Knowledge Capital, Technology Adoption, and Fuel Consumption Policies: An Endogenous Product Choice Study

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Fuel-saving technology plays a key role in reducing greenhouse gas emissions from the transportation sector. This paper studies how environmental policies incentivize carmakers to improve the energy efficiency of their products. I examine how gasoline taxes and R&D subsidies affect vehicle fuel efficiency and private welfare by simulating carmakers' choices of vehicle characteristics and technology improvements, as well as their pricing decisions.

Previous structural studies of fuel consumption policies have focused on vehicle pricing (e.g., Bento et al, 2009; Jacobsen, 2013).[1] However, fuel consumption policies and economic conditions may also incentivize carmakers to change existing products to use fuel more efficiently. In fact, reduced-formed studies have documented unignorable uptakes in energy-saving technologies (e.g., Newell et al., 1999; Knittel, 2012). Ignoring this aspect of firms' decision making can lead to a bias in fuel efficiency and welfare implications. I develop and estimate a demand and supply model of the U.S. new car market over the time period 1986--2006. In contrast to earlier work, this paper endogenizes vehicle performance characteristics (e.g., power and size), choices to adopt specific matured fuel-saving technologies (e.g., variable valve timing (VVT)) and numbers of fuel-saving patents to develop. I also account for standard channels of change in demand and pricing.

My model captures several incentives for technology improvements. The fact that consumers demand fuel-efficient vehicles can incentivize carmakers to adopt matured fuel-saving technologies, e.g., Honda can adopt technologies such as VVT to increase demand. As for fuel-saving patents, I find they affect profits primarily by lowering the marginal cost of producing a vehicle. This finding contributes to prior studies on energy-saving patents (e.g., Aghion et al., 2016) by showing their effects on fuel efficiency and on production costs. Based on my estimates, I simulate the effects of

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[1] Bento et al. (2009) also examines the channel of households' vehicle-mile travelled (VMT). This large literature includes, but not limited to, Berry et al. (1995), Goldberg (1995), Klier and Linn (2012), Whitefoot et al. (2013), and Reynaert (2015). Whitefoot et al (2013) also endogenize weight and acceleration and employ engineering simulations.

raising gasoline taxes and subsidizing R&D on fuel efficiency and on consumer and producer surplus.

I. An Empirical Model of Technology Improvement

A. New Vehicle Demand

I model and estimate a nested logit new car demand. Consumers make purchasing decisions based upon vehicle price, fuel cost, and performance characteristics. I specify consumer i's indirect utility from purchasing vehicle h in year t as $u_{iht} = U_{it}(p_{iht}, fp_t g_{iht}, x_{iht}, \eta^d_{mt}, \xi_{ht}) + \varpi_{iht}$, where p_{iht} is vehicle price, x_{iht} is vehicle performance characteristics (in logs) consisting of horsepower-to-weight ratio and weight, and ξ_{ht} is unobserved vehicle characteristics. I assume the individual-specific structural error ϖ_{iht} takes a nest logit form[2]. Both gasoline price fp_t and fuel efficiency g_{iht} (measured by by fuel consumption rate gallons per mile) enter demand together as part of the fuel cost in dollars per mile $fp_t g_{iht}$.

B. Automakers' Problem

I model the automakers' problem in a static framework. Automakers compete in a Bertrand game each year and maximize profits from multiple products. My model has a two-stage structure following Fan (2013). In the first stage, automakers choose vehicle performance characteristics (e.g., weight), matured fuel-saving technologies to adopt (e.g., VVT), and investment in knowledge capital (measured by the number of fuel-saving patents they develop each year). In the second stage, automakers take the above choices as given and set prices simultaneously. Automaker f's profit:

$$(1)\ \ \Pi_f(p,x,a,i) = \max_{x,a,i}\left\{\max_{p}\left\{\sum\nolimits_{h\in H_f}\left[\left(p_h - c_h(x_h,a_h,i)\right)s_h(p_h, g_h(x_h,a_h,i), x_h)M - F^x_h(x_h) - F^a_h(a_h)\right] - H_f(i_f)\right\}\right\}$$

where s_h is market share determined from vehicle demand and M is market size.[3] I model marginal cost c_h as a function of performance characteristics x_h, technologies adopted a_h, and knowledge stock $ki_f(i_f; ki_f^{-1})$ which is a function of knowledge capital i_f. A carmaker faces fixed costs associated with adjusting performance characteristics F^x_h and adopting fuel-saving technologies F^a_h for each vehicle

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[2] I consider one nest consisting of seven segments: small cars, medium cars, large/luxury cars, crossovers, SUVs, pickups and vans.

