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Greenhouse gas mitigation policies and the transportation sector: The role of feedback effects on policy effectiveness

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ABSTRACT

The US transportation sector is a major contributor to global greenhouse gas (GHG) emissions. As such, policymakers and stakeholder groups have proposed a number of policy instruments aimed at reducing these emissions. In order to fully evaluate the effectiveness of these policies, policymakers must consider both the direct responses associated with policy actions, and the indirect responses that occur through complex relationships within socioeconomic systems. In cases where multiple policy instruments are employed, these indirect effects create policy interactions that are either complementary or competing; policymakers need to understand these interactions in order to leverage policy synergies and manage policy conflicts. Analysis of these indirect effects is particularly difficult in the transportation sector, where system boundaries are uncertain and feedback among systems components can be complicated. This paper begins to address this problem by applying systems dynamics tools (in particular causal loop diagrams) to help identify and understand the role of feedback effects on transportation-related GHG reduction policies. Policymakers can use this framework to qualitatively explore the impacts of various policy instruments, as well as identify important relationships that can be later included in quantitative modeling approaches.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC), in concert with numerous governments around the world, is calling for the mitigation of anthropogenic greenhouse gas (GHG) emissions in order to reduce the negative consequences of climate change (IPCC, 2007). Although historically the United States (US) has resisted implementation of GHG regulations, recent policy proposals have been put forward at the national, state, and local levels that aim to bring GHG emissions under control (Byrne et al., 2007). Indeed, one of the key environmental platforms of the new Obama Administration is the reduction of GHG emissions nationwide.

Predicting the impacts of these policies is difficult. The climate system involves a number of feedback effects that complicate the climate modeling process, and our techno-socio-economic systems also exhibit (perhaps more) complicated dynamics and feedbacks (Fiddaman, 2007). Understanding and modeling these dynamics is important for providing credible, realistic, and usable input to policy decision making (Bahrman et al., 2002).

In the US, the transportation sector emits ~30% of the nation's total GHG emissions annually, and light duty vehicles (LDV) represent ~75% of this transportation component (Energy Information Administration, 2008). Decades of increasing travel demand, combined with low oil prices and consumer preferences for large, heavy, and high-powered vehicles, have exacerbated this problem. Although the US has in place corporate average fuel economy (CAFE) standards, GHG emissions from the LDV sector continue to grow. Policies such as increased efficiency standards (An and Sauer, 2004), low carbon fuel standards (Farrell and Sperling, 2007a), carbon taxes (Nordhaus, 2006), and alternative fuel vehicle incentives (Greene et al., 2004) have been proposed to help to reduce GHG emissions, but as of yet they have either not been implemented or have had little effect. This paper aims to understand why such policies may see resistance in the marketplace through the use of system dynamics (SD) tools.

One of the first steps in modeling these impacts is the development of a conceptual modeling framework that creates system boundaries to capture feedback loops appropriate for a particular policy problem. This paper develops such a framework

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using an important tool of systems modelers: the causal loop diagram (CLD) (Sterman, 2000). A CLD is a useful tool for exploring potential sources of policy resistance, synergies, and unintended consequences. These potentialities can then help define future research questions that can be explored via quantitative modeling methods.

In this paper, we present a CLD developed to explore the impacts of various GHG mitigation policies targeting the LDV segment of the US transportation sector. We include impacts across a time horizon that captures a typical vehicle lifecycle (10–20 years). The CLD considers consumer preferences, producer decision making, LDV market dynamics, and vehicle lifecycle environmental impacts. After presenting the CLD, we demonstrate its use as a decision-making aid by qualitatively evaluating the effectiveness of alternative fuel vehicle subsidies. The CLD also provides insight into opportunities to exploit complementary policies (where policy actions are synergistic), and to avoid incompatible policies (where policy actions are in conflict). Finally, we explore the benefits of using the CLD as an overall systems modeling framework for quantitative simulation analysis.

2. US transportation emissions and climate change

Recent climate modeling studies have found that in order to halt future increases of global average temperatures, and thus avert the negative effects of climate change, US GHG emissions must be reduced to "near-zero" (Matthews and Caldeira, 2008).

To reduce emissions from the passenger vehicle sector, policies have been proposed that affect technology availability (e.g., alternative fuel vehicle mandates), efficiency standards (e.g., corporate average fuel economy standards), fuel characteristics (e.g., low carbon fuel standard), consumer decision making (e.g., tax credits), and producer decision making (e.g., subsidization of corporate R&D) (An and Sauer, 2004; Farrell and Sperling, 2007a, b; Gallagher et al., 2007; Greene et al., 2004; Nordhaus, 2006).

Predicting the impacts of such policies is a challenge. The LDV market is a complex web of technological, social, and economic factors, and policy interventions in one part of this system can have interesting and unexpected consequences in other parts of the system. Interactions among systems variables create feedback loops and rebound effects that can have important consequences regarding the GHG reduction results of different policy options (Small and Dender, 2007). Tools are needed to help policymakers understand these feedback effects. Systems dynamics is a tool designed to address such problems, and it possesses good characteristics for aiding understanding in such complex problems (Sterman, 2008).

3. Systems dynamics, environmental policy, and transportation

Systems dynamics has been used to increase the understanding of complex environmental issues, including emissions from agricultural practices (Anand et al., 2005); water resource planning (Ford, 1996; Saysel et al., 2002); and climate change policy and economics (Fiddaman, 2002; Nordhaus and Yang, 1996; Naill et al., 1992).

Systems dynamics has also been used to study the role of transportation technologies and policies. For example, SD models have been used to evaluate problems related to expanding the use of biofuels (Bush et al., 2008); understanding barriers and increasing the market penetration of various alternative fuel vehicles (Ford, 1995a; Gillingham and Leaver, 2008); exploring the modal mix of urban transportation systems (Han and Hayashi, 2008; Wang et al., 2008); evaluating potential carbon reduction policies (Piattelli et al., 2002); and, predicting the optimal financial structure of a state-run feebate system (Ford, 1995b).

We build off of this existing literature to understand in a larger context, and with the help of SD, the impacts of multiple policy approaches aimed at reducing GHG emissions from LDVs. We craft a CLD that identifies systems boundaries and relationships that are important for understanding the consequences of policy interventions. The CLD is the beginning point for developing quantitative simulation models that can be tested and evaluated as aids to policy analysis.

Setting system boundaries for CLDs is always a challenge and is a function of the research questions for which the model is designed to address (Liu et al., 2008). In our case, we are exploring the long term, decadal scale impacts of GHG reduction policies on total LDV emissions. An example set of such policies are shown in Table 1 that organizes policy mechanisms according to the vehicle emission lifecycle stage it mitigates (a useful taxonomy for conducting policy analyses in a lifecycle context) (Claes, 2007).

The lifecycle aspects of this problem are important in terms of vehicle production, use (e.g., fuel and material consumption) and disposal (Bandivadekar et al., 2008). Hence, our CLD needs to at least capture market behavior (consumers and producers), materials, and technologies used in different stages of the vehicle lifecycle. In addition, many emissions reduction policy options are focused on changing consumer purchasing and producer decisions, such as giving tax breaks for production of a specific technology (e.g., hybrid electric vehicles). Therefore, we also need to consider elements of the consumer/producer decision making process within our overall system. We consider the following questions to help identify appropriate system boundaries for our problem.

1. *Complementary behavior, materials, or technologies*. Are there certain behaviors, materials, or technologies that are complementary to or conflict with the policy interventions we want to study? For example, if we are evaluating the impacts of policies that affect vehicle efficiency (e.g., CAFE standards), our system boundaries should capture behaviors, materials, and technologies that are complementary to or conflict with meeting regulatory expectations, such as the production and use of lightweight materials in new vehicle designs.

Table 1
Vehicle lifecycle policy categories and examples.

