A Dynamic General Equilibrium Model of Driving, Gasoline Use and Vehicle Fuel Efficiency

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Abstract

The paper constructs a dynamic stochastic general equilibrium model to study the endogenous determination of gasoline use, driving and vehicle fuel efficiency. Before vehicles are produced, their fuel efficiency can be chosen optimally. Once produced, their fuel efficiency cannot be changed. The model generates endogenously different short-run and long-run price and income elasticities of gasoline use and vehicle miles of travel. We find that although gasoline taxes, the CAFE standard and mileage taxes can all reduce gasoline use in the long run, they are different in terms of the magnitude of responses and the dynamic paths followed by key variables.

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Gasoline consumption accounts for 44% of the U.S. demand for crude oil. Reducing gasoline consumption has become part of the strategic efforts to protect the nation from the serious economic and strategic risks associated with the reliance on foreign oil and the possible destabilizing effects of a changing climate. There has been heated discussion on policy options to discourage gasoline consumption, including increasing the gasoline taxes, tightening Corporate Average Fuel Economy (CAFE) standards, and levying mileage taxes. In order to evaluate the merits of these policy options, we need a structural framework to understand how people decide on how much to drive and what types of vehicles to produce when faced with stochastic gasoline prices and uncertain economic conditions.

Key to this evaluation is the fact that vehicles are important durable goods with embodied technological characteristics. The durable goods nature of vehicles implies that people are forward looking in making decisions regarding vehicle choice and utilization. The embodiment of technological characteristics also implies that the characteristics of existing vehicles may exhibit nontrivial transition dynamics as old generations of vehicles phase out. Despite the dynamic nature of the issue, to our knowledge prior work in this literature assumes static models of consumer and producer behavior, where the agents are not fully forward looking.[2]

In this paper we construct a dynamic stochastic general equilibrium model to study the endogenous determination of gasoline use, driving and vehicle

[2]For example, Parry and Small (2005), Bento et al (2009), Jacobsen (2007), and etc, as discussed later in the paper.

fuel efficiency by a representative household which maximizes its lifetime utility. The model captures the putty-clay nature of the way transportation capital (vehicles) and gasoline are combined to "produce" vehicle miles of travel. Before vehicles are produced, their fuel efficiency can be chosen optimally in anticipation of future gasoline prices and economic conditions. Once the vehicles are produced, their fuel efficiency cannot be changed ex post. Decisions can be made on whether or not, or how often to utilize a vehicle, but if the vehicle is utilized, the gasoline use required for a given mileage is determined by its fuel efficiency. Since the quantity and fuel efficiency of existing vehicles are pre-determined, in the short run the representative household can only alter its driving behavior in response to exogenous shocks. In the long run, both the quantity and fuel efficiency of new generations of vehicles can be changed over time. The impact of a permanent change in factor prices or aggregate productivity is fully realized after all the pre-existing vehicles are replaced.

The putty-clay specification allows the model to capture different short-run and long-run price and income elasticities of gasoline use and vehicle miles of travel, of magnitudes well within the range of plausible estimates in the empirical literature. These elasticities are obtained from the short-run and long-run responses of gasoline use and vehicle miles of travel to two sources of exogenous shocks: gasoline price shocks and aggregate technology shocks, with the latter being the driving force behind the aggregate productivity of the economy. Gasoline price shocks affect gasoline use through two main channels. The first channel is the endogenous capacity utilization of pre-existing vehicles. As gasoline prices increase, vehicles are driven less due to higher gasoline cost. This channel creates immediate gasoline savings. The second channel is the substitution of more fuel efficient vehicles as new generations of vehicles are produced. This channel leads to continuing gasoline savings as fuel-inefficient vehicles are phased out gradually. The aggregate technology shock, by contrast, affects the equilibrium allocation by relaxing the aggregate resource constraint. Both gasoline use and vehicle miles of travel increase as a result of a positive aggregate technology shock, with their exact dynamic paths depending upon the persistence of the shock.

We use this model to compare three policy options: gasoline taxes, CAFE regulation and mileage taxes. Gasoline taxes have a long history in the United States. The CAFE regulation was enacted after 1973 oil embargo. It imposes a limit on the average fuel economy of new vehicles sold by a particular firm, with fines applied to violations of the standard. Mileage taxes have been advocated as a substitute for gasoline taxes.

We find that although these three policy options can all reduce gasoline use in the long run, they are different in terms of both the magnitude of responses and the dynamic paths followed by key variables. Like permanent gasoline price shocks, a permanent increase in gasoline taxes reduces the capacity utilization of pre-existing vehicles, and increases the fuel efficiency of new generation of vehicles. A tightening of the CAFE standard achieves the gasoline savings by raising the fuel efficiency of new vehicles, with little effect on miles driven by pre-existing vehicles. There is a so-called "rebound" effect in the sense that the capacity utilization of new fuel-efficient vehicles is higher than its predecessors[3]. However, in equilibrium, the aggregate vehicle

[3]Empirical estimates by Jones (1993) and Greene et al. (1999) suggest that this "re-

miles of travel do not increase as an extreme version of the rebound effect would indicate. We find that in order to achieve the same amount of permanent gasoline savings as a one percent permanent increase in gasoline taxes, the CAFE standard has to increase by 0.68% from its initial level which is assumed to be binding to start with. Given the same amount of permanent gasoline savings as gasoline taxes, a tightening of the CAFE standard results in higher fuel efficiency of vehicles in the long run, since the substitution of high fuel efficiency vehicles is the only means for the CAFE regulation to reduce gasoline use. Mileage taxes impose a penalty on the *output* of the production technology of travel, instead of the two production *inputs*. It has no impact on the fuel efficiency of new vehicles in the long run. The gasoline savings are achieved mainly through a reduction in the amount of vehicles produced in the long run in response to taxes. As a result, the mileage tax rate has to increase by 3.2 percentage points permanently to achieve the same amount of permanent gasoline savings as a one percent permanent increase in gasoline taxes would have achieved.

Existing studies in this literature have typically adopted either a structural or an empirical approach. Parry and Small (2005) adopt a structural approach to study the optimal gasoline tax. In their model the representative agent decides on its optimal driving and gasoline use in a one-period utility-maximizing framework. This approach does not examine the dynamic responses of driving and vehicle production in a multi-period setting. Among the papers which employ the empirical approach[4], Bento et al. (2009) es-

bound" effect offsets $10 - 20\%$ or more of the initial fuel reduction from tighter CAFE standards.

[4]Other papers using the empirical approach include Li, Haefen and Timmins (2008),

timate the distributional and efficiency impacts of increased U.S. gasoline taxes using a large sample of household data. Jacobsen (2007) incorporates the producer's decision problem into Bento et al. (2009) framework to study the equilibrium effects of an increase in the U.S. CAFE standards. Both the structural and empirical approaches use static models of consumption and producer behavior, where the agents are not fully forward looking in making their decisions.[5]

In contrast with nearly all prior work, this study adopts the DSGE (dynamic stochastic general equilibrium) modelling approach. The advantages of this approach are threefold. First, the structural framework makes transparent the transmission mechanism from exogenous shocks to optimal decision-making on driving and vehicle fuel efficiency, and makes it possible to analyze the roles played by deep structural parameters. Second, the model is internally consistent, and all the decisions on driving and vehicle production are optimal decisions. Third, it is a dynamic model which is not only forward-looking, but also captures the dynamic path of key economic variables over time. To our knowledge, this is the first paper that employs a

Goldberg (1998), Small and Van Dender (2007) and etc.

[5]Although expected future gasoline prices affect both miles driven and vehicle choices in Bento et al. (2009), the expectations regarding both future rental values of vehicles and future gasoline taxes are myopic. Producers in Jacobsen (2007) are not forward looking in the sense that future demand conditions are not predicted. These assumptions reflect the limitations from the static models of consumer and producer behavior. Both models are solved period by period, different from a dynamic general equilibrium model with rational expectations, where current and future variables are jointly determined and future expectations of variables are consistent with one another. The agents are considered fully forward looking in the latter setting.

dynamic stochastic general equilibrium approach to examine the determination of gasoline use, driving and vehicle fuel efficiency.

