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Modeling Market Dynamics in a Super Octane Ethanol Fuel Blend-Vehicle Powertrain System: Understanding the role of consumer perception in ethanol market growth

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Current ethanol fuel blends (E10 & E85) in the automotive fuel-powertrain system do not result in consumption of the federally mandated ethanol volumes. Models exist for the deployment of alternative fuel powertrain vehicles considering the dynamic limitations imposed by infrastructure co-evolution and delays. These models work when consumers are limited to a single fuel choice per vehicle and when growth is only determined by positive familiarity. A new system dynamics model applied to super octane ethanol blend fuel vehicles encompassing unfavorable word of mouth was developed to capture the asymmetrical effect of unfavorable consumer perceptions and interactions on market growth. The developed model enables new types of system behavior to be observed that was previously not possible. Results show that removal of potential consumers from the market due to unfavorable word of mouth can mitigate or overwhelm marketing and change virtuous growth to a vicious reinforcement leading to market collapse.

Keywords: energy policy, consumer choice, ethanol fuel, word-of-mouth, multi-stakeholder system, complex choice modeling

Introduction

Current regulations and mandates are fostering important changes in the light-duty passenger vehicle market in the United States. The need for higher efficiency powertrains and accommodating increasing volumes of ethanol into the US fuel supply system have created challenges for stakeholders: vehicle manufacturers, ethanol producers, station owners, energy companies, and consumers (Morey, 2014). The current market provides two avenues for the use of ethanol: through flex fuel vehicles (FFVs) coupled with the retail sale of E85 fuel containing up to 85% ethanol, and through conventional powertrains coupled with the low percentage ethanol blend, which is fuel containing up to 10% or 15%, as to convert into conventional gasoline. Both fuels are typically used in engines designed and approved to use 87 anti-knock index (AKI) octane fuel. This engine design architecture fails to take advantage of the high-octane properties of ethanol, and creates challenges for ethanol blend fuels to offer utility advantages to the customer, fuel retailers, and auto manufacturers. As a

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result, the consumption of E85 fuel remains low and the initial federally mandated volumes of ethanol are not consumed by the light-duty passenger vehicle fleet (see Figure 4). While some of this is the result of limited refueling infrastructure, consumers still often choose conventional gasoline even when both are available (Alliance of Automobile Manufacturers, 2013). In general, substantial uncertainty exists with regard to customer acceptance and the corresponding technological development of alternative fuel powertrains. The suite of fuel economy and vehicle regulations means that the automotive industry faces the challenge of improving conventional powertrains, while simultaneously having to introduce a range of alternative powertrains into the market that compete against conventional ones (Walther, Wansart, Kieckhäfer, Schnieder, & Spengler, 2010). Recent attention has turned to using a mid-level super octane (94-96 AKI/99-101 Research Octane Number) ethanol blend fuel to achieve fuel economy improvements and increases in ethanol consumption.

Considerable research has validated the potential fuel economy benefits of a mid-level super octane ethanol blend fuel (Anderson, Ginder, Kramer, Leone, Raney-Pablo, & Wallington, 2012; Jung, Leone, Shelby, Anderson, & Collings, 2013; Leone, 2014; Splitter & Szybist, 2014; Splitter & Szybist, 2013; Stein, Polovina, Roth, Foster, Lynskey, Whiting, T., . . . VanderGriend, 2012). Other research suggests that the Research Octane Number (RON) scale be used to specifically align with the properties of ethanol in the fuel blend (Foong, Morganti, Brear, da Silva,Yang, & Dryer, 2014; Speth, Chow, Malina, Barrett, Heywood, & Green, 2014). The resulting super octane (SO) blends using 20–30% ethanol have the potential to offset increased fuel and vehicle costs with reduced fuel consumption and improved performance. Existing SO system concepts and narratives assume, as they did for the FFV policy design, that the fuel will enter the market and achieve pre-defined market growth on its own as defined by the policy makers or regulators (Chow, 2013; Speth et al., 2014; USDOE, 2010).

There is an incomplete appreciation for and understanding of the challenges of bringing a new fuel-powertrain system with secondary fuel choice to market. Empirical observations of complex systems demonstrate that simple linear and simplified feedbacks modeling can give a misleading representation of the true behavior of the system (Levin, Xepapadeas, Crépin, Norberg, & et al., 2013). The lack of consideration of the full system structure and resulting behavior is a root cause to take into consideration in relation to the problem of ethanol uptake.

Rather than reporting on a full suite of potential system architecture and policy scenarios for the ethanol-gasoline fuel-vehicle system, this paper emphasizes and demonstrates the importance of systems thinking considering the complex stakeholder interactions that drive consumer perception and stakeholder response in energy policy modeling. Within the realm of modeling and analysis techniques, system dynamics (SD) is well suited to capture and investigate the behavior and feedback over time of the different system stakeholders. SD provides a framework to understand the interaction of multiple nonlinear feedbacks where simple intuition is insufficient to understand the behavior of the system. Struben and Keith (S&K) established effective strategies for the use of SD to explore the market growth of an alternative fuel-vehicle system (Keith, 2012; Keith, Sterman, & Struben, 2011; Struben, 2006). Their approach was based on a virtuous cycle with the model not considering the potential for vicious cycles, and related balancing effects to occur within the system. Limitations in these existing models were identified while exploring the SO ethanol fuel options. For example, sales of the Prius were used to calibrate the model developed by Keith. The ubiquitous availability of gasoline infrastructure and the generally favorable perception of the Prius by consumers who purchased the vehicle limit the models applicability to technology systems where these conditions may not exist or may not be assured. The research described in this paper explores the parameters of the ethanol fuel and vehicle powertrain market by extending the system boundaries and utilizing and extending the existing models and techniques to include unfavorable word-of-mouth (WOM) effects and the downstream consumer fuel choice between SO and regular fuel for those consumers who have SO capable vehicles. The perception of consumers using a technology creates WOM through the interaction of the technology owners with other people they come in contact with. WOM and marketing are the principle mechanisms for technology growth (Sterman, 2000). The research explores the feedback effect that the formation of unfavorable views has on both total ethanol consumption and in forming technology perception for technology adopters and potential adopters. This approach moves beyond the prevalent concept of "tipping points" in-which positive support through policy, mandates, and regulations ultimately leads to a self-sustaining growth (Greene, Park, & Liu, 2014). The tipping point is predicated solely on a virtuous cycle with an assumption of consumer utility, and ignores the potential for vicious cycles and balancing effects to occur within the system. Energy policy based on tipping point theory assumes the right policy will move the market from line 3 to line 1 in Figure 1 and does not consider the possibility that even with policy complex stakeholder interactions can lead to market collapse or stagnation (see Figure 1, Line 2 & Line 3) as occurred with compressed natural gas vehicle markets.

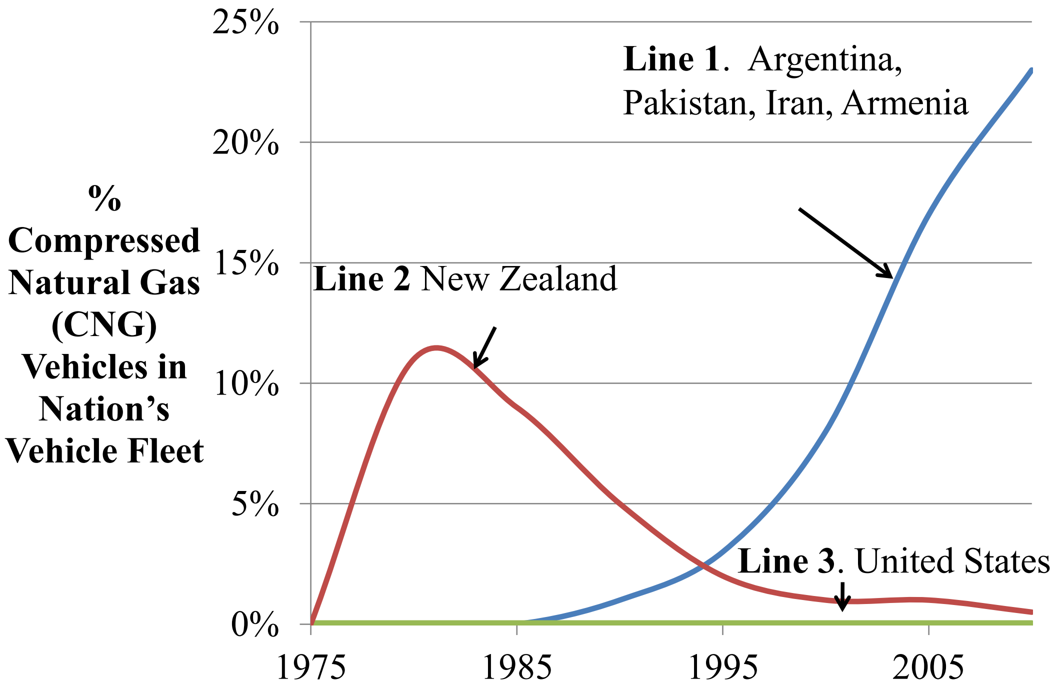
Limited scenarios are tested in order to provide initial insights, validate the concepts embedded in the model design, and demonstrate that the basic concept of unidirectional market growth and tipping points is inadequate for energy policy modeling. The model was exercised by scenario testing to explore the effects of SO adoption relative to the unfavorable WOM. Although this model is applied to an ethanol fuel-vehicle system, the model can be extended to other systems in which consumer choice occurs both during the purchase and use, and/or for which changes and reductions in utility post purchase can lead to unfavorable WOM.