Stage of product lifecycle	Command-and-control	Market based
Supply chain policies	• Regulate supply chain logistics	Subsidize/ tax certain material inputs
Production policies	• Mandate standards (technology forcing mandates) • Mandate technology use (technology driven mandates) • Regulate production process activities	Subsidize or give tax breaks for the production of certain product types
Product use policies	• Restrict certain types of product use • Regulate product use	Subsidize/ tax inputs necessary for product use
End-of-life (EOL) policies	• Mandate EOL practices (e.g. recycling mandate) • Regulate EOL practices	Subsidize/tax EOL activities

2. *Substitute behavior, materials, or technologies*. Are there certain activities, behaviors, or artifacts that are substitutes to the policy interventions we want to study? For example, if we are evaluating the impacts of a fuel carbon tax, our system boundaries should capture behaviors, materials, and technologies that can act as substitutes for the regulated behavior, such as the use of alternative fuels or vehicles.
3. *Temporal aspects*. Are there important lag effects or long time horizons that must be considered in relation to the policy interventions we want to study? For example, if we are evaluating the impacts of policies that affect vehicle fleet turnover rates, our system boundaries have to extend out into the future long enough to capture these turnover effects.

Determining the appropriate extent of our system boundary is an iterative process. As the model's network of interconnected variables increases, its complexity and data costs grow exponentially—while usability and transparency often decrease (two important features to maintain for these types of integrated models) (Liu et al., 2008). In this paper, we develop our CLD heuristically, where each iteration considers model boundary expansion based on answers to the above questions and the expert judgment of researchers, policymakers, and policy stakeholders. In the end, our CLD exhibits a set of many interconnected sub-systems and cause-and-effect loops that interact in complicated ways.

One major value of a CLD is in illustrating important feedback effects that may lead to *unintended consequences* associated with policy interventions. We define feedback as a condition whereby the output of a system affects its inputs through a series of relationships (Deaton and Winebrake, 2000; Sterman, 2000). Two types of feedback structures are particularly important: *reinforcing* and *balancing*. Balancing feedback (also referred to as counteracting or negative feedback) represents a condition whereby causal loops in the system cause a variable that is perturbed to ultimately seek its original value. Conversely, reinforcing feedback (also referred to as positive feedback) represents a condition whereby causal loops in the system cause a perturbed variable to respond in the same direction as the perturbation (Deaton and Winebrake, 2000). However, the magnitude of a perturbation and its respective impacts are not represented in the CLD and must be analyzed through simulation modeling. Complex systems may have both types of feedback loops, each with differing magnitudes and impact delays, creating nonlinearity and lag effects that can lead to *unintended consequences* that confound policymakers.

CLDs can help analysts identify potential unintended consequences of policy interventions qualitatively. By tracing cause-and-effect in the CLD, starting with the variable perturbed by the policy intervention, the analyst can recognize and respond to all feedback loops and individual variables that both directly and indirectly affect the end result (e.g., total GHG emissions). Of particular interest, indirect interactions are those that often lead to an unexpected result, and once identified can be the focus of further quantitative modeling.

The existence of a potential set of unintended consequences may create a need for multiple policies in order to reach policy goals. The CLD can be used to identify complementary policies that take advantage of *policy synergies* and lead to successful policy outcomes. We define a policy synergy as the interaction of two or more policies that, when combined, achieve policy goals more successfully than would be achieved by each policy separately. In contrast, the interaction of two or more policies in combination, where the combined policies lead to negative impacts that would not have occurred by either alone, will be called *policy conflict*. Analysts can use a CLD to identify synergistic and conflicting policies, and as an aid to discuss the feedbacks that drive them with decision makers. After this step is achieved, quantitative modeling based on the CLD framework can be used to measure the magnitude of the synergy or conflict.

4. Causal loop diagram

4.1. Complete system CLD

A CLD displays how variables important to the system interrelate to one another through the use of text, arrows, and symbols. The interaction between two variables is represented by a causal connection (arrow running from the “cause” to the “effect”) and a polarity (indicated by a “+” or “−”). The positive (“+”) polarity indicates that perturbations in the “causal” variable will result in perturbations in the *same direction* in the “effect” variable, *assuming all else is held constant in the system*. Similarly, a negative (“−”) polarity on a causal arrow indicates that perturbations in the “causal” variable will result in perturbations in the *opposite direction* in the effect variable, again assuming all else is held constant. The causal relationships create feedback loops that are denoted as either balancing (B) or reinforcing (R) and each loop is given a name to facilitate discussion of the model (Sterman, 2000).

Before introducing a more complex CLD, we first present the “subsystem diagram” shown in Fig. 1. This diagram depicts the primary subsections that influence lifecycle LDV emissions, and is provided as a high-level guide to the more complicated CLD (Sterman, 2000). The complete CLD and detailed sub-systems are provided in the remaining figures.

The CLD was developed in the Vensim systems dynamics modeling software package (www.vensim.com) and is presented in Fig. 2. Simple text is used for variable names, with the exception of emissions variables, which are represented in boxes to quickly locate them in the diagram. Also, for simplification of presentation, we refrain from crossing causal arrows, and so we duplicate variable names in several places in the diagram; duplication is noted by brackets (< >).

Table 2 summarizes the descriptions and units for each variable in the CLD. Table 3 summarizes each of the 11 identified loops in the CLD, one of which are reinforcing and nine balancing. In the succeeding sections, individual feedback loops and their importance in the policy discussion outlined in this paper are discussed.

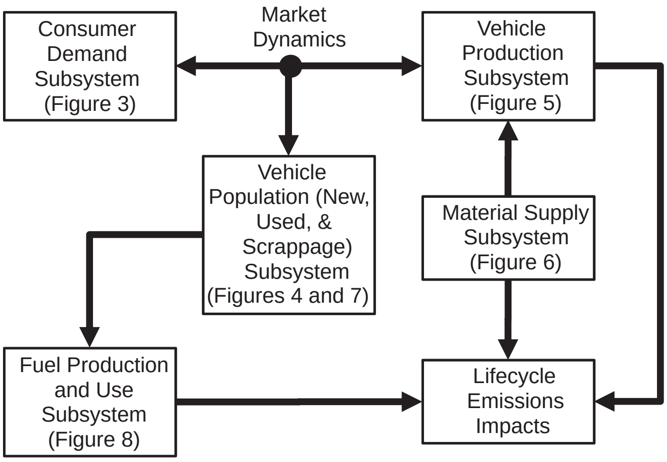

Fig. 1. Subsystems represented by the causal loop diagram.