This paper is related to the literature on the relationship between energy price shocks and the macroeconomy. Wei (2003) utilizes a putty-clay model to study the impact of energy price shocks on the stock market. In that paper, the adverse impact of an oil price shock is limited by the small share of oil costs as a fraction of the total production costs in the aggregate economy. The present study focuses on the effect of gasoline price shocks on transportation. The importance of gasoline to transportation makes it possible to capture the significance of oil to the aggregate economy through the transportation sector. Moreover, Wei (2003) features a perfect foresight model without aggregate uncertainty, while the present study incorporates both stochastic gasoline prices and stochastic aggregate productivity processes. The uncertainty in gasoline prices and aggregate economic environment provide richer complexities to the analysis. This paper also relates to Breshnahan and Ramey (1993) and Ramey and Vine (2009), which use industry data to examine the segment shifts and capacity utilization in the U.S. automobile industry. The household's optimal decisions on vehicle fuel efficiency, as captured in our model, play an important role in the misalignment between supply and demand across vehicle market as documented in the data.

The paper is organized as follows. Section 1 describes the model. Section 2 examines the model dynamics. Section 3 presents the benchmark calibration. Section 4 describes the dynamic responses of key variables to both permanent and temporary gasoline price and aggregate technology shocks.

Section 5 compares the dynamic implications of the three policy options. Section 6 concludes.

1 The Model

This section describes the putty-clay feature of the production technology of travel, and presents the household's problem.

1.1 The Production Technology of Travel

Vehicle-miles of travel, M, are "produced" according to a putty-clay production technology as described in Wei (2003) and Gilchrist and Williams (2000). Transportation capital and gasoline are the only production factors.

The *ex ante* production technology is assumed to be Cobb-Douglas with constant returns to scale. Each period the household can decide on the fuel efficiency (similar to the MPG measure) of new transportation capital by choosing the capital-gasoline ratio before the configuration is embedded. After the configuration is already embedded in the transportation capital, production possibilities take the Leontief form: there is no *ex post* substitutability of transportation capital and gasoline. Transportation capital goods require one period for configuration and remain productive for the next N periods. Once constructed, transportation capital goods cannot be converted into consumption goods or capital goods with different embodied characteristics.

Ex ante constant returns to scale implies an indeterminacy of scale at the level of "vehicles". Without loss of generality, all "vehicles" are normalized to use one unit of gasoline at full capacity. Subject to the constraint that the gasoline used at time t on vehicle i of vintage $t-j$, $O_{i,t,j}$, is nonnegative, and less than or equal to 1, vehicle-miles of travel produced in period t by vehicle i of vintage $t-j$ is

$$M_{i,t,j} = \varsigma_i k_{i,t-j}^{\alpha} O_{i,t,j}, \tag{1}$$

where $k_{i,t-j}$ is the transportation capital-gasoline ratio, $1-\alpha$ is the fraction of gasoline expenses as a fraction of travel-production costs, and ς_i is an idiosyncratic term related to the fuel efficiency of the ith vehicle. The idiosyncratic term, ς_i, is lognormally distributed[6]:

$$\log \varsigma_i \sim N\left(-\frac{1}{2}\sigma^2, \sigma^2\right), \tag{2}$$

where the mean correction term $-\frac{1}{2}\sigma^2$ implies that the mean of ς_i is equal to 1.

Since we assume that the idiosyncratic fuel efficiency term, ς_i, is revealed after the decisions on the transportation capital-gasoline ratio are made, all machines of vintage $t-j$ share the same k_{t-j}. The idiosyncratic term remains fixed during the life span of the vehicle.

In sum, the transportation capital goods owned by households are heterogeneous and are characterized by the transportation capital-gasoline ratio chosen at the time of installation (embedding) and an idiosyncratic fuel efficiency term. The fuel efficiency of transportation capital is fixed *ex post*.

[6] As emphasized in Gilchrist and Williams (2005), the log-normal distribution facilitates the analysis of aggregate quantities while preserving the putty-clay characteristics of the microeconomic structure.

There are no costs for taking vehicles on- or off-road. At each period, the only variable costs to operate one unit of vintage $t-j$ vehicles are the gasoline costs, P_t, where P_t is the real gasoline price. As shown in equation (1), the vehicle miles of travel by vehicle i of vintage $t-j$ is proportional to its gasoline use at time t. As a result, the net gain of operating each vehicle is linear in gasoline used. There is an endogenous cutoff value for the minimum fuel efficiency of vintage $t-j$ vehicles used in travel at any time period t. Those with fuel efficiency higher than this cutoff value are run at full capacity at period t, while those less fuel efficient are left idle. In other words, the gasoline used at time t on vehicle i of vintage $t-j$, $O_{i,t,j}$,is equal to 1 when the vehicle is in operation and equal to 0 otherwise. The variable X_{t-j}, defined as

$$X_{t-j} = k_{t-j}^{\alpha}. \tag{3}$$

can be considered approximately as the average fuel efficiency (similar to the miles per gallon) of the vintage $t-j$ vehicle.

1.2 Vehicle Miles of Travel and Gasoline Usage

We denote $1-\Phi\left(z_t^{t-j}\right)$ as the fraction of vintage $t-j$ vehicles that are run at full capacity at period t, where $\Phi\left(\bullet\right)$ is the cumulative distribution function of a standard normal random variable, and z_t^{t-j} is a decision variable which reflects the representative agent's trade-off on the marginal cost and benefit of utilizing a unit of vintage $t-j$ vehicle. The log-normal distribution of the idiosyncratic productivity term implies that the total vehicle-miles of travel,

M_t, is given by

$$M_t = \sum_{j=1}^{N} \left\{ \left[1 - \Phi\left(z_t^{t-j} - \sigma\right)\right] (1-\delta)^j Q_{t-j} X_{t-j} \right\}, \tag{4}$$

where Q_{t-j} is the quantity of new vehicles started in period $t-j$, and δ reflects the fact that a subset of vehicles has depreciated completely each period. $1 - \Phi\left(z_t^{t-j} - \sigma\right)$ is the ratio of actual travel produced by vintage $t-j$ vehicles to the amount of travel that could be produced if all vehicles are operated at full capacity[7].

The total amount of gasoline usage is given by

$$O_t = \sum_{j=1}^{N} \left\{ \left[1 - \Phi\left(z_t^{t-j}\right)\right] (1-\delta)^j Q_{t-j} \right\}. \tag{5}$$

The summation of gasoline usage uses the fact that in equilibrium each vehicle in operation uses one unit of gasoline.

1.3 The Penalty for Violating the CAFE Standard

Introducing the CAFE regulation into the model involves modeling the penalty for violating the standard. According to the CAFE regulation's official penalties, the fine can be described by[8]

$$F_t = \mathbf{I}\left(\underline{X} > \widehat{X}_t\right) f\left(\underline{X} - \widehat{X}_t\right) Q_t, \tag{6}$$

[7] The proof is contained in Gilchrist and Williams (2000, footnote 10).

[8] The indicator function below is defined for a single year whereas the regulation allows banking or borrowing of credits for up to three years. The approximation to require compliance in a single year provides a tractable model.

where $\mathbf{I}\left(\underline{X} > \widehat{X}_t\right)$ is an indicator function which is equal to 1 when the harmonian average of the fuel efficiency measure of new vehicles[9], $\widehat{X}_t$, is lower than the CAFE standard $\underline{X}$. The parameter f represents the proportional penalty on the deviation from the CAFE standard. The penalty is imposed on all new vehicles, similar to the structure of the official penalty imposed by the CAFE regulation.