Unfavorable Word-of-Mouth

Fundamental to the classical general models of market diffusion and adoption developed by Bass and others is the mechanism of social contagion, which is traditionally, called WOM (Bass, 1969, 1980; Horsky, 1990; Kalish, 1985; Kamakura & Balasubramanian, 1988; Robinson & Lakhani, 1975). Existing models usually only consider positive valence of WOM which supports adoption of the given technology or product under consideration. In competitive markets with positive valence of WOM the relative market growth or dominance of a given platform can only be improved with this positive perception and corresponding social diffusion. This approach does not consider the possibility for the negative valence of WOM, which could switch the reinforcing behavior from virtuous to vicious mode.

The importance of unfavorable consumer views and WOM is illustrated by the

Figure 1. Market penetration patterns and behavior (Keith, 2012a)



failure of the diesel passenger vehicle market in the United States in the 1970–1980s, while the technology platform achieved market success in Europe. Europe proved the potential of diesel technology, but unfavorable consumer perception in the United States effectively eliminated market opportunities for several decades (Greene, 1986; Neumaier, 2014). It is only recently; with a new generation of consumers who do not retain or possess these unfavorable views the market is expected to grow (Healey, 2013; Pyper, 2012).

To date, the application of unfavorable consumer perception in SD policy modeling is limited. The concept of unfavorable WOM was used, but is undocumented in the People Express model developed by Sterman and demonstrates the effect that unfavorable consumer views, rather than the product utility it has on a business (Sterman, 2014). The marketing and consumer research communities studied the importance of unfavorable consumer views and WOM. This work provides critical insight into the structure and behavior of the system. The idea of unfavorable WOM was discussed in the 1960s (Arndt, 1969) and gained more prevalence in the 1980s (Richins, 1983). Wangenheim (2005), later supported by Lee, compiles the analysis on the relative impact of unfavorable WOM versus. Favorable WOM and links the increased impact and probability of consumer conversion from the unfavorable WOM to the perceived importance and risk aversion of the technology (Lee & Romaniuk, 2009; Wangenheim, 2005). A positive correlation between consumer perception and the frequency and strength of the WOM was established, indicating that the stronger the (unfavorable) experience, the more likely an individual is to effectively convert other potential consumers (Yang, Hu, Winer, Assael, & Chen, 2012).

For products or technology systems involving high levels of investment, such as an automobile powertrain or an ethanol production facility, it is increasingly important to avoid unfavorable WOM (Lau & Ng, 2001). The importance and severity of unfavorable WOM is not often appreciated by firms, but can effectively lead to the failure of a product or technology (Lau & Ng, 2001). The mechanism is consumer-to-consumer recommendation to avoid a product, thus effectively removing potential adopters from considering the product (Lau & Ng, 2001). Consumers are more impacted by losses and perceived risk than gains, and need to see a stronger upside to a choice to overcome potential risks (Bettman, Luce, & Payne, 1998; Wangenheim, 2005). Risk is divided into three types: functional, financial, and social. The first two are particularly germane to the consumer choice of fuel purchase. The later was a factor in the Keith model where, for example, social pressures may influence the early uptake of hybrid powertrain technology. The weight placed on the consumer goals (performance, price, range, and availability) will vary and will ultimately impact the relative weighting of the utility factors in a model (Bettman, et al., 1998). The level of dissatisfaction matters, with up to 90% of customers choosing not to repurchase (Richins, 1983). Concurrently, higher contact rates are reported for dissatisfied customers with over one third actively informing others (Richins, 1983). Four general categories of decision making and influence are defined:

1. Low cost to switching and high dissatisfaction.
2. High cost to switching and high dissatisfaction.
3. Low cost to switching and low dissatisfaction.
4. High cost to switching and low dissatisfaction.

The likelihood of switching varies between the above listed categories (Lee & Romaniuk, 2009). Vehicle choice falls into category 2 or 4, and can lead to the persistence of unfavorable views that can in turn, lead to market failure. Research also suggests that the elasticity of WOM may be stronger for newer or less established products or technologies such as the SO platform under consideration (Chen, Liu, Cheng-Hsi, & Tom, 2013).

Stakeholders—Defining the System

Considering unfavorable WOM in developing a new model confronts the complex challenge of identifying an appropriate system boundary. The individual stakeholders for the SO fuel-vehicle system each have different, often conflicting objectives within the larger fuel-vehicle ecosystem. Balancing these objectives is a key impediment to consumer adoption of alternative powertrain and fuel technologies (Byrne & Polonsky, 2001). Achieving policy success depends on finding the operational space that meets all stakeholder needs (see Figure 2). The stakeholder characteristics and needs define the model structure, how the behavior and view formation of each stakeholder is represented in the complex system, and provide a qualitative understanding of the system's complexity.

Vehicle Manufacturers

Vehicle manufacturers (original equipment manufacturers or OEMs) need a lowest cost option for fuel economy compliance. The overlapping design options vary from a system design accommodating up to 20% ethanol SO, designed to use 10% up to 30% ethanol SO, requiring a very specific 30% ethanol SO, and an evolution of the (FFV) to a SO FFV (Graves, 2014; Leone, 2014; Woebkenberg,

Figure 2. Venn Diagram illustrating challenges of identifying the union of stakeholder needs

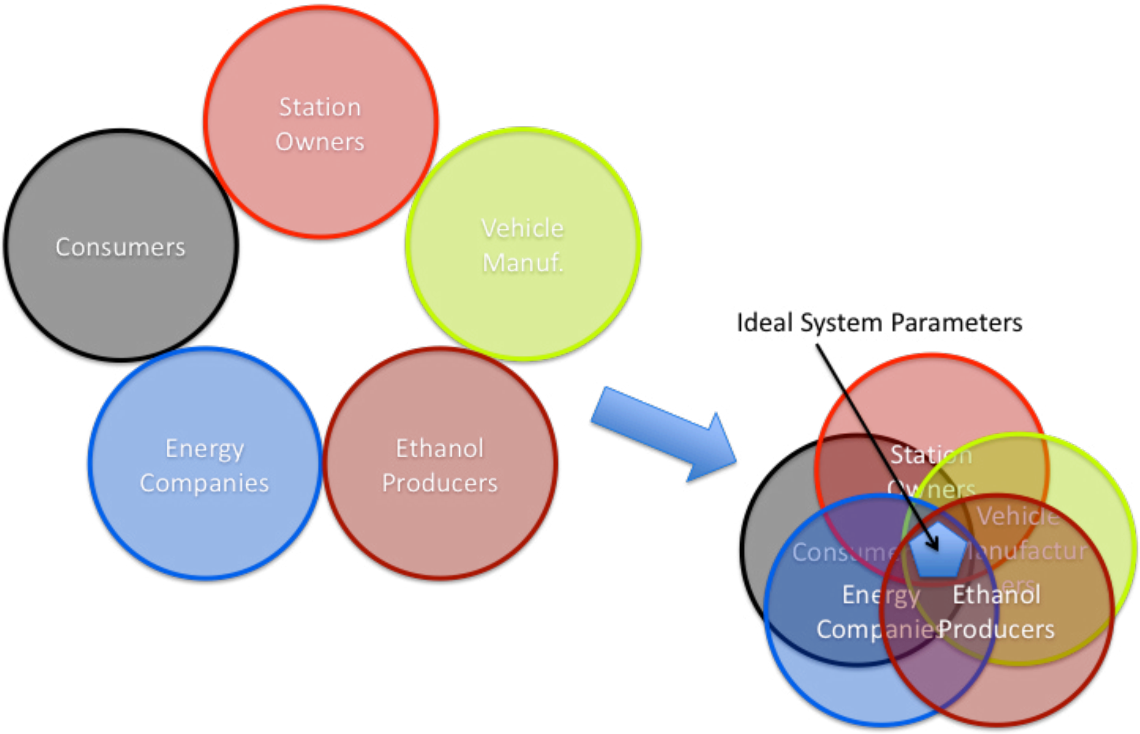
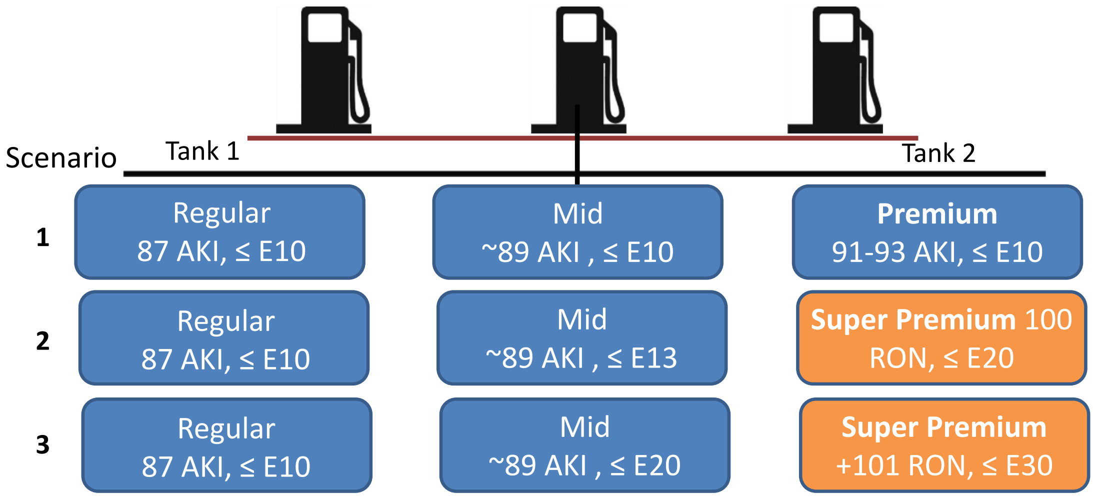


Figure 3. Schematic of two-tank system used in fueling stations



2014). These design options attempt to balance capturing the fuel economy improvement opportunity with system cost and also sensitivity to fuel options. Given fuel availability limitations and consumer behavior, these powertrains also need to function using non-SO fuel. Concurrently, OEMs also need a low-blend (not more than 10% ethanol) fuel available at stations to remain compatible with the existing fleet (see Table 1; see also Figure 3). Although the SO fuel and vehicle may be more expensive, the cost per mile and total cost of ownership may be lower due to the improved efficiency (Anderson et al., 2012; Morey, 2014; Yan et al., 2013).