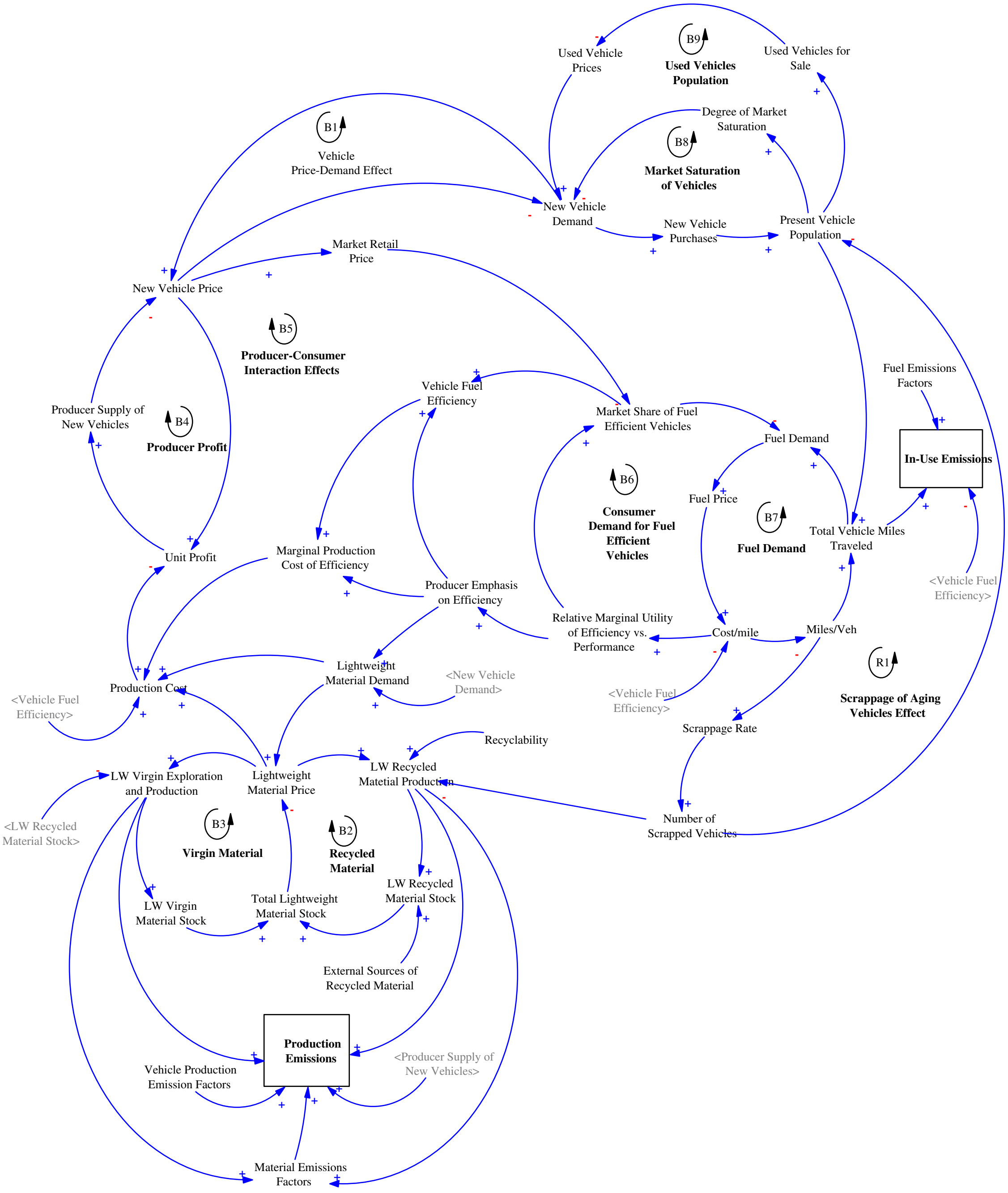

Fig. 2. Causal loop diagram for the entire system.

4.2. Consumer decision-making loops

Since GHG mitigation policies may ultimately be aimed at either changing consumer behavior directly or changing the attributes of products that consumers purchase, capturing consumer decision making is important. Three loops help capture the cause-and-effect relationships that affect vehicle purchase decision making by a consumer. Consumer preferences for vehicles are influenced by a number of factors including price, performance, fuel economy, size, safety features, and other attributes. For this paper, we illustrate our model using three attribute categories that are particularly important: vehicle price, performance, and fuel economy (Berry et al., 2004; Mau et al., 2008). The CLD reflects the decisions consumers make among these three categories of vehicle characteristics through utility. Utility, or the level of desirability of the consumption of a good, dictates what choices are made when well-known assumptions in economic modeling are considered (Berry et al., 1995, 2004; Greene et al., 2004; Turrentine and Kurani, 2007).

Fig. 3 represents the *consumer demand loop for fuel efficient vehicles*. US consumers have historically made purchasing decisions that emphasized performance over fuel economy. However, as shown by the recent increase in fuel prices (i.e. cost/mile), consumers are starting to turn towards more fuel efficient vehicles (Morris, 2008). This implies a positive correlation between fuel prices and the relative marginal utility of fuel efficiency in consumer decision making.

Table 2
Causal loop variables showing each variable in the CLD, its units, and the feedback loop with which the variable is associated.

Variable *(alphabetical)*	Description	Units	**Component of loop?**
Cost/mile	The cost to the consumer per vehicle mile driven.	Dollars/mile	B6, B7, R1
Degree of market saturation	The percentage of maximum saturation of vehicle ownership in the United States. As total market saturation increases, *new vehicle purchases* increase, and vice versa.	Percent	B8
External sources of recycled material	Amount of recycled material drawn from sources other than scrapped vehicles—for instance, aluminum recycled from cans used in vehicle production.	Kilograms	No
Fuel demand	Consumer demand for vehicle fuel, directly related to the *total miles traveled* for the vehicle population.	Gallons	B6, B7, R1
Fuel emissions factors	Conversion factors, including the carbon fraction of gasoline, that equate fuel consumption to emissions produced; note that these could capture upstream emissions (emissions from the production and delivery of fuel to the vehicle) and downstream emissions (emissions from the use of the fuel in the vehicle).	CO_2/gallon of fuel consumed	No
Fuel price	The price of a gallon gasoline equivalent (gge) of vehicle fuel.	Dollars/gge	B1, B6, B7R1
In-use emissions	Total tailpipe emissions (CO_2) emitted by the vehicle population per year.	Million metric tons of CO_2	No
Lightweight material demand	Amount of lightweight material (e.g., aluminum) needed to produce the new year's vehicle population. Lightweighting is one method producers can use to meet efficiency goals.	kg/yr	No
Lightweight material price	The price of lightweight materials (e.g., aluminum) needed to manufacture the *new vehicle purchases*.	Dollars/kilogram	B2, B3
LW recycled material production	The amount of recycled lightweight material produced from the *number of scrapped vehicles* in the given year.	Kilograms/yr	B2
LW recycled material stock	The total amount of recycled lightweight material available for vehicle production; this is determined by the material recycled from the *number of scrapped vehicles* and other external sources.	Kilograms	B2
LW virgin exploration and production	The amount of new virgin lightweight material produced annually.	Kilograms/yr	B3
LW virgin material stock	The total amount of virgin lightweight material available for vehicle production.	Kilograms	B3
Marginal production cost of efficiency	The cost to the producer for increasing fuel efficiency in a new vehicle by one mile per gallon.	Dollars/mile per gallon	B5
Market retail price	The retail price of a new vehicle.	Dollars/vehicle	B5
Market share of fuel efficient vehicles	The share of the total vehicle market belonging to fuel efficient vehicles; this is affected by consumers' utility functions.	Percent	B6
Material emissions factors	Emissions per unit of material (virgin or recycled) produced.	Million metric tons of CO_2/kg of material	No
Miles/Veh.	Miles traveled per vehicle in the *present vehicle population* for a given year.	Miles/vehicle-yr	B7, R1
New vehicle demand	The number of new vehicles demanded for a given year.	Vehicles/yr	B1, B9, B5, B8
New vehicle purchases	The number of new vehicles purchased in a year; determined by the degree of market saturation and the price of a new vehicle vs. the price of a used vehicle.	Vehicles/yr	B9, B5, B8
New vehicle price	The price of a new vehicle, determined by market equilibrium achieved by producers (maximizing profit) and consumers (maximizing utility).	Dollars	B4, B5, B1
Number of scrapped vehicles	The number of vehicles scrapped per year, determined by the scrappage rate of each model year vehicle population.	Vehicles/yr	R1
Present vehicle population	Total vehicle population in a given year.	Vehicles	R1, B8, B9
Producer emphasis on efficiency	The extent to which producers emphasize fuel efficiency as a vehicle attribute.	Emphasis value	No
Producer supply of new vehicles	Producers' supply of new vehicles in a given year.	Vehicles/yr	B4, B1
Production cost	Total cost of vehicle production based on the cost of materials and technologies needed to meet vehicle efficiency and performance attributes.	Dollars/vehicle	No
Production emissions	Emissions (e.g., CO_2) produced in the manufacturing stage of the *new vehicle purchases* population per year.	Million metric tons of CO_2/yr	No
Recyclability	The percentage of total available recycled material that is reusable after the recycling process.	%	No
Relative marginal utility of efficiency vs. performance	The ratio of consumer utility of one mile per gallon of fuel efficiency to one unit of performance, where in this example vehicle acceleration and horsepower are used as proxies for performance.	Units of utility/mile per gallon	B6
Scrappage rate	The percentage of each model year vehicle population that is scrapped each year.	%	R1
Total lightweight material stock	The total amount of lightweight material (both virgin and recycled) available for vehicle production in a given year.	Kilograms	B2, B3
Total vehicle miles traveled	The total miles traveled per year by the vehicle population.	Miles/year	B7, R1
Unit profit	Producer profit on each vehicle sold in a given year.	Dollars/vehicle	B4
Used vehicle prices	The price of used vehicles in a given year.	Dollars/vehicle	B9
Vehicle fuel efficiency	The fuel efficiency of the vehicle population.	Miles/gallon of fuel	No
Vehicle production emission factors	Emissions due to the production of vehicles.	Million metric tons of CO_2/vehicle	No