We approximate the indicator function $\mathbf{I}\left(\underline{X} > \widehat{X}_t\right)$ with a smooth transition function of a logistic type:

$$\mathbf{I}\left(\underline{X} > \widehat{X}_t\right) \approx H\left(\underline{X}, \widehat{X}_t\right) = \frac{1}{1 + \exp\left[-\gamma\left(\underline{X} - \widehat{X}_t\right)\right]},$$

where the parameter γ determines the abruptness of the transition of the indicator from 0 to 1 as $\underline{X} - \widehat{X}_t$ changes from negative to positive. For example, for very large γ, a small negative value of $\underline{X} - \widehat{X}_t$ results in $H\left(\underline{X}, \widehat{X}_t\right)$ being very close to 0. A smooth transition eliminates the kinks brought by abrupt transition, and thus facilitates the numerical analysis.

1.4 The Household's Problem

The economy consists of many identical, infinitely-lived households which derive utility from the consumption of goods, vehicle-miles of travel, and leisure. The utility from travel comes from mobility provided to the household. The representative household maximizes the following lifetime utility:

[9]The violation of the CAFE standard is determined using the harmonian average of fuel efficiency for the entire fleet. A harmonic mean is not a simple arithmetic mean. It is the reciprocal of the average of the reciprocals of the fuel economies of the vehicles in the fleet. Given the log-normal distribution of the idiosyncratic term, the harmonian average of the fuel efficiency, $\widehat{X}_t$, is equal to $X_t \exp\left(-\sigma^2\right)$.

$$\max E_0 \sum_{t=0}^{\infty} \left\{ \beta^t U \left(C_t, M_t, 1 - L_t - T_t \right) \right\}, \tag{7}$$

where C is the quantity of a numeraire consumption good, M is vehicle-miles of travel,[10] T is time spent driving, and L represents labor. The household has a fixed time endowment of 1. Accordingly, $1 - L_t - T_t$ represents the amount of leisure. Driving time is determined as follows:

$$T_t = \psi \left(\overline{M}_t \right) M_t, \tag{8}$$

where $\psi (\bullet)$ is the inverse of the average travel speed and $\overline{M}_t$ is aggregate miles driven. An increase in the aggregate vehicle-miles of travel leads to more congestion on roads, so $\psi' (\bullet) > 0$. Agents take $\psi \left(\overline{M}_t \right)$ as fixed. They do not take into account of their own impact on congestion.

We assume that the household produces output using a linear production technology with labor as the only production input. The household production function is

$$Y_t = A_t L_t, \tag{9}$$

where A_t represents the aggregate technology shock. We assume that the logarithm of the technology shock, a_t, follows an AR(1) process as follows:

$$a_t = \rho_a a_{t-1} + \sigma_a \varepsilon_{a,t}. \tag{10}$$

At the beginning of each period t, there are N vintages of transportation capital in existence. Each vintage is identified by the capital-gasoline ratio,

[10] Note that vehicle miles of travel, M, is different from person miles of travel. A decline in the vehicle miles of travel can be achieved by a carpool of multiple people, which generates the same person miles of travel.

k_{t-j}, and the quantity of vehicles produced per vintage, Q_{t-j}, $j = 1, \cdots, N$. At each period t, the representative household takes the vintage structure of vehicles $\{Q_{t-j}, k_{t-j}\}_{j=1}^{N}$, the real gasoline price P_t, and the aggregate technology shock a_t, as given. The household then chooses k_t, the capital-gasoline ratio to be embedded in the new vehicles, Q_t, the quantity of new vehicles, and $\left\{z_t^{t-j}\right\}_{j=1}^{N}$, the cutoff value for vehicle utilization, to maximize its lifetime utility as described in equation (7),[11] subject to equations (4), (5), (10), an exogenous gasoline log-price process and the aggregate resource constraint[12]:

$$C_t + (1+\tau_o) P_t O_t + Q_t k_t + \frac{\theta}{2} Q_t (k_t - k_{t-1})^2 + F_t + \tau_M M_t = A_t L_t + \zeta_t. \quad (11)$$

The left hand side of the budget constraint represents the total spending, including consumption C, after-tax gasoline expenses $(1+\tau_o) P_t O_t$, with the gasoline tax rate being τ_o, investment in new vehicles, $Q_t k_t$, the adjustment cost of changing the fuel efficiency configuration from that of the previous period, possible penalty on CAFE standard violations F_t, and the mileage tax payment, $\tau_M M_t$. The cost of adjusting the fuel efficiency is convex at $\frac{\theta}{2}(k_t - k_{t-1})^2$ per vehicle. We assume that all the revenues or expenses from the energy policy, including gasoline taxes, mileage taxes and penalty for violating the CAFE standard are redistributed to the household in lump-sum amount of ζ_t.[13]

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[11] Since there are no costs for taking vehicles on- or off-road, a vehicle which is below cutoff for utilization in a given year sits idle for that year and then return for consideration in the next year.

[12] The household also owns all vintages of vehicles. In equilibrium the value of vehicles enters symmetrically on both sides of the budget constraint. We omit them for the sake of simplicity.

[13] We assume that the fines collected from the CAFE violation are redistributed in a

In equilibrium, all produced goods are either consumed, invested, or used to pay for gasoline expenses and cost of adjusting the fuel efficiency from the previous generation of vehicles.

2 Model Dynamics

In this section, we examine the decisions on driving, fuel efficiency of new vehicles and the quantity of new vehicles.

2.1 Driving Decisions

The first-order condition for the capacity utilization rate $\left\{z_t^{t-j}\right\}_{j=1}^{N}$ is given by

$$\mu_t \phi\left(z_t^{t-j} - \sigma\right) X_{t-j} = \lambda_t \left(1 + \tau_o\right) P_t \phi\left(z_t^{t-j}\right), \tag{12}$$

where $\phi(\bullet)$ is the probability density function of a standard normal random variable, μ_t, the Lagrange multiplier for equation (4), is the marginal value of travel, and λ_t, the Lagrange multiplier for equation (11), is the marginal value of the consumption good.

The first-order condition for M_t defines μ_t as

$$\mu_t = U_2\left(C_t, M_t, 1 - L_t - T_t\right) - U_3\left(C_t, M_t, 1 - L_t - T_t\right)\psi\left(M_t\right) - \lambda_t \tau_M. \tag{13}$$

As shown in the above equation, the marginal value of travel is the marginal utility of travel subtracting the combined cost of the marginal value

lump-sum fashion. By doing this, we not only abstract from the income effect, but also partially account for the credits (debits) the firm is allowed to accumulate according to the CAFE regulations.

of travel time and marginal value of mileage tax revenues. The mileage taxes affect the optimal decisions by reducing the marginal value of travel. The marginal value of consumption good, λ_t, is given by:

$$\lambda_t = U_1 \left(C_t, M_t, 1 - L_t - T_t \right). \tag{14}$$

The left hand side of equation (12) represents the marginal benefit from increasing the marginal capacity utilization, and the right hand side represents the marginal cost of larger capacity utilization due to higher marginal cost of gasoline input.

Simple algebra manipulations of equation (12) also yields

$$z_t^{t-j} = \frac{1}{\sigma} \left(\log \lambda_t + \log \left[\left(1 + \tau_o \right) P_t \right] - \log \mu_t - \log X_{t-j} + \frac{1}{2} \sigma^2 \right), \tag{15}$$

which shows that the lower fuel efficiency (the lower X_{t-j}), the lower capacity utilization rate among vehicles of vintage $t - j$. In addition to the pre-determined fuel efficiency X_{t-j}, three price variables, P_t, λ_t and μ_t also affect the decision on vehicle utilization. Among them, the gasoline price P_t is exogenously given, but λ_t and μ_t are endogenously determined marginal values of consumption good and travel.

As the gasoline price increases, λ_t and μ_t—the shadow prices of the consumption goods and travel—change accordingly. In the case when the increase in $\lambda_t P_t$ dominates that in μ_t, the marginal cost of driving the vehicle with fuel efficiency X_{t-j} increases relative to the marginal benefit of driving this type of vehicle. As a result, the capacity utilization for the particular vintage of vehicles declines. A higher gasoline tax rate, τ_o, also contributes to a higher marginal cost of driving.