Energy Companies

Energy companies require a lowest cost fuel blend option for regulatory compliance, and are motived to maximize their profit through the sale of cost-effective fuel. Although more expensive to produce, premium fuels also command a better profit margin. Concurrently, the energy companies need to meet the volume and carbon intensity reduction requirements in the renewable fuel standard (RFS) (see Figure 4) and other state regulations (API, 2014; EIA, 2013). These regulations impose significant risks and challenges to the industry and other stakeholders (Committee of Economic and Environmental Impacts of Increasing Biofuels Production & National Research Council, 2011). The Renewable Fuel Standards requires that up to 15 billion gallons of renewable corn ethanol and 16 billion gallons of cellulosic ethanol be produced and consumed per year by 2022. An additional 5 billion gallons of other advanced renewable fuel is also required. The mandated volumes would result in ethanol fuel blends that exceeded the 10% allowed in most conventional engines and fuel systems. However, due to production capacity limitations the U. S. Environmental Protection Agency has lowered the mandated volumes on a year by year basis.

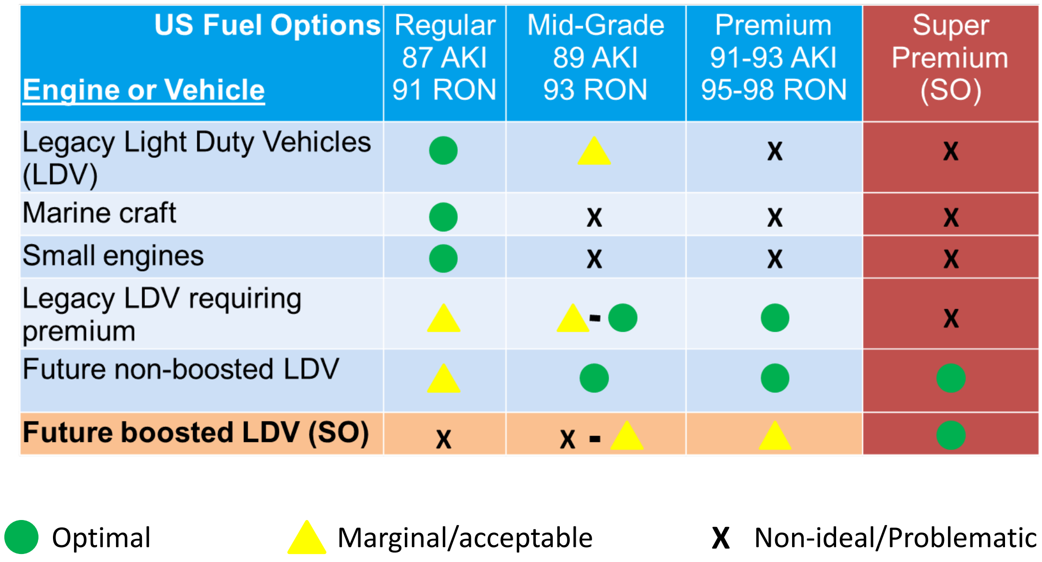
Station Owners

Station owners have higher profit margin on premium fuels and want to increase the demand for these products (Eichberger, 2014). In order to minimize financial risk, any additional expense for the equipment—several thousand dollars per station for above ground components—will need to be recovered through the sale of the higher profit super premium (SO) fuel (Coker, 2014; Eichberger, 2014; Morey, 2014).

Ethanol Producers

Ethanol investors need to see a profit opportunity that outweighs the investment risk. Ethanol producers and their supporting interests must put forth billions of dollars in upfront investment to build out new capacity with lead times over three years (Abengoa, 2014; Cosan, 2013). In order to justify this investment and manage risk, they must foresee significant profits and hold confidence that those profits will be actualized (Parsons, 2014; Stech, 2014). As demand for a nascent industry like ethanol is hard to forecast, producers are dependent upon the current demand and growth patterns to estimate what future demand is, and thus may use conservative forecasts (Parsons, 2014). Capital expenditure investment in cellulosic ethanol (biofuel from plant lignocellulose) production to meet the renewable fuel standards occurred, but the failure to produce ethanol at a competitive market price has resulted in the bankruptcy and halted further expansion (Mongeau, 2010).

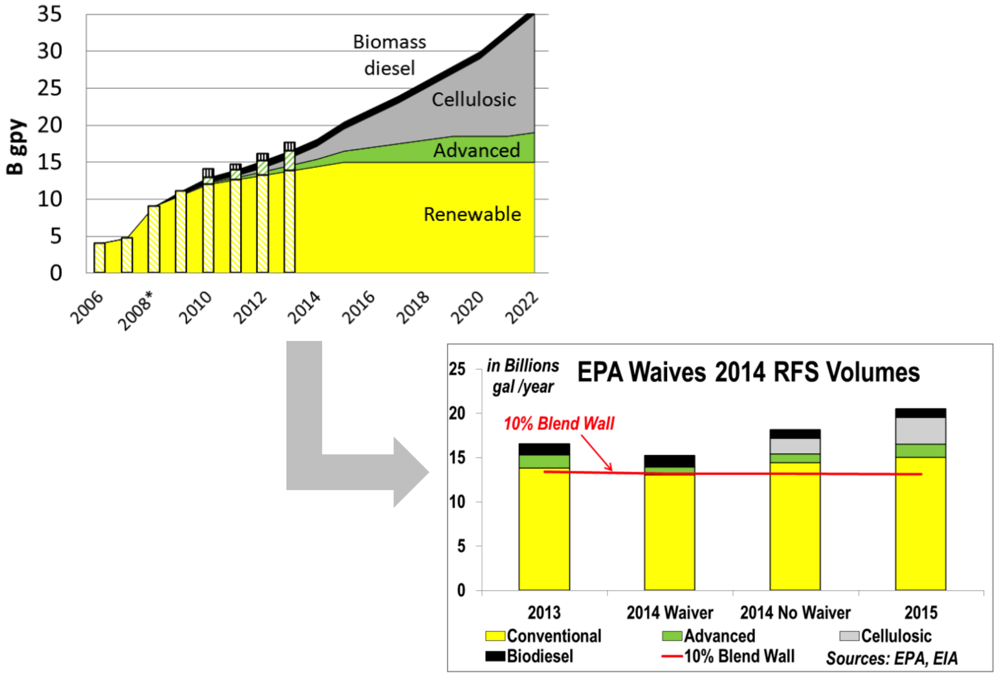
Table 1. Scope of Existing and Potential US Fuel Blend Options and Fuel Users



US Fuel Options **Engine or Vehicle**	Regular 87 AKI 91 RON	Mid-Grade 89 AKI 93 RON	Premium 91-93 AKI 95-98 RON	Super Premium (SO)
Legacy Light Duty Vehicles (LDV)	●	▲	X	X
Marine craft	●	X	X	X
Small engines	●	X	X	X
Legacy LDV requiring premium	▲	▲ - ●	●	X
Future non-boosted LDV	▲	●	●	●
Future boosted LDV (SO)	X	X - ▲	▲	●

● Optimal ▲ Marginal/acceptable X Non-ideal/Problematic

Figure 4. Renewable fuel standard mandated fuel by year (EIA, 2013; "Regulation of Fuels and Fuel Additives: 2013 Renewable Fuel Standards, " 2013)



Consumers

Consumers need to perceive improved utility in the fuel and vehicles relative to competing options. Otherwise market adoption will *not* occur. Risk aversion may often lead to suboptimal choices (Denrell, 2008). This behavior is currently observed with FFVs, where despite vehicles and stations, the average FFV refuels with E85 is less than once per year (Alliance of Automobile Manufacturers, 2013). Analysis shows that the choice is often driven by availability and convenience of access as well as price and range (Pouloit & Babcock, 2014). Consumers respond to their individual and immediate needs (Walther et al., 2010). Concurrently, early failures or poor experiences can preclude future experiences that may correct the perceived utility (Denrell, 2008). The SO vehicles offer a platform that when fueled with SO gasoline blends can offer efficiency, performance, and range, but can also run on non-SO fuel (see Table 1) with reduced performance. The utility of the SO platform must be positive relative to the competing options in order for widespread adoption to occur.

High Level causal loop diagram

The causal loop diagram based on the stakeholder characteristics (see Figure 5) illustrates the complex relationships and feedbacks between stakeholders. The variables in red capture the word-of-mouth (WOM) and add to the traditional alternative fuel structure developed by Keith (2012b). Specifically, it illustrates the tension and interplay between the energy companies, fuel producers, and retailers (black font dark blue arrows), OEMs (brown font, teal arrows), and consumers (red font and light blue arrows). Even this relatively high-level causal loop diagram contains significant complexity, including reinforcing loops that can work in both vicious and virtuous cycles depending on the strength of favorable versus unfavorable WOM. The qualitative static analysis of the causal loop demonstrates the importance of dynamic modeling of the complex interactions and choices in the multi-stakeholder system. Understanding the exact behavior and causes under a given set of exogenous inputs calls for formal modeling and is covered in the results and discussion sections.