Fuel demand is dependent on the number of miles traveled and the average fuel efficiency of the vehicle population. The fuel economy of the vehicle population is dependent on the market share of fuel efficient vehicles; under a fixed VMT, this market share is negatively correlated to fuel demand. Economically, fuel price is positively related to fuel demand, and in turn fuel price determines the cost of traveling per mile. Therefore, because fuel demand is intrinsically tied with the population of fuel efficient vehicles, perturbations in either will produce an individual balancing effect. Lee and Ni (2002) provide a good summary of the relationship between oil price changes (e.g., oil price shock in the 1970s and

Table 3
Causal feedback loops for the CLD, indicating the loop classification, whether the loop is balancing or reinforcing, the name of the loop, the components of the loop, and external model elements that influence the loop.

Loop ID	Balancing (−) or reinforcing (+)	Full name	Components	External elements influencing loop
*R*1	Reinforcing	Scrappage of aging vehicles effect	Number of scrapped vehicles Present vehicle population Total vehicles miles traveled Fuel demand Fuel price Cost/mile Miles/veh. Scrappage rate	Present vehicle population New vehicle purchases Market share of fuel efficient vehicles
*B*1	Balancing	Vehicle price-demand effect	Producer supply of new vehicles New vehicle price New vehicle demand	Unit profit Used vehicle prices Degree of market saturation
*B*2	Balancing	Recycled material	Lightweight material price LW recycled material production LW recycled material stock Total lightweight material stock	Recyclability Number of scrapped vehicles External sources of recycled material LW virgin material stock Lightweight material demand
*B*3	Balancing	Virgin material	Lightweight material price LW virgin exploration and production LW virgin material stock Total lightweight material stock	Lightweight material demand LW recycled material stock
*B*4	Balancing	Producer profit	New vehicle price Unit profit Producer supply of new vehicles	Production cost New vehicle demand
*B*5	Balancing	Producer–consumer interaction effects	Market retail price New vehicle price New vehicle demand New vehicle purchases Present vehicle population Total vehicles miles traveled Fuel demand Fuel price Cost/mile Miles/veh. Scrappage rate Number of scrapped vehicles LW recycled material production LW recycled material stock Total lightweight material stock Lightweight material price Production costs Unit profit Producer supply of new vehicles	Vehicle fuel efficiency Marginal production cost of efficiency Lightweight material demand Recyclability External sources of recycled material LW virgin material stock Degree of market saturation Used vehicles prices
*B*6	Balancing	Consumer demand for fuel efficient vehicles	Market share of fuel efficient vehicles Fuel demand Fuel price Cost/mile Relative marginal utility of efficiency vs. performance	Total vehicle miles traveled Marginal utility of performance New vehicle price
*B*7	Balancing	Fuel demand	Fuel demand Fuel price Cost/mile Miles/veh. Total vehicle miles traveled	Market share of fuel efficient vehicles Present vehicle population Vehicle fuel efficiency
*B*8	Balancing	Market saturation of vehicles	Degree of market saturation New vehicle demand New vehicle purchases Present vehicle population	Number of scrapped vehicles Used vehicle prices
*B*9	*Balancing*	Used vehicles population	Used vehicle prices New vehicle demand New vehicle purchases Present vehicle population Used vehicles for sale	Degree of market saturation New vehicle price Number of scrapped vehicles.

1980s) and the automobile industry, demonstrating this balancing feedback.

For another illustration, we can consider consumer decision-making loop *B*6. As the consumer's marginal utility of fuel efficiency increases compared to the marginal utility of performance, more fuel efficient vehicles are purchased, and the market share of fuel efficient vehicles increases. Loop *B*6 is informative in that it shows how policies aimed at increasing the

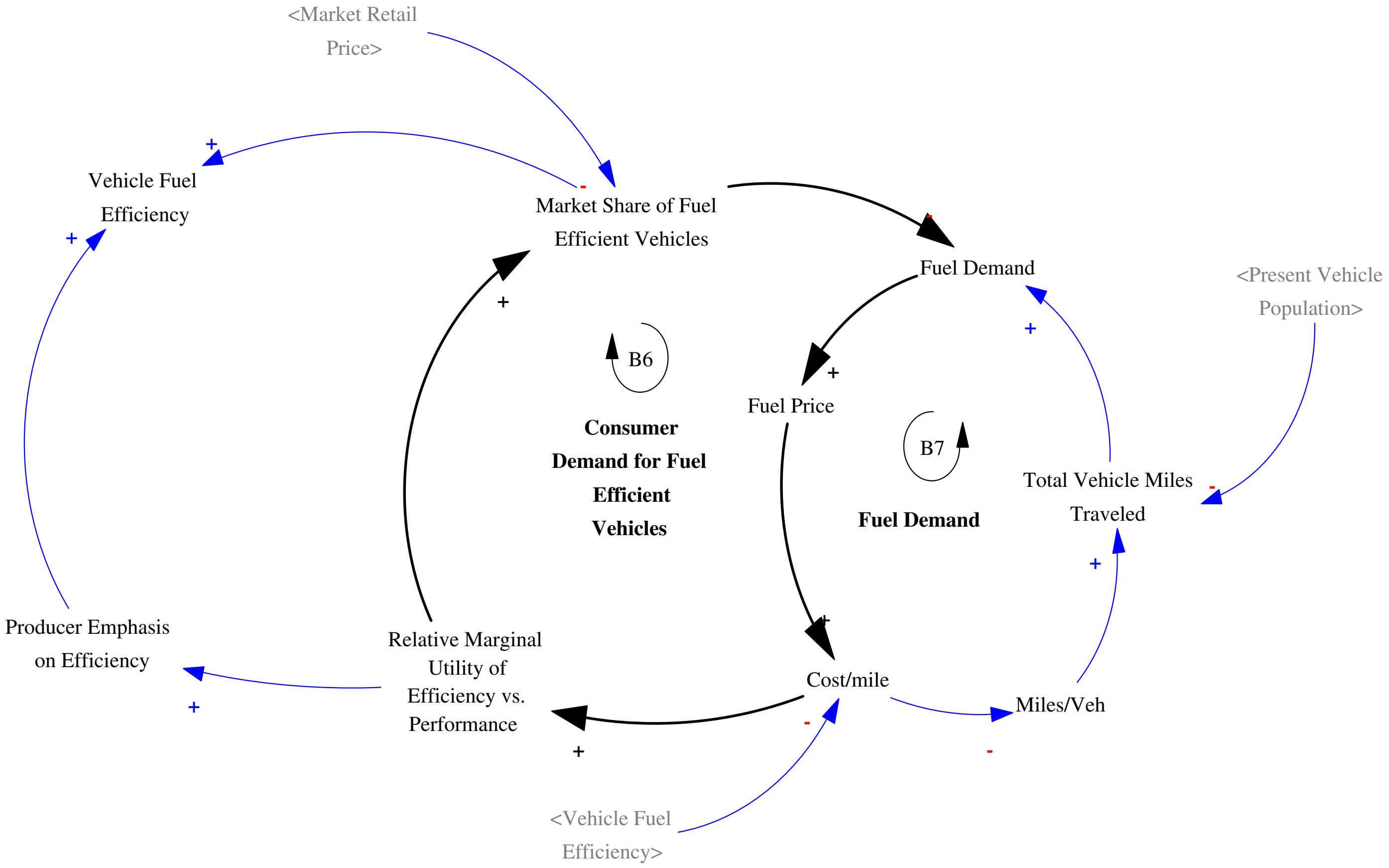

Fig. 3. Consumer demand for fuel efficient vehicles loop.