2.2 Fuel Efficiency Decisions

The first-order condition for the capital-gasoline ratio of new vehicles, k_t, and equivalently the fuel efficiency of new vehicles, X_t, is given by

$$
\begin{aligned}
& 1+\theta\left(k_t-k_{t-1}\right)+f\left(\underline{X}-\widehat{X}_t\right) \frac{\partial H\left(\underline{X}, \widehat{X}_t\right)}{\partial k_t}+f H\left(\underline{X}, \widehat{X}_t\right) \frac{\partial\left(\underline{X}-\widehat{X}_t\right)}{\partial k_t} \\
= \; & E_t \sum_{s=1}^N\left\{\beta^s(1-\delta)^{s-1} \frac{\mu_{t+s}}{\lambda_t}\left[1-\Phi\left(z_{t+s}^t-\sigma\right)\right] \alpha k_t^{\alpha-1}\right\}+\beta E_t\left[\frac{\lambda_{t+1}}{\lambda_t} \theta\left(k_{t+1}-k_t\right) \frac{Q_{t+1}}{Q_t}\right].
\end{aligned}
\tag{16}
$$

The left-hand side is the marginal cost per vehicle of choosing the transportation-gasoline ratio, k_t. For each new vehicle the marginal cost has three components: the resources cost of one unit of the consumption good, the adjustment cost of choosing a different fuel efficiency for new vehicles, and the marginal impact on both the probability of violating the CAFE standard and the amount of penalty itself. The right-hand side is the marginal benefit of choosing a particular fuel efficiency. The marginal benefit comes from marginal increases in mileage over the vehicles' life span and the saving of the adjustment cost next period.

2.3 Market Value and Quantity of New Vehicles

The first-order condition for the quantity of new vehicles, Q_t, is given by

$$
\begin{aligned}
& k_t+\frac{\theta}{2}\left(k_t-k_{t-1}\right)^2+f\left(\underline{X}-\widehat{X}_t\right) H\left(\underline{X}, \widehat{X}_t\right) \\
= \; & E_t \sum_{s=1}^N\left\{\beta^s(1-\delta)^{s-1}\left[\frac{\mu_{t+s}}{\lambda_t}\left[1-\Phi\left(z_{t+s}^t-\sigma\right)\right] X_t-\frac{\lambda_{t+s}}{\lambda_t}\left(1+\tau_o\right) P_{t+s}\left[1-\Phi\left(z_{t+s}^t\right)\right]\right]\right\}.
\end{aligned}
\tag{17}
$$

The left hand side of the equation is the marginal cost of producing a marginal unit of new vehicle, which includes the expenses on transportation capital itself, the adjustment cost of varying the fuel efficiency of the new vehicle from the previous vintage, and possible penalty for violating the CAFE standard. The right hand side is the marginal benefit of producing such a vehicle, which is the present discounted value of driving subtracted by the present discount value of gasoline usage over the vehicle's life span.

3 Calibration

This section describes the benchmark calibration. There are four categories of parameters. The first category contains parameters related to the travel technology and gasoline use. The second category relates to the CAFE standard. The third category relates to the preference specification. The fourth category contains parameters which specify the processes for gasoline prices and the aggregate technology shock.

3.1 Parameters Related to Travel and Gasoline Use

A model period corresponds to a calendar year. We set the maximum life span of vehicles, N, to be equal to 15. Vehicles have 15 years of life span.

The production technology of travel is ex ante Cobb-Douglas. We calibrate the parameter α to 0.42 to match the ratio of real gasoline expenditure over the expenditure on new vehicles, which is equal to 1.68 according to

BEA (2006) data[14].

The standard deviation of idiosyncratic uncertainty, σ, is set to 0.3403 to match the fraction of vehicles in use out of all available vehicles. According to 2001 National Household Travel Survey (NHTS) , there are about 204 million personal vehicles available for regular use in the United States.[15] Also, according to the National Transportation Statistics, there are 228 million registered vehicles in 2001.[16] The ratio of the two is 89%, which corresponds to the fractions of vehicle in use in the model.

The parameter θ indexes the cost of adjusting the fuel efficiency k. This parameter governs the evolution of fuel efficiency of new generations of vehicles. According to the estimate of the National Research Council (2002), an

[14] According to the steady state equilibrium of the economy,

$$\begin{aligned} & \frac{\text{real expenditure on gasoline}}{\text{real expenditure on new vehicles}} \\ = \quad & \frac{1-\alpha}{\alpha} \times \frac{\sum_{s=1}^{M}\left[(1-\delta)^{s-1}\right]}{\sum_{s=1}^{M}\left[\beta^{s}(1-\delta)^{s-1}\right]}. \end{aligned}$$

According to the BEA (2006) data, the real expenditure on gasoline and new vehicles respectively make up for 1.63% and 0.97% of GDP. The data on real personal expenditure on new autos (Line 4, 109.1 billions of chained 2000 dollars) and gasoline (line 75, 184.2 billions of chained 2000 dollars) are obtained from Table 2.4.6. The data on real GDP (11294.8 billions of chained 2000 dollars) is obtained from Table 1.1.6. Both tables are available at the BEA website: http://www.bea.gov/national/nipaweb/SelectTable.asp?Selected=N#S2

[15] The number of personal vehicles available for regular use is obtained from Highlights of the 2001 National Household Travel Survey, p8.

[16] I subtract trucks with 6 or more tires and buses from the total number of registered vehicles. The data are obtained from Table 1-11 of the National Transportation Statistics at the Bureau of Transportation Statistics. The table can be downloaded from http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html

extra \$1000 could increase the fuel efficiency of a conventional gas-powered vehicle by between 15 and 25 percent. We calibrate θ to 0.12 to match the adjustment cost in relative terms.[17]

The parameters υ and ϖ are the parameters which transform travel mileages into time spent on travel.[18] We set υ to 0.2, which implies that it takes 20% more time to travel the same distance. The parameter ϖ measures time spent on one unit of travel. We calibrate ϖ to 9.54 so that the travel time makes up for 4% of the household's discretionary time in the steady state.[19]

[17]According to the model, the marginal cost of adjusting the fuel efficiency is $\theta\left(k' - k\right).$ Assuming that the increase in the fuel efficiency, $\frac{k'^{\alpha}-k^{\alpha}}{k^{\alpha}}$, is 1%, the model specificiation implies that $\frac{\theta\left(k'-k\right)}{k}$, which is the marginal adjustment cost of 1% increase in the fuel efficiency as a fraction of the value of a new vehicle, is 0.02θ. If we use the estimate that an extra \$1000 could increase the fuel effiiciency by 15%, the average adjustment cost of 1% increase in the fuel efficiency as a fraction of the value of a new vehicle (assumed to be \$25000) would be $\frac{1000/15}{25000}$. Equating this value with 0.02θ yields the calibrated value of θ around 0.12.

[18]We assume that $\psi\left(M_t\right)$ takes the form of ϖM_t^{υ}.

[19]According to *Highlights of the 2001 National Household Travel Survey* (p.11), overall for all adults, including nondrivers and those who may not have driven in a given day, 55 minutes are spent behind the wheel a day. We can infer from Juster and Stafford (1991) that the total weekly discretionary time endowment is 146.67 hours. Based on the two estimates above, travel time makes up for 4.38 percent of the total discretionary time endowment.

3.2 Parameters Related to the CAFE Standard and Taxes

According to the NHTSA, the penalty for failing to meet CAFE standards is \$55 for each mile per gallon below the standard multiplied by the total volume of those vehicles manufactured for a given model year. In relative terms, the penalty amounts to a fraction of $\frac{55}{25000}$ of the value of a new vehicle per 4% of the standard[20]. We set f to 0.15 to match the fine in relative terms.[21]

We assume that both the gasoline tax rate, τ_o, and the mileage tax rate, τ_M, are equal to zero in the benchmark specification.