Static analysis of the causal loop diagram generates questions and hypothesis for dynamic model testing. First, for SO vehicles availability of infrastructure is not sufficient to ensure stable adoption. Second, the experience from using the vehicle and infrastructure depends on the availability of fuel, vehicle performance on given fuel options, and price of the fuel. Unfavorable consumer experience can overwhelm or undermine efforts to introduce the platform through marketing and classical familiarity accumulation. Third, aggressive vehicle deployment and long delays in fuel production capacity may cause the virtuous reinforcement to flip to vicious and system collapse reinforcement when consumers become dissatisfied with fuel price or availability.

Model

Consumer choice and negative feedback

The current alternative fuel adoption model developed by Keith utilizes the social contagion/diffusion model common in SD (Keith, 2012b; Sterman, 2000). This model does not contain any mechanisms for market growth turning to collapse based on unfavorable experience and consumer perception. This limits the opportunity to observe a growth then collapse scenario other than through exogenously imposed limits on infrastructure. Even then,

Figure 5. Causal loop diagram of an alternative fuel—powertrain system

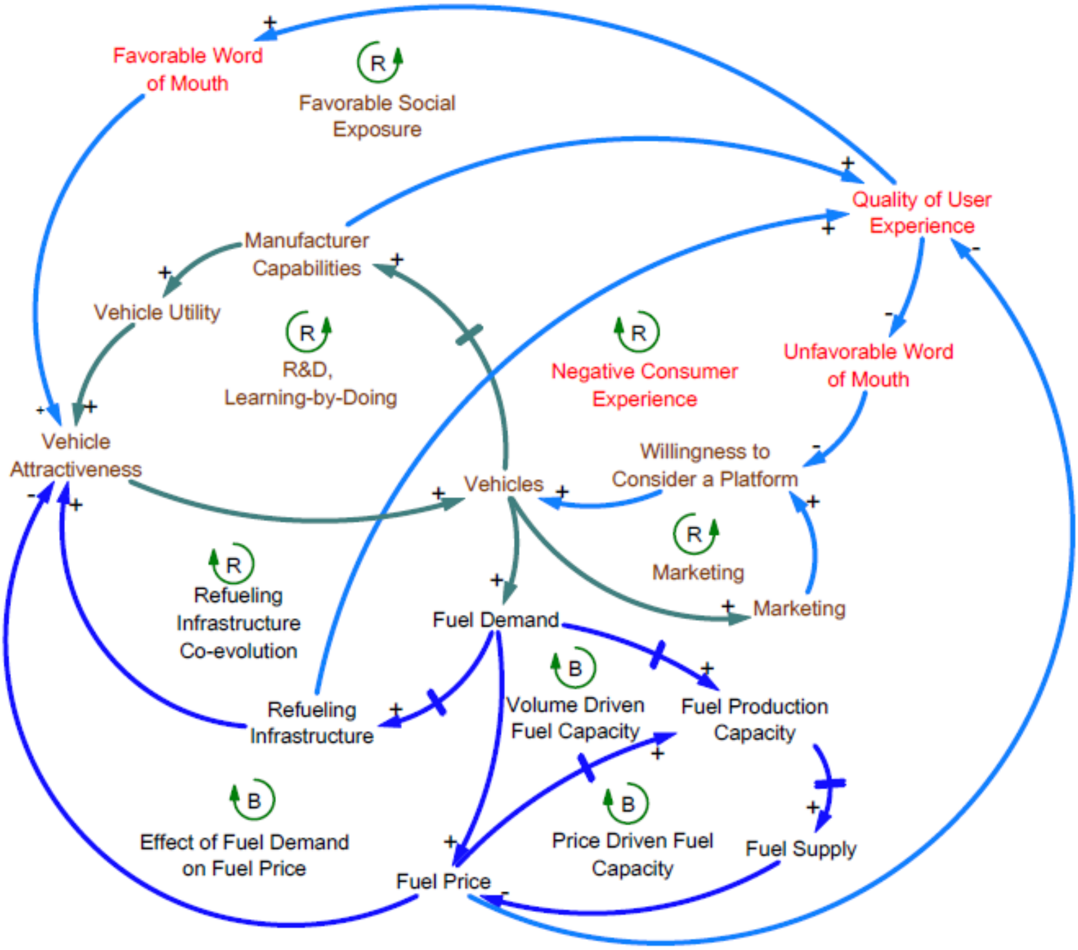
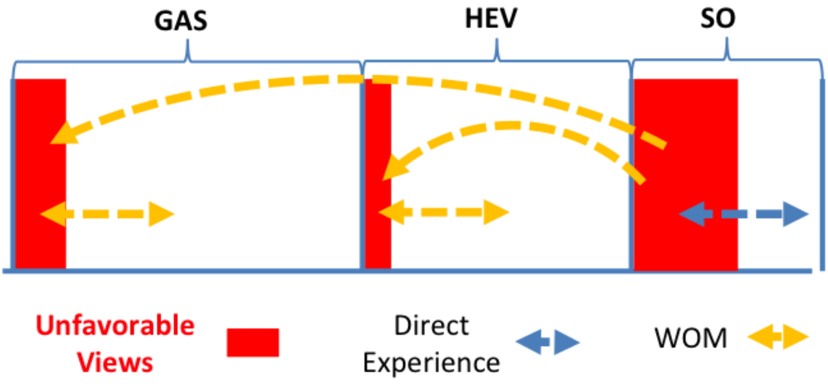


Figure 6. View formation about SO platforms held by each technology platform



this only affects the immediate decision of potential consumers and does not capture long-term effects and delays of opinions in the technology platform. If the infrastructure lag is closed then sales would resume, but in reality the market doesn't behave that way. Unfavorable opinions will be held and will impact the technology uptake. Since the unfavorable opinions tend to prevail, it is much harder to move people from an unfavorable view to a favorable view than it is to disappoint them because of a bad first-hand experience.

The inclusion of the unfavorable view and WOM has an asymmetrical impact. Favorable views result in a behavior similar to the conventional familiarity. If potential adopters with favorable views are willing to consider the new platform more (which doesn't guarantee adoption and depends on the choice model), the potential adopters with unfavorable views are not going to even consider the technology unless their views change, and are removed from the market.

Unfavorable views form and evolve differently for users and potential adopters. Users change their views based on direct experience, while potential adopters of a technology rely on WOM. Figure 6 shows the main mechanisms of transmitting the views between users of SO vehicles and non-users. While users can change views of potential adopters this link is unidirectional, as potential adopters cannot change views of actual users. In addition, the structure shown in Figure 6 is working simultaneously in all directions, affecting and converting all potential views—favorable, unfavorable, and uninformed as people contact each other. Although not explicit, the strength of the conversion is different, and reflects inherent asymmetry of the unfavorable and favorable WOM mechanisms identified in the literature review.

In general SD models do not consider the effect of utility function on WOM. There is a single utility for a given technology platform that is evaluated by the consumer at the time of purchase and is assumed to remain constant for the duration of ownership of the durable good (automobile). Given the relatively higher utility of a platform a market failure will only occur when there is inadequate WOM to accumulate and sustain critical market share or volume (Struben, 2006). However, utility not only affects the purchasing decision, but it influences the vehicle owner's experience, and in turn shapes the quantity and quality of the WOM stories. In the model presented in this paper, the utility of the buyer and user are distinct variables. Utility of the buyer is defined as

$$U_1 = f(\overline{u_1}, \overline{u_2}, \dots, \overline{u_n})$$

where $\overline{u_i}, i \in S_b$ is the average perceived utility component (attribute) at the time of purchase, S_b is the relevant set of utility components used to evaluate competing market offers at the time of purchase. Utility of a user is defined as

$$U_2 = f(u_1, u_1, \dots, u_n)$$

where $u_i, i \in S_u$ is the actual utility component (attribute) during the use of the vehicle, S_u is the relevant set of utility components used to evaluate owned vehicle/product.

The utility of a user reflects the perception post purchase during the use of the durable good (vehicle) which may be affected by a different set of factors not considered by the consumer at the time of purchase, or which change over time. Generally, both sets don't have to be equal, $S_b \neq S_u$ but there exists an overlapping subset of utility components used both for purchasing decision and for evaluating $S_b \cap S_u \neq \emptyset$. The purchase utility function is determined by such parameters as fuel price, fuel availability, vehicle price, and vehicle performance attributes. The user utility has some overlapping components such as fuel price and availability, and the actual perceived performance of the vehicle based on the fuel choice. The values of the factors will dynamically change over time and shape the quality and quantity of the WOM and the influence it has on the potential consumer. For example, in a static condition the utility at a given point in time may be very positive for SO vehicles due to the current fuel price and possible marketing and incentives, but the perception and resulting WOM from existing consumers may be negative due to the actual experience on fuel availability and price over time.