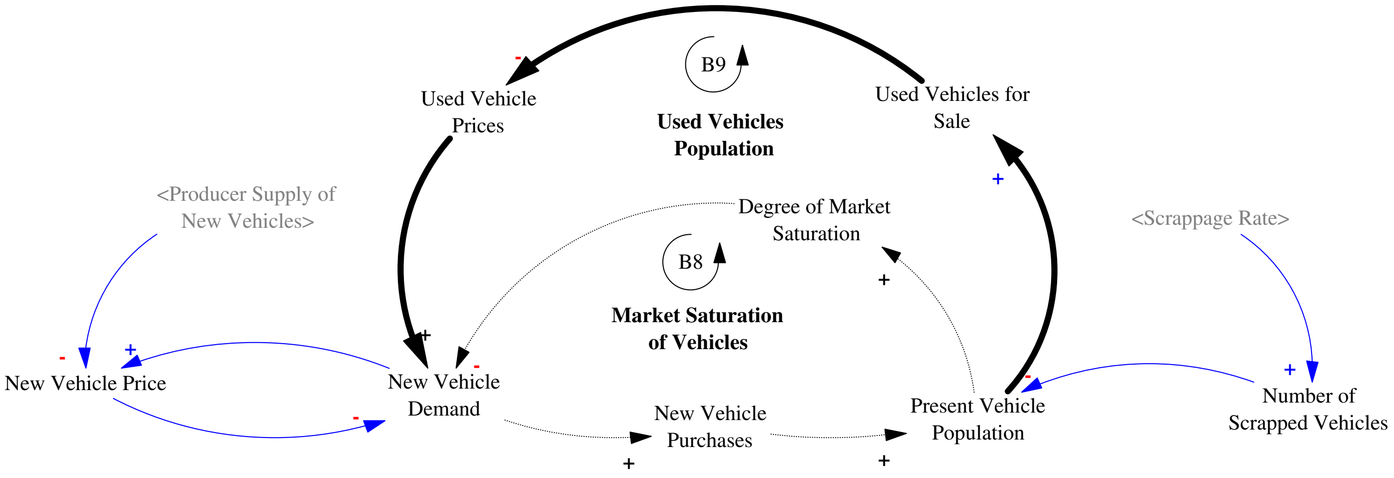

Fig. 4. New and used vehicle purchase loops.

number of fuel efficient vehicles on the road may involve balancing feedback loops related to fuel prices that reduce consumers' willingness to pay for such vehicles.

Another example shows the relationship between new vehicle demand and the market share of fuel efficient vehicles. Fig. 4 represents two feedback loops (*B*8 and *B*9) that depict the dynamics between used vehicle and new vehicle markets. In this case, the purchase of new vehicles leads to increased availability of used vehicles (after a lag effect). The lagged increase in used vehicle supply will affect markets for new vehicles in later years, by providing a potentially less fuel efficient, less costly purchase option for vehicle buyers (Sterman, 2000). Analysts should include an evaluation of such dynamics when conducting policy assessments.

4.3. *Producer decision-making loops*

Automobile manufacturers play an important role in determining the type of vehicles that consumers ultimately choose to purchase, as well as setting the initial prices that consumers will

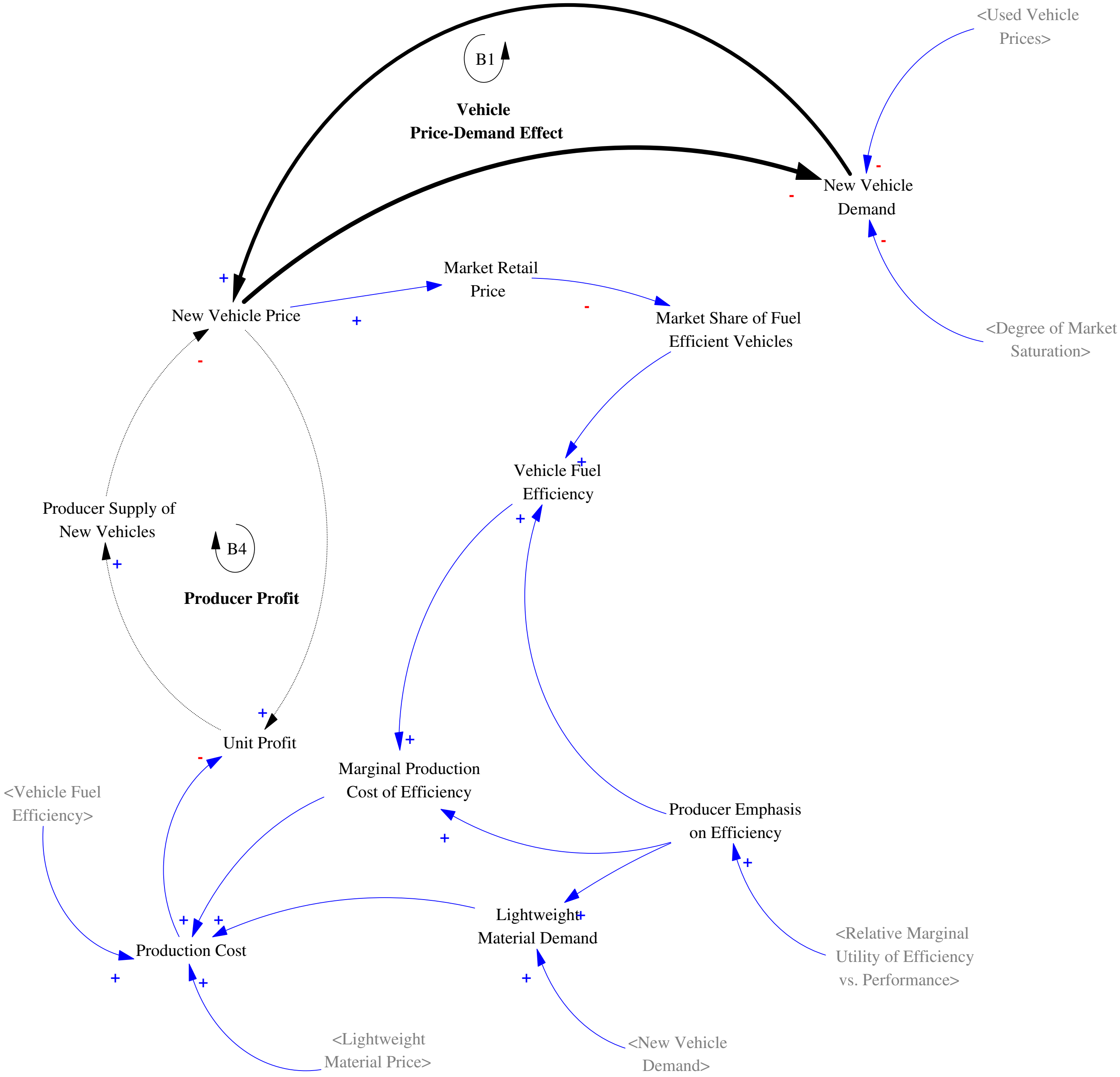

Fig. 5. Vehicle supply, demand, and profit loops.

pay for such vehicles. Automobile producers need to make their decisions in the context of both consumer demands and government regulation (e.g., fleet wide fuel efficiency standards). Fig. 5 depicts some of the important relationships that affect producer decision making.

Specifically, the interactions of supply, demand, and price are encapsulated in loops *B*1 and *B*4. Prices are set by the interaction of the negative effects of supply (*B*4) and the positive effects of demand (*B*1), bridging the gap between consumer and producer decision making. Market price is determined when the two feedbacks equilibrate, as computed through various techniques, such as a Nash equilibrium oligopoly model (Ackerberg et al., 2006; Berry et al., 1995).