3.3 Preference Specifications

We set β, the subjective discount rate, to 0.97. In the benchmark framework, we assume log-preferences on consumption, travel and leisure:

$$U\left(C_t, M_t, 1 - L_t - T_t\right) = \varphi_1 \log C_t + \varphi_2 \log M_t + \left(1 - \varphi_1 - \varphi_2\right) \log\left(1 - L_t - T_t\right).$$

Such a specification implies that these two types of goods are not fully substitutable. The parameters φ_1 and φ_2 are calibrated to 0.34 and 0.05 respectively to match the fraction of time spent on market activities, which

[20] The current CAFE standard is around 25 miles per gallon for a combination of passenger cars and light trucks. 4% of 25 miles per gallon is exactly equal to 1 mile per gallon.

[21] Specifically, the normalized penalty for violating the CAFE standard in the model is $\frac{55}{25000} k_{ss} \times \frac{25}{\underline{X}} \left(\underline{X} - \widehat{X}\right) Q$, where k_{ss}, the steady-state capital-gasoline ratio, also represents the steady-state value of new vehicle in the model. When k_{ss} is equal to 25000 and $\underline{X}$ is equal to 25, we have the penalty standard applied in reality. The normalized penalty implies that the value of f is equal to $\frac{55}{25000} k_{ss}$ divided by $0.04\underline{X}$.

is 0.35,[22] and the fraction of gasoline expenditures out of output, which is 1.63%.

3.4 Gasoline Price and Aggregate Productivity Processes

We work with two alternative specifications of the gasoline price process. For the first specification, we assume that the annual gasoline price follows a random walk:

$$\log P_t = \log (P_{t-1}) + \varepsilon_{p,t}.$$

For the second specification, we follow Atkeson and Kehoe (1999) and estimate an ARMA (1,1) process parameterized by

$$\log P_t = \left(1 - \rho_p\right) \log (\overline{p}) + \rho_p \log (P_{t-1}) + \varepsilon_{p,t} + \eta \varepsilon_{p,t-1}, \tag{18}$$

where $\varepsilon_{p,t} \sim N\left(0, \sigma_p^2\right)$ and $\overline{p}$ is the average gasoline price in the data.

The gasoline price is the ratio of the implicit deflator for gasoline to the GDP deflator[23]. The estimation of annual real gasoline prices yields an

[22] Ghez and Becker (1975) and Juster and Stanfford (1991) have found that households allocate about one third of their discretionary time-i.e, time not spent sleeping or in personal maintenance-to market activities.

[23] The data series for nominal retail gasoline prices are downloaded from the web site http://www.eia.doe.gov/emeu/steo/pub/fsheets/real_prices.xls. We compute the implicit deflator for gasoline using year 2000 as the base year. The GDP implicit price deflator series are from the Department of Commerce, Bureau of Economic Analysis. The data on deflator are quarterly and seasonally adjusted. We convert the quarterly deflator series into annually and use year 2000 as the base year as well. The real gasoline prices are constructed as the ratio of the implicit deflator for gasoline to the GDP deflator.

estimated value of 0.858 for ρ_p, 0.562 for η, and 1.0872 for $\overline{p}$.

We set ρ_a in equation (10) to 1 and then 0.95 to examine the cases of both permanent and transitory productivity processes. We parameterize σ_a to replicate the annual output growth volatility.

4 Responses to Temporary and Permanent Shocks

In this section, we examine the impulse responses of key variables in response to gasoline price shocks and aggregate technology shocks, both permanent and transitory. One of the advantages of a dynamic model in contrast to a static one is its ability to generate dynamic responses of endogenous variables in response to shocks. The responses are different depending upon the persistence of the exogenous process. Below we examine the dynamic responses to gasoline price and aggregate technology shocks.

4.1 Short-Run and Long-Run Gasoline Price Elasticities

Figure 1 plots the impulse responses of key economic variables to a 1% gasoline price shock. The left column displays the dynamic responses to a 1% permanent gasoline price shocks, that is, the case of the gasoline prices following a random walk. The right column shows the case of gasoline prices following an ARMA process.

4.1.1 Permanent Gasoline Price Shocks

First we examine the dynamic responses to a 1% permanent gasoline price shock. The 1% gasoline price shock can also be considered as a permanent 1% gasoline tax hike we discuss in detail later. We focus on the short-run and long-run gasoline price elasticities implied by the model. In response to a 1% permanent gasoline price hike, gasoline use declines by 0.2% instantly. Gasoline use continues to decline till reaching the new steady state, which represents around 0.5% decline from the value before the gasoline price hike, These numbers correspond to a short-run price elasticity of -0.2 and a long-run price elasticity of -0.5 of gasoline demand, well within the region of plausible estimates in the empirical literature. Using a large sample of household data, Bento et al (2009) estimate that each percent increase in the price of gasoline leads to a reduction of between 0.25 and 0.30 percent in the equilibrium demand for gasoline. The U.S. Department of Energy (USDOE, 1996) proposes an estimate of price elasticities of -0.38. Our model is able to endogenously generate the price elasticities of a magnitude close to those empirical estimates.[24]

The differences in the short-run and long-run demand elasticity stem from the putty-clay nature of the production technology of travel. In the period of the gasoline price shock, both the quantity and the fuel efficiency of all the vehicles are pre-determined, the household can only adjust the capacity

[24] Goodwin (1992) categories estimates of the elasticity of gasoline consumption with respect to fuel prices. He finds the average of short term price elasticities to be -0.27, and the average of the long term price elasticities to be -0.71 when time series data are used. However, much lower values are found when using data after 1990.

utilization of these vehicles in response to the gasoline price shock. In other words, the household utilizes its vehicles less, which leads to a short-run demand elasticity of -0.2. In the periods following the gasoline price shock, the household can substitute more fuel efficient vehicles to replace those obsolete, less fuel-efficient vehicles. As a result, the long-run price elasticity settles at -0.5 after all the pre-existing vehicles at the time of the gasoline price hike become obsolete.

As shown in equation (12), the representative household decides whether to drive a particular vehicle based on the comparison of marginal benefit of driving, $\mu_t X_{t-j}$, versus its marginal cost, $\lambda_t P_t$. Since X_{t-j} and P_t are exogenously given, the driving decision depends upon endogenously determined λ_t and μ_t. In our model, the responses of consumption, and thus λ_t, to the gasoline price shocks are minimal, while the marginal utility of driving, μ_t, increases due to reduced travel in response to the gasoline price shock. As shown in the second left panel of Figure 1, although the increase in μ_t results in higher marginal benefit of travel, the increase is not sufficient to compensate for the increase in the marginal cost of driving due to a 1% gasoline price increase. As a result, the marginal cost of driving exceeds its marginal benefit, resulting in around 0.2% reduction in the utilization of vehicles, which corresponds to the short-run demand elasticity of -0.2. We only display the dynamic responses of the capacity utilization of the oldest vintage for each given period. However, since the economy is assumed to be at the steady state at the time of the gasoline price shock, all the vintages share the same fuel efficiency to start with. As a result, the decline in the capacity utilization is the same across all pre-existing vintages.

In the long run, the representative household adjusts both the fuel efficiency and quantity of new generation of vehicles to respond to the gasoline price hike. The fourth left panel of Figure 1 shows a gradual increase in the fuel efficiency of new vehicles over time due to the cost of adjusting the fuel efficiency. In the long run, the fuel efficiency of vehicles is 0.4% higher than before the gasoline price shock. The increase in the fuel efficiency of new vehicles is also reflected in the capacity utilization. After 15 periods, the oldest vintage of vehicles is the generation produced at the time of the gasoline price shock. As shown in the third left panel, this vintage has a slightly higher capacity utilization due to higher fuel efficiency. After the fuel efficiency of new vehicles reach its permanent level, the capacity utilization of vehicles also returns to the pre-shock level.

As the fuel efficiency of new vehicles increases and the demand for travel decreases in response to gasoline price shock, the quantity of new vehicles produced also declines in the long run. Vehicle miles of travel decline in the long run as well.

4.1.2 Transitory Gasoline Price Shocks

The right column of Figure 1 displays the dynamic responses to a 1% transitory gasoline price shock. The dynamic responses are markedly different from the case of permanent gasoline price shock. Gasoline use declines instantly as the capacity utilization of all vehicles decline. However, as the gasoline price slowly declines to its steady state level, gasoline use and the capacity utilization of vehicles all return to the original steady state in the long run. The fuel efficiency of new vehicles increases in the short run in response to the transitory gasoline price shock. However, the responses are much smaller compared to the case of permanent gasoline price shock, due to the transitory nature of the gasoline price increase. In the long run, the fuel efficiency of new vehicles reverts to the steady state level.