Unlike battery electric vehicles, compressed natural gas vehicles, and fuel cell vehicles that are dependent on a single dedicated fuel, the SO vehicles have multiple fuel options. Fuel purchase post vehicle purchase is determined by user by comparing consumer utility U_2 for two fuel options (regular gasoline and SO fuel) and is important for determining SO vehicle and ethanol market growth. The Keith model doesn't take into account the post vehicle purchase consumer choice presented to SO vehicle owners of what fuel to use to maximize their current utility based on fuel price, availability, and vehicle performance. Presumably, consumers choose the SO platform to take advantage of extra features (better range, acceleration, etc.) offered by means of using SO. While SO vehicles are downward compatible and can run on non-SO gasoline, their performance is subpar. A consumer considering U_2 might decide to choose regular gasoline fuel due to high SO fuel price or its low availability. The resulting performance gap or efforts expended to search for SO fuel impacts perception and consumer experience as described in the unfavorable view formation section of this paper, which in turn influences market adoption.

The model makes no pre-determinations as to how future consumers may respond to fuel price, fuel availability, and vehicle performance. In reality, consumers are heterogeneous. If the average utility of using a non-SO fuel is greater for a SO vehicle, this will result in some fraction of those consumers using the non-SO fuel based on the relative utility. Depending on the frequency of this condition, SO adopters will develop a negative view of the technology and will result in lower total ethanol consumption.

The existing model developed by Keith (2014) is used as the foundation with an additional module developed for the consumer view. The exogenous inputs and variable set points are drawn from the literature and model developed by Keith (2014). The incorporation of the asymmetrical feedbacks of favorable and unfavorable WOM in the new model (see Appendix A; see also Figure 10) can inform the system parameters in which the needs of the stakeholders can all simultaneously be met.

The model evolved from the traditional aging chain and co-flow structure (typically required to track attributes) to one with a single stock and four-dimensional subscripts. This approach offers benefits and flexibility needed to capture the additional system complexity and allows the model to be used in other applications.

The following subscripts are used:

- *i- the technology platform of the owners (GAS,HEV,SO GAS),*
- *j-the technology they are evaluating (GAS,HEV,SO GAS),*
- *v-the current views of technologies (favorable, unfavorable, uninformed),*
- *u-the new views of technologies (favorable,unfavorable,uninformed),*
- *a-age group of the vehicles.*

Drivers change their views based on direct experience

$$\Delta_{i,j,v,u,a}^{drivers} = \begin{cases} \dfrac{V_{i,j,v,a}\, \mathcal{M}_{v,u}\, P^{drivers}(CSL_i)}{\tau^{drivers}}, u = favorable \\ \dfrac{V_{i,j,v,a}\, \mathcal{M}_{v,u}(-\, P^{drivers}(CSL_i))}{\tau^{drivers}}, u = unfavorable \end{cases} \left[\frac{vehicles}{year}\right], \forall\, i = j$$

where $V_{i,j,v,a}$ is a stock of vehicles, $M_{v,u}$ is the square matrix of allowed directions and strengths of view changes from view v to view u, $P^{drivers}$ is function of probability of view change given the customer satisfaction level CSL_i, and $\tau^{drivers}$ is the time to change views of drivers of a platform in years.

Nondrivers form their opinions through the word of mouth by interacting with both drivers and other nondrivers of a technology platform.

$$\Delta_{i,j,v,u,a}^{nondrivers\ from\ drivers} = V_{i,j,v,a}\, \lambda\, \mathcal{M}_{v,u}\, P_{j,v}^{drivers}\, \pi^{drivers} \left[\frac{vehicles}{year}\right]$$

$$\Delta_{i,j,v,u,a}^{nondrivers\ from\ nondrivers} = V_{i,j,v,a}\, \lambda\, \mathcal{M}_{v,u}\, P_{j,v}^{nondrivers}\, \pi^{nondrivers} \left[\frac{vehicles}{year}\right]$$

$$\Delta_{i,j,v,u,a}^{WOM} = \Delta_{i,j,v,u,a}^{nondrivers\ from\ drivers} + \Delta_{i,j,v,u,a}^{nondrivers\ from\ nondrivers}$$

where λ is average contact rate, $P_{j,v}^{drivers}$ and $P_{j,v}^{nondrivers}$ are probabilities of contact with drivers and nondrivers of technology j holding view v, and $\pi^{drivers}$ and $\pi^{nondrivers}$ are probabilities of view change after contact with drivers and nondrivers.

In addition, marketing provides the way to facilitate conversion of nondrivers to favorable category. The model assumes that drivers cannot be influenced by marketing efforts; as they form their views based on the direct experience with the platform.

$$\Delta_{i,j,v,u,a}^{marketing} = V_{i,j,v,a}\, M_j\, \mathcal{M}_{v,u} \left[\frac{vehicles}{year}\right], \quad \forall\, i \neq j$$

where M_j is the total marketing effect for a platform j.

There is also a possibility that nondrivers will forget their opinion if not exposed to a platform for a certain period of time.

$$\Delta_{i,j,v,u,a}^{forgetting} = \frac{V_{i,j,v,a}}{\tau^{view\ forgetting}} \left[\frac{vehicles}{year}\right], \quad \forall\, i \neq j, u = uninformed$$

Where $\tau^{view\ forgetting}$ is time to forget the view in years. More detailed description of the model including explanations of other variables is in the Appendix A.

Model testing

The objective is to uncover the mechanisms influencing the adoption of the technologies. Given that empirical information is incomplete for the system, an exploratory approach to modeling is used. Although the resulting model cannot be taken as a precise image of the system, it does provide relevant insight into the resulting behavior from the structure (Bankes, 1993).

In order to evaluate the influence of unfavorable and favorable WOM the customer satisfaction level $CSL_{SO\ GAS}$ as affected by the utility U_2 (Eq. (1) was defined exogenously with low starting points explored through the scenario evaluation. This means that $U_2 < U_1$ creates frustration from the actual experience being below expectations set at the time of purchase.

Ford's loop knockout methodology was used to test the model mechanics and demonstrate the importance of the unfavorable WOM in determining market size (Ford, 1999). Loop knockout identified the dominant loops and underlying factors and relationships that lead to the observed system behavior necessary to inform policy development. Simulations were run with the set of parameters corresponding to aggressive promotion of SO vehicles ($500 million of additional marketing/year) (Keith, 2012b). Customer satisfaction level $CSL_{SO\ GAS}$ reflecting the combination of infrastructure availability, vehicle performance, and SO fuel price was defined on the dimensionless scale from -1 to 1 to start at negative 0.1 and end at 0, leaving consumers unsatisfied with the value proposition of a new SO platform. Two identical scenarios were defined with only a difference in the sensitivity S to the negative WOM dynamics such that the square matrix $M_{v,u}$ of allowed directions and strengths of view changes from view v to view u becomes

$$\mathcal{M}_{v,u} = \mathrm{S}\begin{bmatrix} 0 & Sp_1 & 0 \\ Sp_2 & 0 & 0 \\ p_3 & Sp_4 & 0 \end{bmatrix}$$

$$p_1 = p_{favorable\ to\ unfavorable}\,, \quad p_2 = p_{unfavorable\ to\ favorable}$$

$$p_3 = p_{uninfluenced\ to\ favorable}\,, \quad p_4 = p_{uninfluenced\ to\ unfavorable}$$

Where p_1 - p_4 are the strengths of the allowed transition between consumer views of a platform (see Appendix A for full specification). Having sensitivity S as a multiplier for all strengths except for p_3 ensured that setting S = 1 set up the scenario with the full effect of unfavorable and favorable WOM and by setting S = 0 the baseline scenario is set with no effect of unfavorable WOM, but where favorable WOM is functioning.

Figure 7 shows a simulation of the model based on conventional structure where there is no unfavorable WOM (S = 0), which

Figure 7. Model results without negative word of mouth

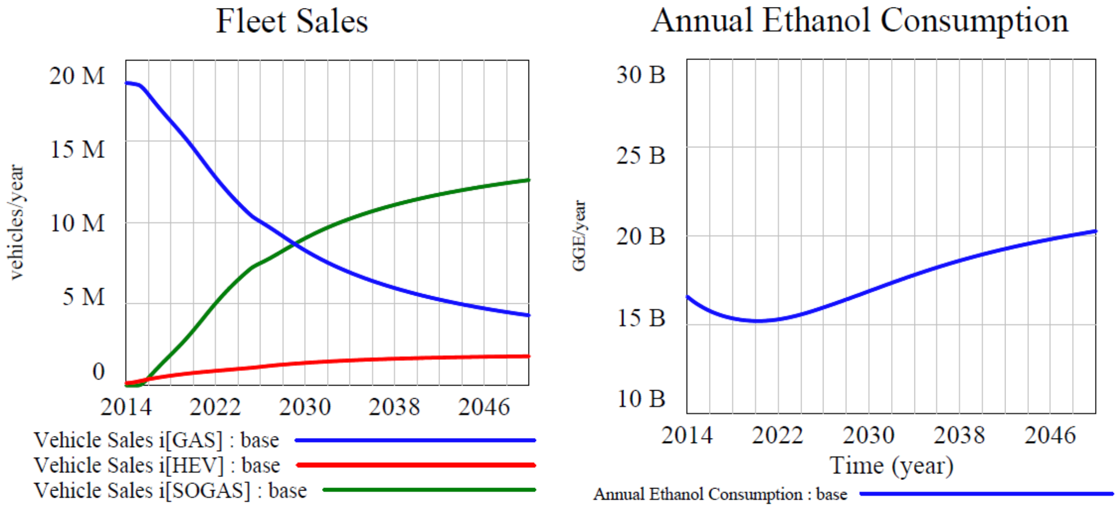
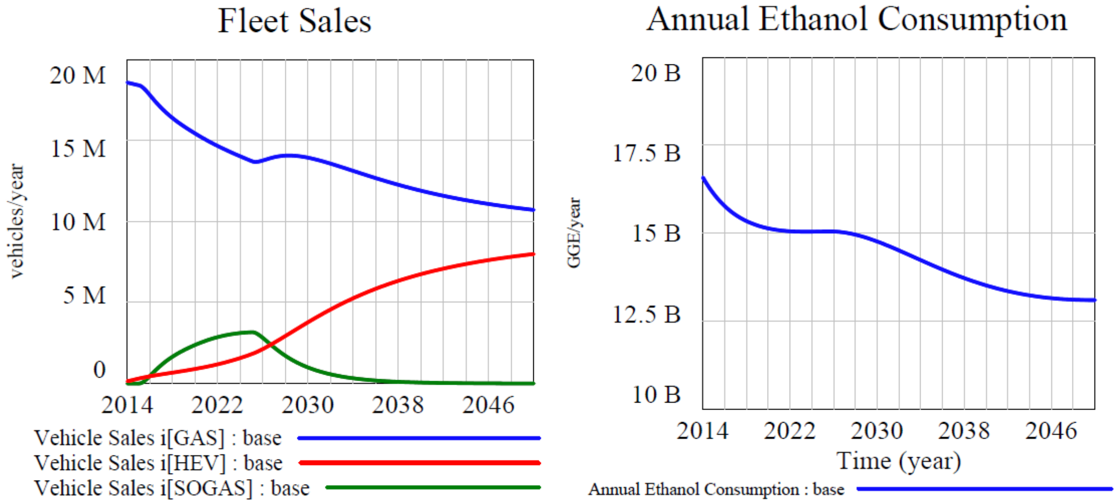