The producer profit loop (*B*4) captures the influence of profit on producer decision making. This profit is a function of other elements in the system model, such as production cost (which is further influenced by government regulation, technology and material choice, and other factors). Many recent studies have identified relationships between performance, cost, and other vehicle attributes, particularly with respect to alternative fuel vehicles (Austin, 1999; Energy and Environmental Analysis, 2002; Greene and Plotkin, 2001). To maximize profits, firms will produce vehicles with attributes that meet consumers' preferences as defined by their utility functions (see Fig. 3 for example).

As an example, consider the role that material selection plays on producer and consumer decision making. Fig. 6 shows two

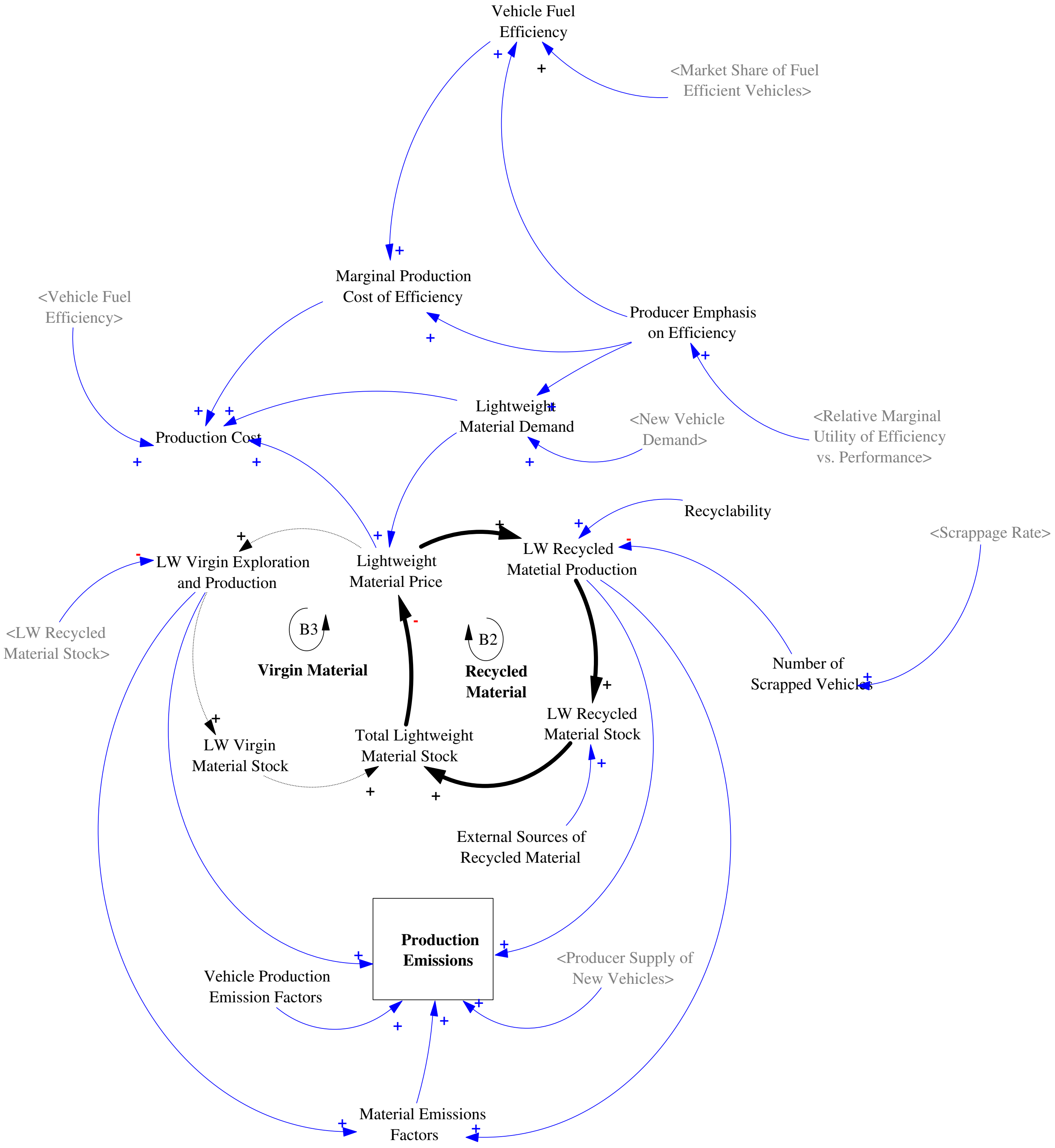

Fig. 6. Recycled and virgin material production loops.

loops related to lightweight material (e.g., aluminum) selection; lightweighting is one method producers can use to improve vehicle efficiency (Kim, 2008; Klimisch, 2007; Saur, 1995). Loops *B*2 (bold line) and *B*3 (gray, dashed line) represent recycled lightweight material and virgin lightweight material decisions, respectively. As shown in the CLD, decisions on whether to use virgin or recycled material are dictated by supply (material stock), price (influenced by supply), and demand. These elements are further influenced by a number of other variables, such as recyclability and vehicle scrappage rates (Kim, 2008). In this case, we ignore the price differentials that may exist between recycled and virgin material, and instead assume a single price signal for both virgin and recycled lightweight material. This is a simplification that restricts the use of this CLD for exploring policies aimed

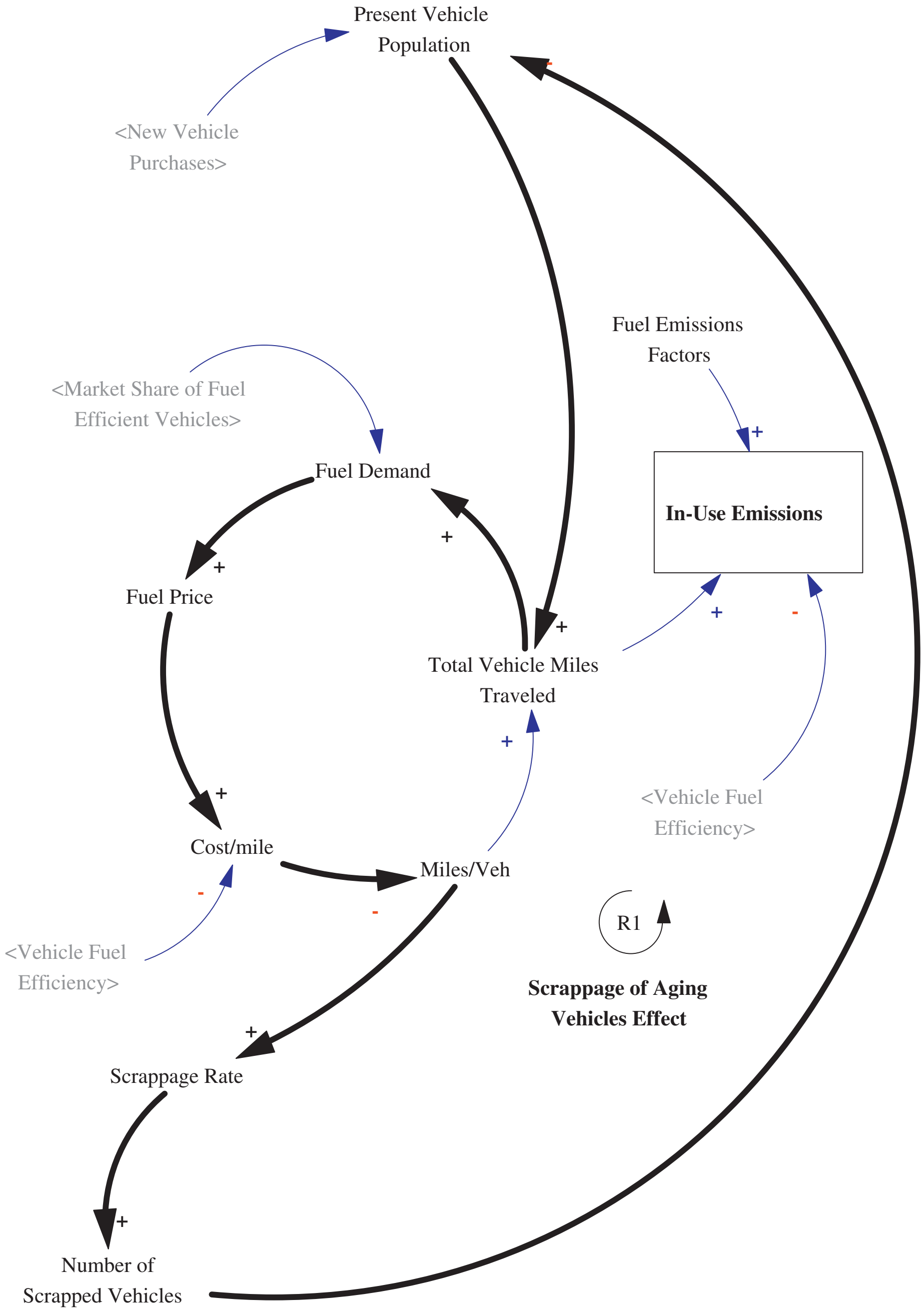

Fig. 7. Scrappage of aging vehicles loop.