In summary, permanent gasoline price shocks have permanent impact on the driving behavior, gasoline use and vehicle fuel efficiency, while transitory gasoline price shocks have no long-run impact on the economy.

4.2 Short-Run and Long-Run Income Elasticities

Figure 2 plots the dynamic responses of key economic variables to a 1% aggregate technology shock. The left column displays the case when the aggregate productivity follows a random walk, while the right column presents the case of an auto-regressive process.

4.2.1 Permanent Technology Shocks

In contrast to a positive gasoline price shock which encourages the use of one production factor against the other, a positive aggregate technology shock affects the equilibrium allocation through relaxing the aggregate resource constraint. As shown in the left column, a permanent 1% increase in the aggregate productivity has no impact on the fuel efficiency of vehicles in either the short run or in the long run. The marginal value of travel, μ_t, decreases by approximately the same amount as the marginal cost of travel, $\lambda_t P_t$. As a result, the capacity utilization of the oldest vintage barely changes after the initial period. The symmetric movement of μ_t and $\lambda_t P_t$ also explains why the fuel efficiency of new vehicles remains unchanged in response to aggregate technology shocks.

The impact of the positive permanent technology shock falls almost entirely on the quantity of new vehicles produced, resulting in a proportional 0.17% increase in gasoline use and vehicle miles of travel in the long run. In response to a permanent aggregate technology shock, the short-run and long-run income elasticities of both gasoline use and vehicle miles of travel are fairly similar since, unlike the fuel efficiency of new vehicles, the quantity of new vehicles produced can be quickly adjusted in the model.[25]

4.2.2 Transitory Technology Shocks

The case of a transitory but persistent technology shock is a different story. In response to the positive technology shock, an increase in consumption translates to a decline in λ_t, the marginal value of consumption good. The marginal value of travel, μ_t, declines as well as more resources allow for more travel. The decline in λ_t surpasses that of μ_t in the initial period, resulting in higher utilization of vehicles. More driving in the initial period leads to 0.1% increase in vehicle miles of travel, and 0.2% increase in gasoline use in response to a 1% deviation of the technology shock. The vehicle miles of travel increases for another period as new vehicles are produced for travel purposes, but eventually returns to the steady state. Gasoline use also slowly returns to the steady state level as well. As shown in the right column, a transitory positive aggregate technology shock alters the ratio of the marginal value of travel over the marginal value of consumption good in future periods,

[25] The cost of adjusting the quantity of vehicles can also be incorporated into the model to capture the difference between short-run and long-run income elasticities.

resulting in slightly higher fuel efficiency of new vehicles during the transition period.

5 Comparison of Three Policy Options

In this section, we compare the short-run and long-run impact of three policy options to reduce the gasoline demand. These three policy options are: gasoline taxes, CAFE standard and mileage taxes. We ask how much percentage changes in the CAFE standard and the mileage tax rate are required respectively, in order to reduce gasoline use by the same magnitude in the long run as a 1% permanent increase in the gasoline tax rate. We then examine the dynamic responses of key variables under these three policy options which bring about the same long run effect on gasoline use.

We set the starting point of the minimum CAFE standard as the largest $\underline{X}$ which allows the household to choose the same X as in a model without CAFE standard. That is, the starting value of $\underline{X}$ is very close to be a binding constraint. Starting from this value of $\underline{X}$, we examine how much percentage increase in this standard results in the same amount of gasoline savings as 1% permanent increase in gasoline taxes.

We find that given the benchmark calibration, the minimum CAFE standard $\underline{X}$ has to be increased by 0.68%, and the mileage tax has to increase by 3.2 percentage points to reduce gasoline use by 0.5% in the long run, the same amount of permanent gasoline savings as a permanent 1% gasoline tax hike would have achieved.

Figure 3 sheds light on the different mechanisms through which these three policy options reduce gasoline use. We will first examine the cases of gasoline taxes and the CAFE standard since both have long run implications for the fuel efficiency of vehicles, whereas mileage taxes do not have any long run impact on the fuel efficiency.

5.1 Gasoline Taxes Versus CAFE Standard

As illustrated in our model, vehicle miles of travel are produced with two inputs: transportation capital and gasoline. By levying taxes on gasoline use, the gasoline tax policy encourages higher fuel efficiency for new vehicles. CAFE standard, on the other hand, encourages higher fuel efficiency of new vehicles by imposing penalty on new vehicles with lower fuel efficiency than the minimum standard.

A 1% gasoline tax increases the fuel efficiency of new vehicles by around 0.2% in the first period, and after four periods, the fuel efficiency of new vehicles increases permanently to 0.4% above the pre-tax value. The slow adjustment reflects the cost of adjusting the fuel efficiency over time. By contrast, in response to the elevation of the minimum CAFE standard by 0.68%, the fuel efficiency of new vehicles rises to its new permanent level immediately, reflecting that the penalty for violating the CAFE standard is a more important consideration than the cost of adjusting the fuel efficiency.

Gasoline taxes and the CAFE standard are different in terms of the mechanism through which they reduce the gasoline consumption. The former reduce the gasoline consumption through two channels. First, a 1% gasoline tax leads to lower capacity utilization of pre-existing vehicles. As shown in Figure 3, the capacity utilization of pre-existing vehicles declines by around

0.2% during their life span. Since pre-existing vehicles are endowed with the choice of fuel efficiency at the time of their production, higher gasoline costs lead to lower capacity utilization. Lower utilization of vehicles means that people are driving less, thus contributing to lower gasoline use. As pre-existing vehicles phase out over time, the capacity utilization of vehicles slowly returns to its pre-tax level. Besides the reduction in capacity utilization, higher fuel efficiency of new generations of vehicles also contribute to gas savings.

A tightening of the CAFE standard raises the fuel efficiency of new vehicles, but has very small impact on the capacity utilization of pre-existing vehicles. Unlike the 1% increase in the gasoline taxes, the marginal benefit and cost of utilizing pre-existing vehicles barely change in response to the new CAFE standard. Instead, the capacity utilization of newly produced vehicles increases by 0.4%. Higher fuel efficiency of new vehicles increase the marginal benefit of driving, while the marginal cost of gasoline remains barely changed. This is the so-called "rebound effect".

A 1% gasoline tax and a 0.68% increase in the minimum CAFE standard both reduce the gasoline usage by 0.5% in the long run. However, gasoline use declines by 0.2% in the first period of the gasoline tax hike. The immediate gasoline savings come from lower capacity utilization of pre-existing vehicles. By contrast, the immediate gasoline savings from a higher CAFE standard is close to zero, since it does not have an impact on gasoline use of pre-existing vehicles. As the pre-existing vehicles gradually phase out, gasoline use is reduced to its new permanent level around 15 years after the introduction of these two policies.

5.2 Mileage Taxes

Instead of affecting the relative proportion of the two *inputs* of travel, mileage taxes impose taxes on the *output*: vehicle miles of travel directly. In response to a 3.2 percentage point increase in the mileage tax rate, the capacity utilization of all pre-existing vehicles declines by around 0.5% in the initial period[26]. Given the pre-determined quantity and the fuel efficiency of vehicles in the first period, reducing the capacity utilization of vehicles is the only means to reduce vehicle miles of travel in response to taxation. Since mileage taxes do not encourage the use of one input versus the other, it is understandable that the fuel efficiency of new vehicles remains unchanged in the long run. The reduction in vehicle miles of travel is mainly achieved through a proportional reduction in quantity of vehicles produced in the long run. The vehicle miles of travel declines by 0.48% in the long run in response to a 3.2 percentage point increase in the mileage tax rate, implying a 2.7% increase in mileage tax revenues. By contrast, a 1% increase in the gasoline tax rate, which brings about the same amount of permanent gasoline savings as a 3.2% increase in the mileage tax rate, leads to a 0.5% increase in gasoline tax revenues.