Figure 8. Model results with negative WOM



demonstrates a very optimistic picture about the potential adoption of SO even when the perceived utility of the vehicle is poor. This simulation leads to a conclusion that SO (SOGAS) will overtake conventional gasoline (GAS) platform before the end of the simulation (2046), and the annual ethanol consumption will exhibit a strong growth trajectory.

However, with the unfavorable WOM turned on (S = 1), the simulation shows that this scenario does not guarantee SO success and results only in the temporary mitigation of the downward ethanol consumption trend (see Figure 8). As soon as the marketing program that was promoting the new vehicles ends after 10 years (2024), the unfavorable consumer experience takes over and drives down vehicle sales.

In the scenarios explored in this research, 100% of the adverse effect on market share of SO vehicles observed between Figure 7 and Figure 8 is due to unfavorable WOM because the buyer utility U_1 (Eq. (1)) of the SO vehicle was set to have a *higher* relative value versus competing platforms. This means that the SO platform is a clear winner in the absence of unfavorable WOM. Therefore, the negative market change observed in the simulation with full unfavorable WOM sensitivity (S = 1) is solely due to low customer satisfaction level affected by inferior post purchase user utility U_2 (Eq.(2)). While in a general market unfavorable WOM will not be the only mechanism influencing market change, this paper focuses on establishing the need and providing arguments to directly consider unfavorable WOM as a distinct phenomenon affecting market growth. It does not negate the role of also considering the classic market mechanisms utilized in traditional models and policy development.

Results & Analysis

The specific conditions that lead to loop dominance in a given time interval are dependent on the exogenous inputs. Consequently analysis focuses on qualitative observations and explanations that provide insight into policy formation.

Based on the model structure and analysis, the marketing and consumer views, in part derived by the utility of the fuel choice, were identified as the most important factors in affecting the views of potential adopters and total ethanol demand. Lack of empirical data on the consumer perception exists on how to relate availability and price of fuel and performance of SO vehicles on the different fuel options to consumer experience. Therefore, the link was intentionally broken and a range of inputs spanning the entire factor space tested using multivariate Monte-Carlo analysis. This identified the ranges under which the different loops dominate and inform where the system boundaries need to be and where the stakeholders will need to operate in order to achieve sustained ethanol consumption increases.

Scenario runs with varying marketing ranging between \$0 and \$500 million/year over a 10-year period were performed and the consumer view was varied. The entire consumer response space (-1 to +1) was mapped showing ethanol consumption and SO vehicles (see Figure 9). Final consumer experience is always equal to 1 and the trajectory is second order polynomial.

Marketing is needed to initiate sales, but sees rapidly diminishing returns. Concurrently, the marketing impact is highly affected by consumer view. This can result in the unintended consequence of growth then collapse. The effect is pronounced when marketing is reduced but consumer experience is still negative. This occurs because the only counterbalance to the negative WOM is the existing positive views, which are diminished over time.

Analysis of the surface plot (see Figure 9) suggests certain thresholds for market growth. In effect, the consumer view must be positive by the time marketing for platform introduction has ended to achieve the sharp increase in ethanol consumption. The strength of consumer experience is observed to be more dominant than marketing in determining ethanol demand and SO vehicle market share. When the experience is poor (<0), marketing is unable to generate substantial increase in ethanol consumption, and when the experience is positive (>0) there is diminishing return on marketing investment especially above $150 million/year.

Discussion

The results show the importance of including unfavorable views and WOM in the SO market model and understanding their mechanism of influence on the observed system behavior. Although all models can be considered wrong to some degree, they can inform policy development by providing valuable insight into the behavior and sensitivities of components of the system in question (Sterman, 2002). This discussion focuses on the importance of including unfavorable perceptions, and multiple stakeholders and assumes the precision of the results is of secondary importance. The application of loop knockout illustrates the difference between the behavior seen in the existing single stakeholder model and new model. A key difference is the ability to allow for a change in reinforcing social exposure loops from a virtuous to a vicious cycle. Fuel choice, and the ability of the market to maintain adequate supply and price point, plays a role in influencing the consumer perception and vehicle utility. Although the instantaneous perception and utility of the SO fuel can quickly change, the views of the vehicle owners are harder to change. This can lead to persistent negative reinforcement than can undermine long-term prospects for the technology platform, and place increased importance of accommodating all stakeholder needs in the earlier years of technology deployment.

The influence of unfavorable WOM depends on consumer satisfaction, rates of forgetting, and rates of conversion. If the rate of forgetting is very high, this reduces down to the immediate experience and the ratio of favorable to unfavorable WOM. The end result is a delay in market growth until adequate utility is reestablished and favorable WOM dominates the social diffusion. As long as some unfavorable views exist, the rate of market growth and carrying capacity will always be lower than what is observed in the Keith model and projected in current policy and regulations, and will either follow a reduced positive trajectory or stagnate. However, under more severe conditions unfavorable WOM will dominate after initial market introduction and can lead to a reverse tipping point in which the market collapses through the growth of the unfavorable view. In the case suggested by Chen, et al. (2013) and Denrell (2008) where consumer forgetting of unfavorable experiences is zero or very low and risk aversion to new technology remains high the stock of unfavorable views will continue to grow and erode the potential market capacity (favorable view stock) even when the consumer experience is very high and conversion of favorable views to purchase of SO capable vehicles is high. The total flow of new SO vehicle purchases will remain low, and the stock of SO vehicles in use will decline over time. If adequate marketing or positive changes in vehicle and fuel utility are not introduced in a timely manner then growth of the unfavorable consumer stock will accelerate the negative reinforcement and drive a decay of potential customers towards zero. In reality, the system is likely to collapse well before then as auto manufacturers, fuel suppliers, and retailers are unable to sustain their investment due to diminishing sales.

Conclusions

The new structure presented in this paper helps refine the mental model and analysis of market uptake of complex alternative fuel systems with multiple stakeholders and competing interests with significant implications for regulatory and policy development. The results show that under certain conditions if policy or behavior of one stakeholder is out of sync with the others, then negative feedbacks can occur. Policy that focuses on generating growth in one area (even using SD modeling) can miss critical structure/behavior and lead to erroneous conclusions when only traditional favorable views are assumed and positive feedbacks occur. The inclusion of the unfavorable view stock and associated loop can play a dominant role in determining the growth or collapse of the system. The negative feedback behavior generated by the unfavorable WOM was not previously observable, not considered in the formulation of US ethanol policy, and narrows the system boundaries in which all stakeholders: consumers, energy companies, ethanol producers, OEMs, and fuel retailers can achieve a positive outcome.

In the real world, there is almost certainly some fraction of dissatisfied customers with a given product. In a mature market it is more likely that the system will behave in a manner comparable to the commonly observed market share fluctuation where the growth of unfavorable views is approximately balanced by forgetting. This reflects a system where multiple loops are dominant. In a nascent industry like the SO fuel and vehicle market the role of unfavorable experiences and WOM can dominate and establish a path dependence early on that can ultimately lead to market collapse. This suggests the critical importance of creating and maintaining a very high positive experience, potentially at the expense of technology growth rate, for initial customers and system stakeholders until system maturity is reached. Although the mathematical possibility of marketing levels and manufacturer subsidies to improve the utility exists, policy makers should be aware that this is not a practical long-term strategy. Other factors that can influence consumer view include policy that influences the price of the fuel, the availability of the fuel at the initial vehicle deployment, or policies that change the amount of technology investment in the powertrain platform and improve the vehicle performance.