at adjusting market prices for recycled and/or virgin material. However, the CLD does imply that such policies could have an effect on lifecycle vehicle emissions through material selection. Therefore both "downstream" and "upstream" impacts should be assessed when considering such policies directly impacting material selection.

For example, virgin aluminum production emits 30–40% more CO_2 than steel production. As a result, policies aimed at forcing vehicle manufacturers to increase the fuel economy of new LDVs may lead to production emissions increase. Alternatively, recycled aluminum or recycled steel presents much lower production emissions compared to their virgin counterparts (Das, 2000). Policies simultaneously encouraging use of recycled material where technologically feasible can reduce these emissions. The CLD allows decision makers to explicitly identify these relationships in order to understand how decisions related to recycling, for example, can affect overall lifecycle emissions of autos. The CLD also facilitates communication with key stakeholders about these inherently complex issues.

Another important aspect of vehicle production systems, and one not captured in our CLD, is the impact of "learning" and economies of scale on reducing average unit costs for vehicles. As vehicle manufacturers gain knowledge of production systems for new types of vehicles, and as the sales volumes for these vehicles increase, one might expect unit costs to decrease once a certain production threshold is reached (Sterman, 2000). This could be a feature that is added as part of the vehicle production system in future work

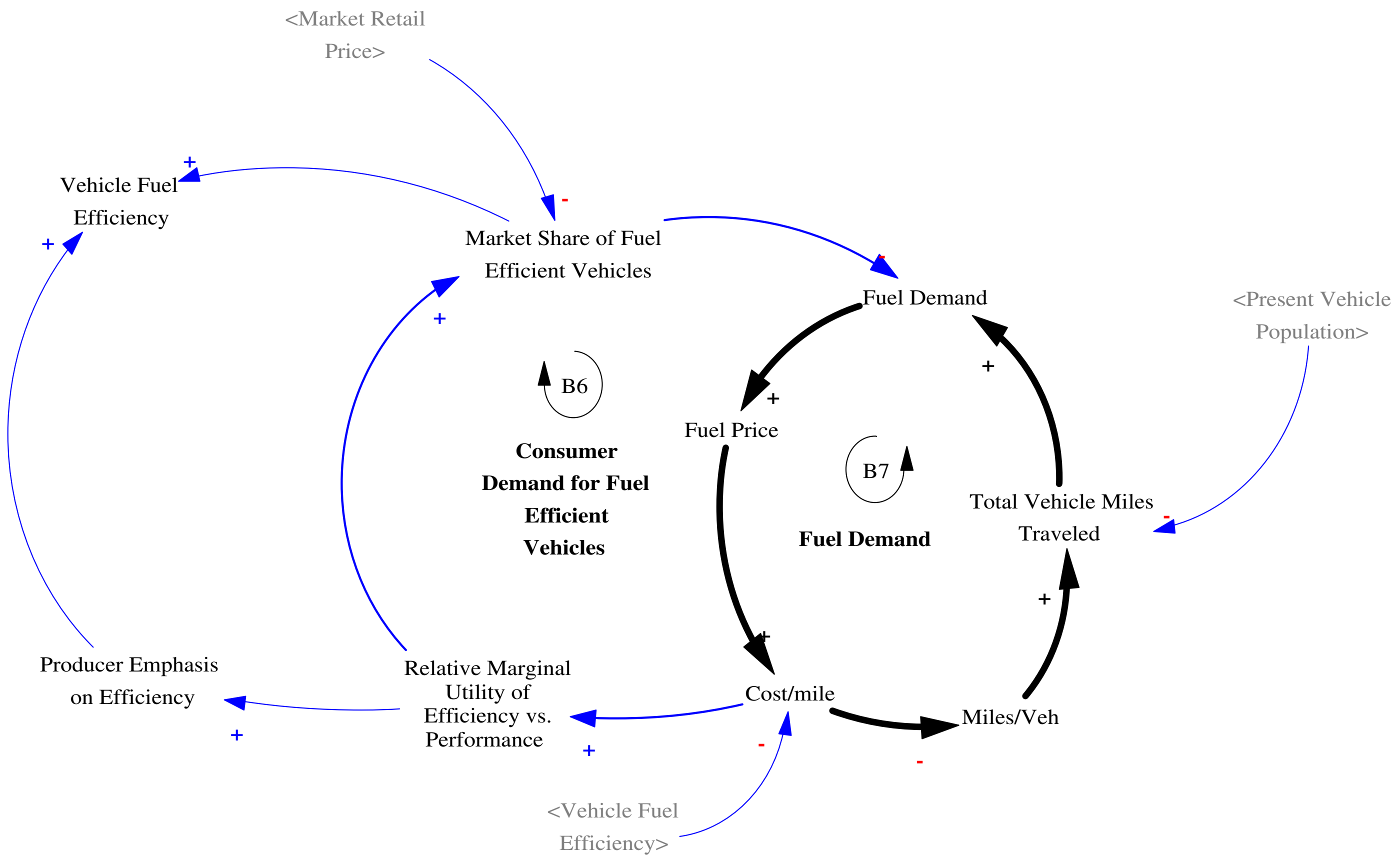

Fig. 8. Vehicle fuel demand loop.

4.4. *Vehicle use loops*

GHG mitigation policies for the transportation sector have been primarily focused on vehicle use, since the vast majority of emissions come from the operation stage of the vehicle lifecycle. Loops *R*1 and *B*7 in Figs. 7 and 8, respectively, identify the relevant variables that impact vehicle operation emissions. Some of the key determinants of operational emissions from a fleet of vehicles include total vehicle population, average vehicle miles traveled (VMT), and average vehicle fuel economy. Indirectly (also shown in Figs. 7 and 8), fuel demand and prices affect VMT, and vehicle populations are affected through the consumer and producer decision loops presented earlier. Again, the CLD demonstrates how changes in fuel price not only can *directly* influence emissions (through the VMT relationship), but also can *indirectly* influence emissions by stimulating changes in consumer decision making that ultimately affect the attributes of the vehicle population.

5. The use of CLDs for policy analysis

The complete CLD offers a decision maker insight into how policy mechanisms aimed at one part of the system may generate dynamic responses in other parts of the system. These impacts may be in the form of *policy resistance* due to balancing feedback loops exhibited in the CLD, or *policy synergy* due to reinforcing feedback loops as discussed previously. For example, Fig. 9 illustrates the complete CLD within the context of a vehicle subsidy (policy mechanism) offered to consumers who purchase a high-efficiency vehicle (e.g. hybrid electric vehicles; boxed, top left corner). This subsidy lowers the cost to consumers of high-efficiency vehicles, and is represented in this CLD by a reduction in *market retail price*. We will now demonstrate how the CLD can help identify the policy resistances and synergies that may exist as a result of this subsidy.