5.3 Summary Comparison

To summarize, the gasoline taxes, CAFE standard, and mileage taxes can all achieve the goal of reducing the gasoline usage in the long run. However,

[26] The mileage taxes in the model are levied on vehicle miles of travel. Since the marginal value of one unit of travel, μ, is close to 1 in the steady state, a mileage tax rate of 3.2 percent approximates a tax rate on the value of travel as well.

the gasoline savings are achieved through different mechanisms.

Gasoline taxes produce gasoline savings by reducing the capacity utilization of all pre-existing vehicles and increasing the fuel efficiency of new generation of vehicles. Gasoline use drops immediately upon imposing the gasoline taxes and continues to decline as more fuel efficient vehicles phase out the previous generations. The CAFE standard, on the contrary, barely changes the capacity utilization of all pre-existing vehicles, but increases the capacity utilization of new generations of vehicles. The CAFE standard achieves gasoline savings mainly through higher fuel efficiency of new vehicles. As a result, there are no immediate gasoline savings in the first period. The gasoline savings accumulate over time as older generations of vehicles gradually phase out. The mileage taxes generate gasoline savings by discouraging travel. Gasoline savings start immediately as the vehicles are less utilized for travel purposes. Mileage taxes do not change the fuel efficiency of new vehicles. Given the same fuel efficiency in the long run, a reduction in mileage corresponds proportionally with a reduction in gasoline use.

In terms of magnitude, in order to achieve the same amount of gasoline savings in the long run, CAFE standard has the strongest impact on the fuel efficiency of new vehicles, since it does not have the extra channel of reducing the capacity utilization of pre-existing vehicles. Mileage taxes reduce the vehicle miles of travel by the largest percentage, while a tightening of the CAFE standard has very little impact on vehicle miles of travel in the long run as higher fuel efficiency offset the adverse effect of gasoline taxes on travel. All the three policy options reduce the quantity of new generation of vehicles.

6 Conclusion

By incorporating a putty-clay specification in the "production" technology of travel, the dynamic general equilibrium model developed in this paper provides a rich framework for analyzing the endogenous determination of gasoline use, driving and vehicle fuel efficiency. The model is able to generate endogenously different short-run and long-run price and income elasticities of gasoline use and vehicle miles of travel, with the magnitude of these elasticities well within the region of plausible estimates in the empirical literature. The model also demonstrates that the dynamic responses of key variables can be drastically different depending upon the persistence of the stochastic gasoline price and aggregate productivity processes.

We use the model to evaluate three policy options: gasoline taxes, CAFÉ standard and mileage taxes. We find that although these three policy options can all reduce gasoline use in the long run, they are different in terms of both the magnitude of responses and the dynamic path followed by key variables. The model can also be used to analyze the new policy initiatives under the current administration and environment-related issues. We leave a full exploration of these issues to future research.

References

[1] Atkeson, A. and P. Kehoe, 1999, Models of Energy Use: Putty-Putty versus Putty-Clay, American Economic Review, 89 (4), 1028-1043.

[2] Austin, D. and T. Dinan, 2005, Clearing the Air: The Costs and Consequences of Higher CAFE Standards and Increasing Gasoline Taxes, Journal of Environmental Economics and Management 50: 562-582.

[3] Bento, A., L. Goulder, M. Jacobsen, and R. Von Haefen, 2009, Distributional and Efficiency Impacts of Increased U.S. Gasoline Taxes, American Economic Review, 99 (3), 667-699.

[4] Bresnahan, Timothy and Valerie Ramey, 1993, Segment Shifts and Capacity Utilization in the U.S. Automobile Industry, American Economic Review, 83, 213-218

[5] Congressional Budget Office, 2002, Reducing Gasoline Consumption: Three Policy Options, Washington, DC.

[6] Ghez and Becker, 1975, The Allocation of Time and Goods over the Life Cycle, published by the NBER.

[7] Gilchrist, S.and J.Williams, 2000, Putty-Clay and Investment: A Business Cycle Analysis, Journal of Political Economy, 108 (5), 928-960.

[8] Gilchrist, S.and J.Williams, 2005, Investment, Capacity and Uncertainty: A Putty-Clay Approach, Review of Economic Dynamics 8.

[9] Goldberg, P. 1998. The Effects of the Corporate Average Fuel Economy Standards in the U.S., Journal of Industrial Economics, 46: 1-33.

[10] Goodwin, P.B. 1992, A Review of New Demand Elasticities with Special with Special Reference to Short and Long Run Effects of Price Changes, Journal of Transportaion Economics and Policy, 26 (2) 155-169.

[11] Greene, D.L., J.R. Kahn, and R.C. Gibson, 1999, Fuel Economy Rebound Effect for U.S. Household Vehicles, The Energy Journal 20: 1-31.

[12] Hamilton, James, 2009, Causes and Consequences of the Oil Shock of 2007-2008, Working Paper, UCSD.

[13] Highlights of the 2001 National Household Travel Survey, U.S. Department of Transportation, Bureau of Transportation Statistics

[14] Jacobsen, Mark, 2007, Evaluating U.S. Fuel Economy Standards in a Model with Producer and Household Heterogeneity, Ph.D. Dissertation, Stanford University, Stanford, CA.

[15] Jones, C. 1993, Another Look at U.S. Passenger Vehicle Use and the "Rebound Effect" From Improved Fuel Efficiency, The Energy Journal 14: 99-110.

[16] Juster and Stafford, 1991, The Allocation of Time: Empirical Findings, Behavioral Models and Problems of Measurement, Journal of Economic Literature, June 1991, 29(2), 471-522.

[17] Li, Shanjun, Roger Haefen and Christopher Timmins, 2008, How Do Gasoline Prices Affect Fleet Fuel Economy? NBER Working Papers 14450.

[18] National Research Council, 2002, Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, Washington, DC: National Academy Press

[19] National Transportation Statistics, 2009, Bureau of Transportation Statistics, U.S. Department of Transportation.

[20] Parry, Ian and Kenneth Small, 2005, Does Britain or the United States Have the Right Gasoline Tax? American Economic Review, 95 (4)..

[21] Ramey, Valerie, and Daniel Vine, 2009, Oil Shocks, Segment Shifts and Capacity Utilization in the U.S. Automobile Industry: What Has Changed in 30 Years?", mimeo, UCSD.

[22] Small, K., and K. Van Dender. 2007. Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect, Energy Journal 28: 25-51.

[23] U.S. Department of Energy, 1996, Policies and Measures for Reducing Energy Related Greenhouse Gas Emissions: Lessons from Recent Literature, Report No. DOE/PO-0047.

[24] Wei, Chao, 2003, Energy, the Stock Market, and the Putty-Clay Investment Model, American Economic Review, 93 (1), 311-323.