To achieve the policy objectives of a regulatory mandate imposed on a single stakeholder all stakeholders have to work together to not only fulfill each of their specifications before the platform launch (e.g., create optimized engine, start conversation of stations to be SO fuel compatible, build initial ethanol capacity), but also create the environment where all these elements work together and guarantee everyday positive experience of early adopters. This can be adjusted through one of several mechanisms: price of the vehicle, availability of the SO fuel, and the price of the fuel. These are balanced by needing to maintain positive finances for the other stakeholders. For example, the early investment in fueling infrastructure and ethanol production infrastructure ahead of the vehicle deployment will increase the supply and availability of SO fuel, improving consumer utility, but will also lead to cash flow and financial risk for the respective stakeholders resulting in delayed price and availability risks. The relative fuel economy and performance of the vehicle can also be adjusted but not simply by policy or marketing levers. It is clear that each of the items on this list belongs to the domains of different stakeholders, meaning such an environment can only be created by all stakeholders acting together and synchronizing their efforts to make sure they do not fall prey to capability traps. These capability traps could include prescribed or mandated sales volumes. From a policy perspective the capability traps in the ethanol-fuel and vehicle system derive from the fact that different government agencies regulate or manage policy for each of the stakeholders. While they depend on the behavior of the other stakeholders they lack the ability to directly control or influence their behavior. This should serve as a warning to policy and regulatory development that if ethanol supply is not closely matched to demand due to aggressive vehicle sales, poor vehicle performance, constraints in ethanol supply, or ethanol price then the outcome may be opposite of what is intended. In effect, the behavior of the multiple stakeholders serves to mitigate the growth rate of ethanol consumption.

Specific to ethanol consumption the analysis demonstrates that SO platforms have the potential to reverse the downward trend of ethanol consumption and achieve a substantial increase compared to the business as usual scenario where the ethanol consumption plummets over time due to fuel economy improvements of the vehicle fleet. The current scenarios tested don't show that it is possible to increase the ethanol consumption to the RFS mandated level of ~30 billion gallons by 2022 given the current ethanol content of regular gasoline fuel and the projected 20–30% of ethanol in SO fuel for the vehicle stock used in the model (using current fuel economy regulations out to 2025). Therefore, in order to reach ~30 billion gallons of ethanol from today's level of about 15 billion gallons requires other sources or uses of ethanol consumption, such as trucks, and other policies that may incentivize the use of SO ethanol fuels (such as carbon pricing). More broadly, the results imply a reorientation of policy from a prescriptive approach to a performance-based approach with incentives. This finding is consistent with the "narrow" version of the Porter Hypothesis proven by Lanoie et al. (2011), which states that flexibility in regulations such as performance based regulations lead to better innovation and outcomes Furthermore, the results support the framework developed by Carlson requiring economic value as the precursor to disruptive technology change in a policy framework that is able to adopt to future unknown conditions and maintain flexibility (Carlson & Fri, 2013). Given the relative long-term uncertainty of the factors affecting relative utility, vehicle demand, and travel demand the current RFS is poorly structured to ensure sustained ethanol market growth. The system behavior and limitations derived from an expanded policy analysis can better inform expectations and help manage risk for the stakeholders by informing more constrained expectations and stakeholder behavior.

Figure 9. Surface map for ethanol consumption as a function of marketing and consumer view

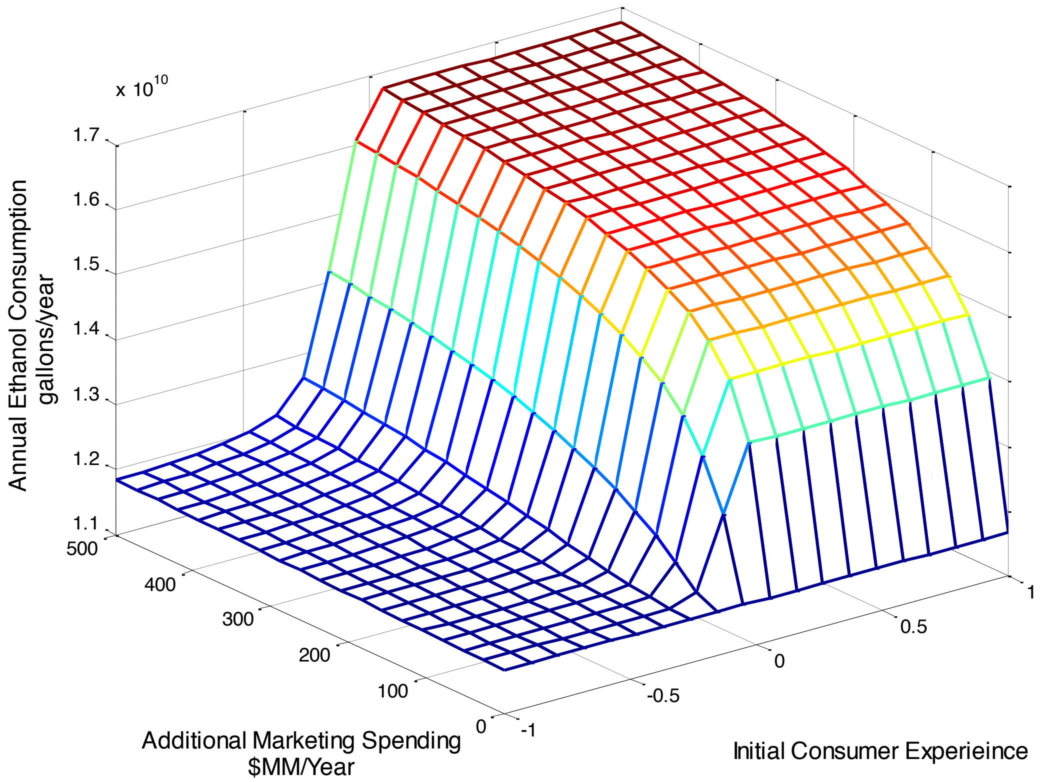
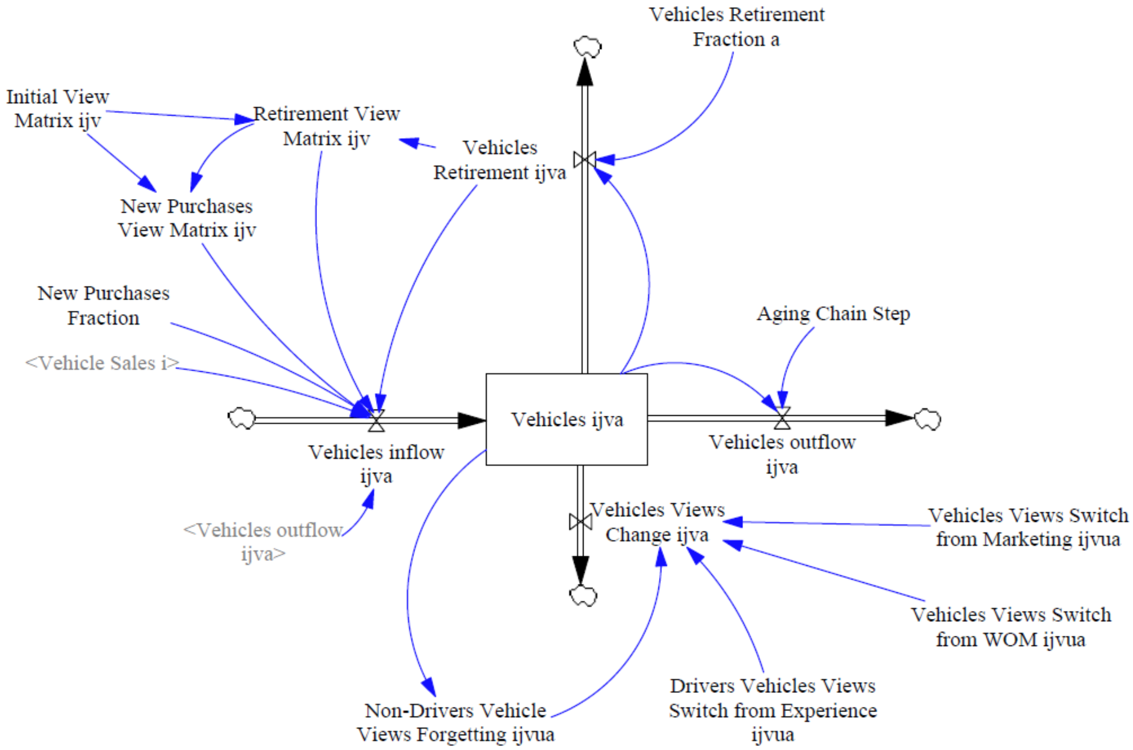


Figure 10. Simplified model structure using subscripts



Appendix A

The current model structure (Figure 10) covers the following dimensions though subscripts:

- *i- the technology platform of the owners (GAS,HEV,SO GAS),*
- *j-the technology they are evaluating (GAS,HEV,SO GAS),*
- *v-the current views of technologies (favorable,unfavorable,uninformed),*
- *u-the new views of technologies (favorable,unfavorable,uninformed),*
- *a-age group of the vehicles.*

Since every platform owner has to have an opinion of every platform, increasing the number of platforms on the market leads to the $O(avi^2)$ expansion of model state variables.

Mathematical formulation

It is important to maintain the integrity of stock levels, so that the same number of drivers has opinions about every existing platform.

