to explore dynamic relationships in the vehicle and fuel markets in a controlled, observable setting.

The work described here is only the beginning. Much of it is the construction of the models and metaphors that underpin the game. Many games were played, in various formats, and the games demonstrate the data that the system can generate. The general trends from the games illuminate many of the challenges that can be expected as the transportation system adapts to an unknown future. The authors believe that the pursuit of this method can yield important insights into how to best manage this uncertainty.

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*The Alternative Transportation Fuels and Technologies Committee peer-reviewed this paper.*