Figure 1: Dynamic Responses to Gasoline Price Shocks

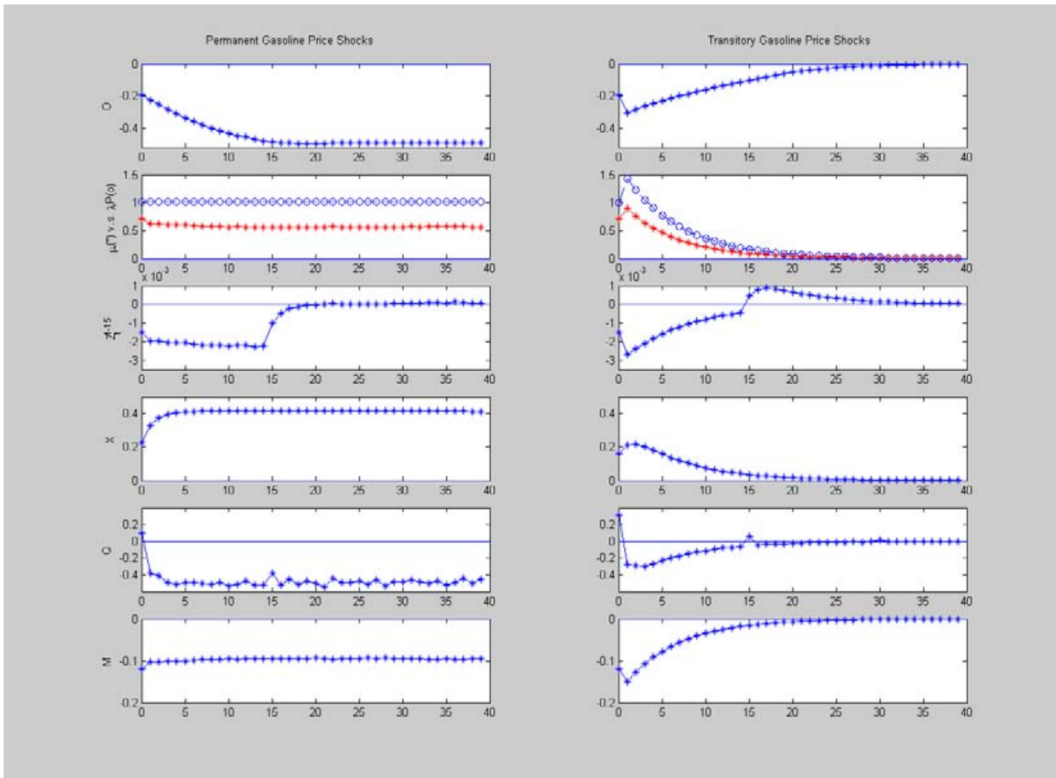


Figure 1 displays the dynamic responses of key endogenous variables to a 1% permanent (left column) and transitory (right column) gasoline price shock. The variables from the top to bottom are: O, the gasoline usage; μ versus λP, the marginal value of travel (*) versus the marginal cost of travel (o); $1 - \Phi\left(z_t^{t-15}\right)$, the capacity utilization of the oldest vintage of vehicles; X, the fuel efficiency of new vehicles; Q, the quantity of new vehicles; and M, the vehicle miles of travel.

Figure 2: Dynamic Responses to Technology Shocks

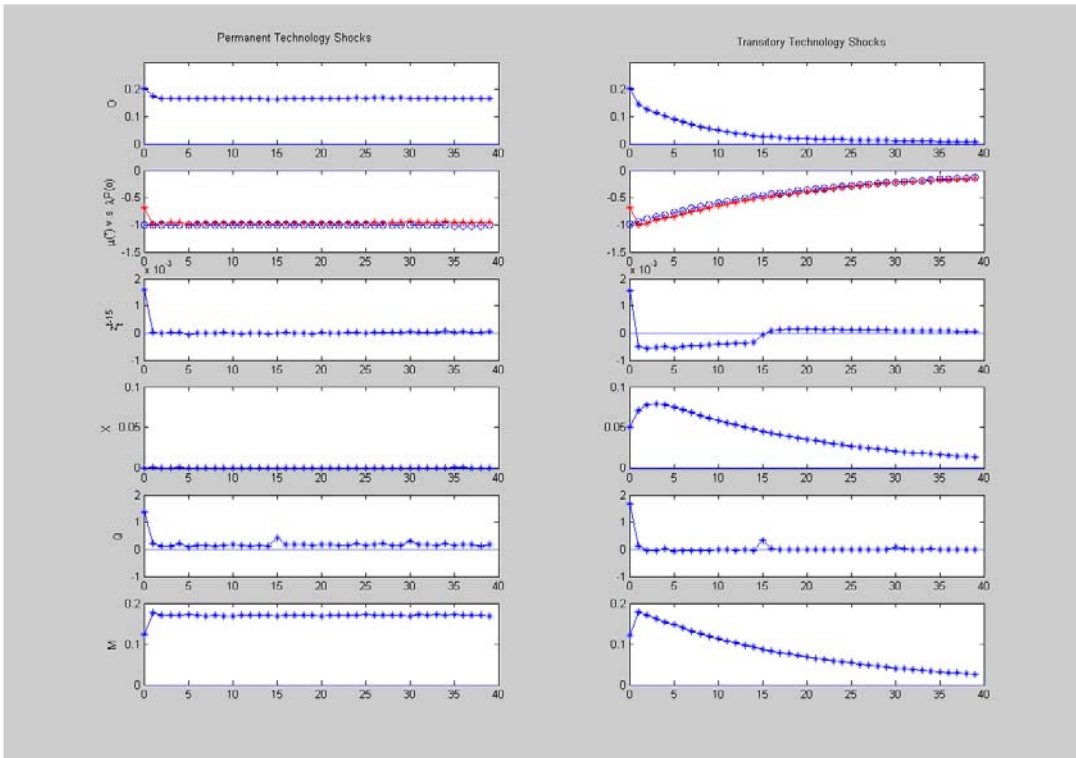
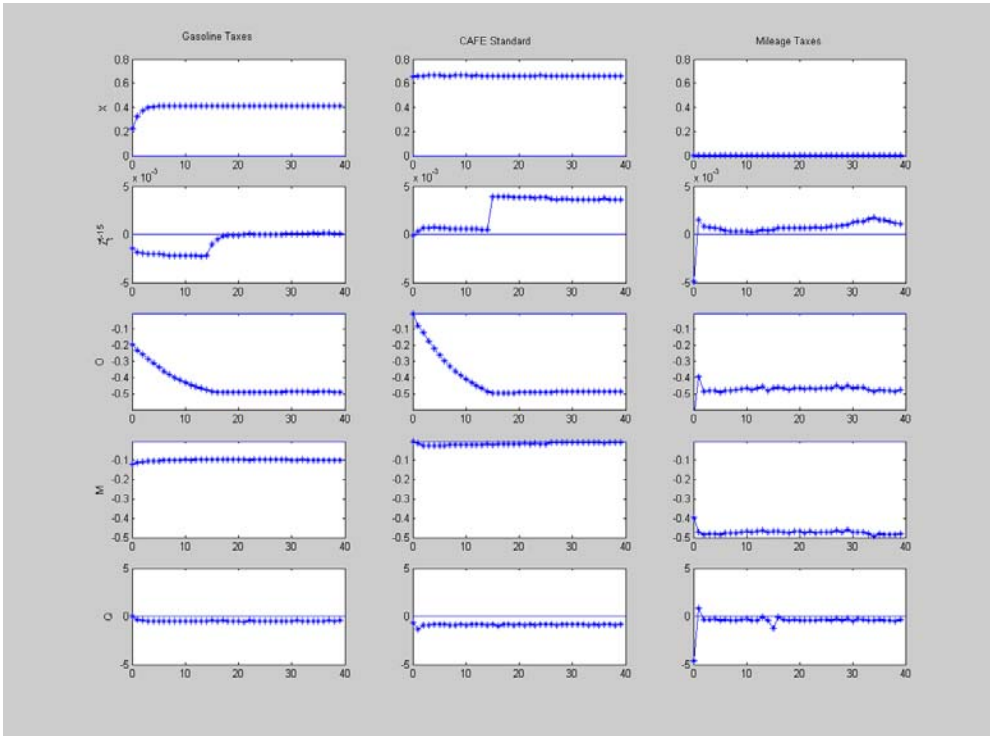


Figure 2 displays the dynamic responses of key endogenous variables to a 1% permanent (left column) and transitory (right column) technology shock. The variables from the top to bottom are: O, the gasoline usage; μ versus λP, the marginal value of travel (*) versus the marginal cost of travel (o); $1 - \Phi\left(z_t^{t-15}\right)$, the capacity utilization of the oldest vintage of vehicles; X, the fuel efficiency of new vehicles; Q, the quantity of new vehicles; and M, the vehicle miles of travel.

Figure 3: Comparison of Dynamic Reponses Under Three Policy Options



The first, second and third columns respectively display the dynamic responses of key variables to a 1 percentage-point permanent increase in gasoline taxes, a 0.68 percent increase in the CAFE standard, and a 3.2 percentage point increase in mileage taxes. All these policy options bring about a 0.5 percent decline in gasoline use in the long run.