Mathematically, it is represented as the following constraint

$$\sum_{v,a} V_{i,k,v,a} = \sum_{v,a} V_{i,l,v,a}\,, \qquad k,l \in J, k \neq l, J = \{available\ platforms\}, \qquad \forall\ i$$

The matrix $M_{v,u}$ is defined as

$$\mathcal{M}_{v,u} = \begin{bmatrix} 0 & p_1 & 0 \\ p_2 & 0 & 0 \\ p_3 & p_4 & 0 \end{bmatrix}$$

where the diagonal elements are equal to 0, as the views cannot be changed to themselves. The last column is also 0, as the model does not allow views to change to “uninfluenced” through the WOM mechanism since WOM implies influence (favorable or unfavorable). Changes to uninfluenced are taken care of by the separate process of forgetting. Other elements p_1 - p_4 are the strengths of the transition between other combinations of views. Exact values depend on the market. In this model the following values are:

$$p_1 = p_{favorable\ to\ unfavorable} = 0.9$$

$$p_2 = p_{unfavorable\ to\ favorable} = 0.5$$

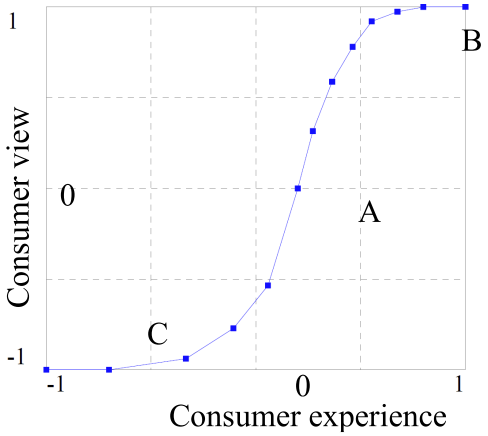
$$p_3 = p_{uninfluenced\ to\ favorable} = 1$$

$$p_4 = p_{uninfluenced\ to\ unfavorable} = 1$$

where different values for p_1 and p_2 reflect the asymmetry of WOM, i.e., it is easier to convert people to a negative opinion, than to bring them back to the favorable camp.

Probability of view change $P^{drivers}$ is best defined using empirical data. In the absence of this data a table function (see Figure 11) suggest by the literature is used that reflects consumer risk aversion and behavior based on strength of view. Consumer experience is normalized on a scale of -1 to 1 where -1 reflects full dissatisfaction and 1 is full satisfaction. Consumer view is also dimensionless variable that reflects the strength and valence of the consumer influence on a scale of -1 to 1.

Figure 11. Table function for consumer view change versus consumer experience.



The shape of the graph reflects the asymmetry of the effect of consumer experience on the view change. Neutral position (0 on the Y axis) corresponds to the slightly above median consumer experience (0.2, point A), as customers remain unsatisfied until the product performs at the above average level. In addition, saturation occurs at the level of consumer experience equal to 0.8 (point B), reflecting the fact that people are going to be fully satisfied when the experience is close to ideal, and people remain fully unsatisfied until the experience moves above -0.7 (Point C), illustrating that people are still fully unhappy about the product when the experience is very low.

The time to change views of drivers of $\tau^{drivers}$ is set at one month; considered to be a reasonable time to form strong perception about the car a person owns.

Probabilities of contact with drivers and nondrivers of technology j holding view v, and probabilities of view change after contact with drivers and nondrivers are defined as

$$P_{j,v}^{drivers} = \frac{\sum_a V_{i,j,v,a}}{\sum_{i,v,a} V_{i,j,v,a}}, \qquad \forall\, i = j$$

$$P_{j,v}^{nondrivers} = \frac{\sum_{i,a} V_{i,j,v,a} - \sum_a V_{j,j,v,a}}{\sum_{i,v,a} V_{i,j,v,a}}$$

$$\pi^{drivers} = 0.1$$

$$\pi^{nondrivers} = 0.01$$

$$\lambda = 20\left[\frac{vehicles}{year}/vehicle\right]$$

Total marketing effect for a platform j is

$$M_j = M_j^{initial} + \int \left(M_j^{accumulation} - M_j^{forgetting} \right) dt$$

$$M_j^{accumulation} = \mathcal{S}_j \sigma \left[\frac{1}{year} \right]$$

$$M_j^{forgetting} = \frac{M_j}{\tau^{marketing}} \left[\frac{1}{year} \right]$$

where S_j is the total marketing spending per platform j in \$MM/year, σ is market effectiveness in 1/\$MM, and $\tau^{marketing}$ is marketing forgetting time in years.

Given all the possible mechanisms of view change listed above, the full equation for the flow changing stock of vehicles $V_{i,j,v,a}$ is

$$f_{i,j,v,a} = \sum_u \left(\Delta_{i,j,v,u,a}^{drivers} + \Delta_{i,j,v,u,a}^{WOM} + \Delta_{i,j,v,u,a}^{marketing} + \Delta_{i,j,v,u,a}^{forgetting} \right)$$
$$- \sum_v \left(\Delta_{i,j,v,u,a}^{drivers} + \Delta_{i,j,v,u,a}^{WOM} + \Delta_{i,j,v,u,a}^{marketing} + \Delta_{i,j,v,u,a}^{forgetting} \right)$$

Since $\Delta_{i,j,v,a}$ is the outflow, the first term depletes the stock of vehicles having view v to all other potential views, and the second term fills stock of vehicles having view v with the inflow from all other views.

Each age group has the outflow of retirement of vehicles

$$f_{i,j,v,a}^{retirement} = V_{i,j,v,a} \rho_a \left[\frac{vehicles}{year} \right]$$

$$\rho_a = \{0.001, 0.01, 0.1, 0.3\} \left[\frac{1}{year} \right]$$

where ρ_a is retirement fraction for each age group.

The inflows and outflows to establish the mechanism of aging along the aging chain are given as

$$f^{inflow}_{i,j,v,a_k} = \begin{cases} N_i\left(\mathcal{V}^{new}_{i,j,v}\alpha + \mathcal{V}^{retirement}_{i,j,v}(1-\alpha)\right), & k = 1 \\ f^{outflow}_{i,j,v,a_{k-1}}, & \forall\, k \neq 1 \end{cases} \quad \left[\frac{vehicles}{year}\right]$$

$$f^{outflow}_{i,j,v,a} = \begin{cases} 0, & a = last\ age\ group \\ \frac{V_{i,j,v,a}}{\tau^{age}}, & a = otherwise \end{cases} \quad \left[\frac{vehicles}{year}\right]$$

$$\mathcal{V}^{new}_{i,j,v} = \int \frac{\left(\mathcal{V}^{retirement}_{i,j,v} - \mathcal{V}^{new}_{i,j,v}\right)}{\tau^{view\ perception}}dt + \mathcal{V}^{initial}_{i,j,v}$$

$$\mathcal{V}^{retirement}_{i,j,v} = \begin{cases} 0, & \forall\,(i = j) \wedge ((v = unfavorable\,) \vee (v = uninformed)) \\ \frac{\sum_a f^{retirement}_{i,j,v,a}}{\sum_{v,a} f^{retirement}_{i,j,v,a}}, & otherwise \end{cases}$$

$$\alpha = 0.25$$

$$\mathcal{V}^{new}_{i,j,v} = \begin{cases} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, & i = GAS \\ \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, & i = HEV \\ \begin{bmatrix} 0.95 & 0.05 & 0 \\ 0.05 & 0.85 & 0.1 \\ 1 & 0 & 0 \end{bmatrix}, & i = SO\ GAS \end{cases}$$

Where N_i is the vehicle sales of platform i in vehicles per year, $\mathcal{V}^{new}_{i,j,v}$ is the matrix of views of first time vehicle buyers, and is $\mathcal{V}^{retirement}_{i,j,v}$ the matrix of views of existing owners of vehicles, α is fraction of first owners in the vehicle sales, $\tau^{view\ perception}$ is time to change the views of first time buyers based on the prevailing opinions of retired vehicles owners, and τ^{age} is the aging chain step in years.

In order to ensure the stocks are initialized in equilibrium, the following equations are used to compute the initial values, assuming four age groups

$$V^{initial}_{i,j,v,a} = I_{ia}\mathcal{V}^{initial}_{i,j,v}$$

$$V_{i,a} = \sum_{v} V_{i,j,v,a}$$

$$I_{ia} = F_i \times \begin{cases} \frac{\rho_{a_4}\tau^{age}\left(1 + \rho_{a_3}\tau^{age}\right)\left(1 + \rho_{a_2}\tau^{age}\right)}{1 + \rho_{a_4}\tau^{age}\left(3 + \tau^{age}\left(\rho_{a_2} + 2\rho_{a_3} + \rho_{a_2}\rho_{a_3}\tau^{age}\right)\right)}, & a = a_1 \\ \frac{V_{i,a_1}}{\left(1 + \rho_{a_2}\tau^{age}\right)}, & a = a_2 \\ \frac{V_{i,a_2}}{\left(1 + \rho_{a_3}\tau^{age}\right)}, & a = a_3 \\ \frac{V_{i,a_3}}{\rho_{a_4}\tau^{age}}, & a = a_4 \end{cases}$$

For other aging steps and number of links in the aging chain, the equations for initial equilibrium conditions become more complicated and are not included in this paper.

Acronyms

- AKI: Anti-Knock Index octane rating
- E20: Gasoline blend with up to 20% ethanol
- E85: High ethanol blend of up to 85% ethanol with the balance gasoline
- FFV: Flex Fuel Vehicle. A vehicle capable of using a fuel blend up to 85% ethanol with the balance gasoline
- HEV: Hybrid Electric Vehicle
- LDV: Light-Duty Vehicle
- OEM: Original Equipment Manufacturer. The automobile brand manufacturers
- RFS: Renewable Fuel Standard
- RON: Research Octane Number
- S&K: Struben & Keith
- SO: Super Octane. Gasoline fuel blends with Anti-Knock Index ratings of 94 or higher, or Research Octane Number ratings of 99 or higher

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