5.1. *Policy resistance*

The bold arrow from *market retail price* shows how a subsidy may increase the market share of fuel efficient vehicles (*market share of fuel efficient vehicles*). Initially, the intended consequence of the policy is evident. Larger populations of fuel efficient vehicles will increase the overall fuel efficiency of the total vehicle population (*vehicle fuel efficiency*). If *total vehicle miles traveled* (consumers maintain the same driving habits) remains constant, one would expect a concomitant reduction in tailpipe emissions (shown in the right-side portion of Fig. 9).

However, the potential for unintended consequences becomes evident when viewing the CLD. First, there is a direct linkage shown between *vehicle fuel efficiency* and *cost/mile*. For an individual consumer, an improvement in vehicle efficiency (miles per gallon) will reduce the cost of driving ($/mile). This reduced cost incentivizes the consumer to drive more (i.e., increase in *total vehicle miles traveled*), and will reduce the effectiveness of a high efficiency vehicle subsidy. This effect is commonly referred to as the “rebound effect” in the energy policy field (Greening et al., 2000; Small and Dender, 2007).

Second, as shown following the bold arrow emanating from *market share of fuel efficient vehicles*, the increase in fuel efficient vehicles decreases the demand for gasoline at a macroeconomic level (*fuel demand*). The decrease in *fuel demand* may lower *fuel price*, thereby lowering the cost of driving for the consumer (*Cost/mile*), and increasing *total vehicle miles traveled*.

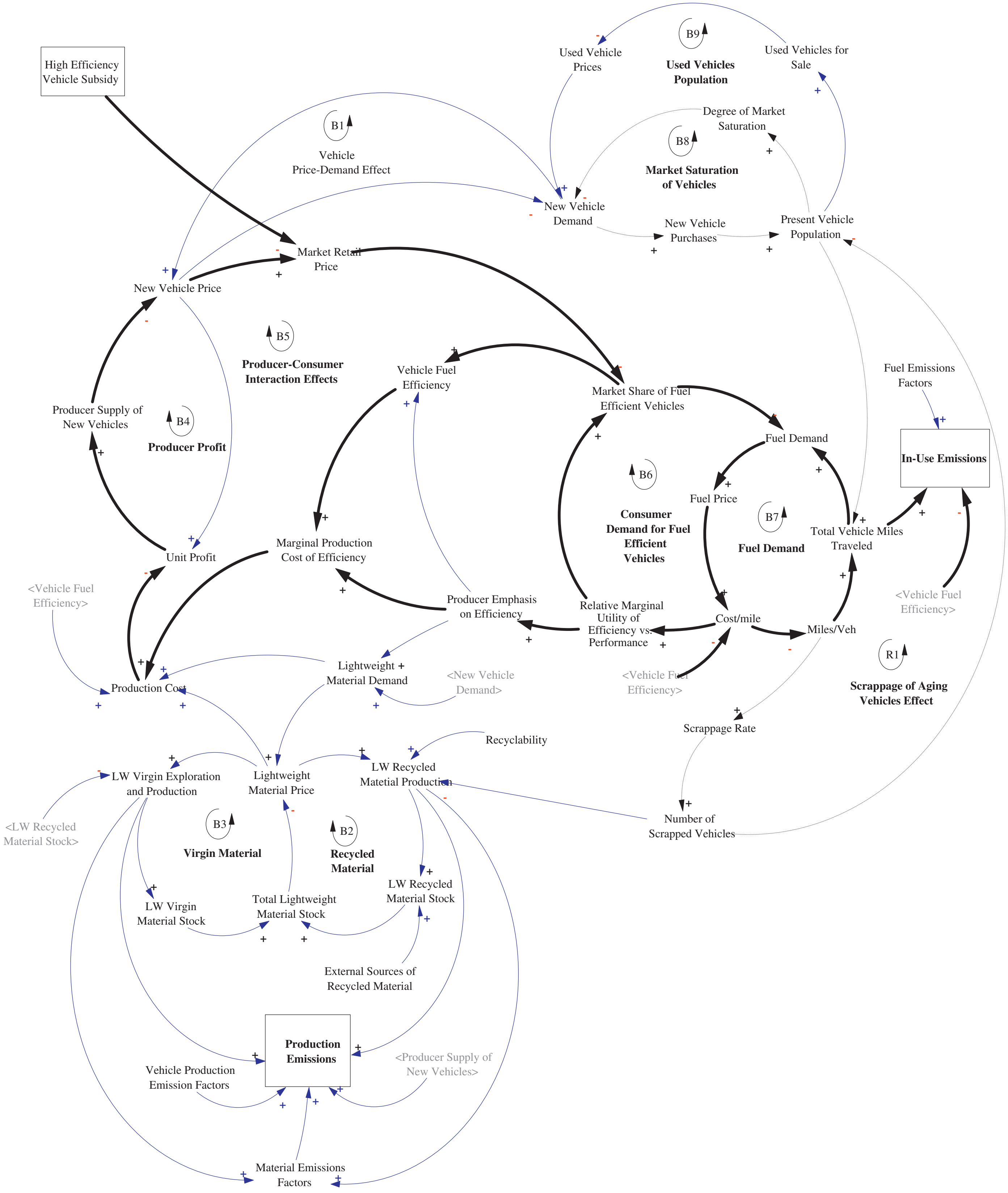

Fig. 9. Example feedbacks to a fuel efficient vehicle price subsidy policy.

Third, as shown in the dashed lines on the right side of Fig. 9, the increase in VMT may also influence vehicle scrappage. As shown in the CLD, an increase in VMT can lead to an increase in *scrappage rate* due to higher accident rates as vehicles are driven more, as well as a shorter product lifespan (in years) due to the additional vehicle use. The increased scrappage and shorter vehicle lifespan will require additional vehicle production, which implies increased emissions from the manufacture of such vehicles—another subtle relationship made clearer by the use of the CLD.

Lastly, observing the left side of Fig. 9 a high efficiency vehicle subsidy triggers an increased demand for fuel efficient vehicles. This higher demand, and its associated impacts on production costs and unit profits, could likely increase the price of such vehicles (in the short term), thereby dampening the potential market demand. Said another way, a subsidy for fuel efficient vehicles may create feedback that increases vehicle prices to an extent that reduces the intended purposes of the initial subsidy.

5.2. Policy synergies

If policy resistance is significant, policymakers may want to identify opportunities to implement complementary policies that can create synergies that counter such resistance. Continuing with the subsidy example presented above, a possible policy synergy becomes evident. Complementary policies could be developed that aim to reduce the potential increase in VMT due to the introduction of high-efficiency vehicles. In the CLD, we see VMT influenced largely by *cost/mile*, which is further influenced by *fuel prices*. A policy that increases *cost/mile* (e.g., road taxes) or increases *fuel prices* (e.g., carbon taxes or pay at the pump insurance) could have the effect of constraining VMT increases. The CLD demonstrates that enacting such policies in conjunction with a high efficiency vehicle subsidy may help reduce the policy resistance discussed above. Combined, the effect of a vehicle subsidy and road/fuel tax could be to increase the efficiency of the vehicle population, while also creating disincentives for potential increases in driving mileage.

6. Conclusion

This paper demonstrates a qualitative framework for understanding the direct and indirect impacts of GHG reduction policies aimed at the transportation sector. By employing a causal loop diagram (CLD), we identify important feedback loops that allow for the identification and discussion of unintended consequences, policy resistances, and policy synergies.

The role of qualitative analysis is important in the policymaking process, especially in automotive analysis where many key decision factors are uncertain or unknowable. In the development of policies affecting such complex systems, the creation and use of a CLD provides insights and clarification into the myriad of relationships that may diminish a policy's effectiveness. The CLD may also be used as follows: (1) to provide a platform by which stakeholders can engage in policy development discussions (since the formulation of a CLD forces decision makers to systematically engage in a discussion of important assumptions, variables, and relationships); (2) to highlight the most important relationships that may require a more thorough analysis prior to implementing quantitative policy analysis techniques such as systems dynamics modeling; and, (3) to illustrate and communicate direct and indirect policy impacts to policymakers, constituents, and other stakeholders. All three of these applications help provide a better understanding of the consequences of policy portfolios aimed at incentivizing consumer behavior, producer behavior, and technological development.

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