[3] Measured by the total number of US households each year.

model and a firm-level cost associated with developing fuel-saving patents H_f.

To relate technology improvements to fuel efficiency, I model gallons per mile $g_h\left(x_h, a_h, ki_f(i_f; ki_f^{-1})\right)$ being determined by product characteristics and technology improvements. In contrast to previous studies that have estimated technology improvements using model year fixed effects (e.g., by estimating $g_h(x_h, T)$ as in Knittel (2012)), I directly estimate how choices of technology adoption and fuel-saving patents separately affect fuel efficiency.

While the model is static, which reflects the state of the literature for modeling endogenous product characteristics (Fan, 2013; Wollmann, 2014), I interpret my results as reflecting automakers' abilities to update their cars between model years as well as changes in prices.[4]

II. Data

I assemble a unique panel dataset linking fuel-saving patents information from the OECD Triadic Family Patent (TFP) database and fuel-saving technology adoption data from the U.S. Environmental Protection Agency (EPA) Fuel Economy Trend database, to vehicle characteristics (e.g., horsepower and weight) and sales data from Ward's Auto for new gasoline-powered vehicles in the US over 1986--2006.[5]

I measure technology adoption by a vector of technology choices, each of which describes the adoption of energy-efficient powertrain or transmission technologies.[6] Figure 1 plots the market penetration trends of five major fuel-saving technologies that were well adopted over 1986--2006.

I measure knowledge capital by the number of fuel-saving engine patents for which a firm has applied, following Aghion et al. (2016).

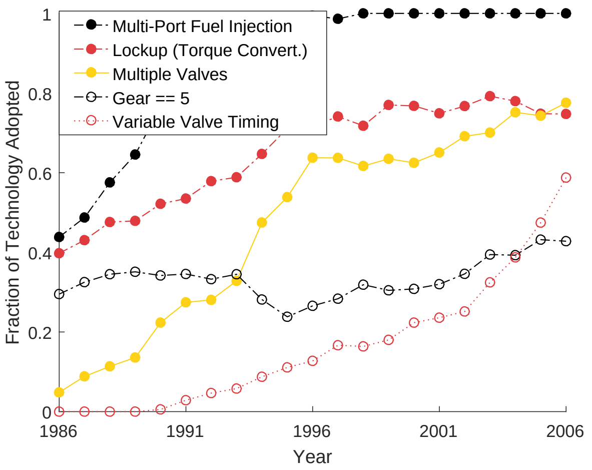

FIGURE 1. ADOPTION OF FUEL-SAVING TECHNOLOGIES: 1986-2006

Note: The above five technologies are selected according to EPA Fuel Economy Trend Annual Reports.

Source: EPA Fuel Economy Guide Database and EPA Fuel Economy Trend Database.

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[4] While this paper does not model regulatory constraints directly as in Jacobsen (2013), I account for them in a reduced form way by having various time, segment, and brand fixed effects in cost components.

[5] I exclude diesel vehicles, and hybrid and electric vehicles which account for about 1 percent and 0.3 percent in 2006.

[6] For instance, in the 1991 model-year, 86 percent of Honda Civics sold had multiple valves.

III. Estimation and Empirical Results

Estimation: I estimate demand and supply jointly using General Methods of Moments with panel data. As for demand, I integrate consumers' indirect utility to product level and estimate a linear market share equation following Berry (1994). As for supply, I estimate parameters for marginal cost, fixed cost, and knowledge capital cost using automakers' first-order conditions and their ownership structure similar to Fan (2013) and Villas-Boas (2009). I estimate fuel efficiency frontier $g_h(x_h,\cdot)$ assuming a Cobb-Douglas functional form similar to Knittel (2012).[7]

Empirical results: Estimates of fuel efficiency frontier $g_h(x_h, a_h, i)$ suggest that technology adoption has been the main source of fuel efficiency improvements. From 1986 to 2006, adoption of fuel-saving technologies explains 92 percent of fuel efficiency improvements, holding performance characteristics constant. As a comparison, fuel-saving patents affect profits mostly by lowering production cost. An additional 10 patents would reduce marginal costs by $67 per car (2006 USD).

Demand estimates suggest mean elasticity with respect to a vehicle's own price at -3.5 and mean elasticity with respect to a vehicle's own fuel cost (dollars per mile) at -2.1. The latter implies that fuel consumption policies such as a gasoline tax increase have the potential to incentivize carmakers to improve fuel-saving technologies to increase demand.

IV. Policy Simulations

I simulate effects of raising gasoline taxes and subsidizing R&D in Table 1.[8] Column 1 shows the equilibrium choices with other outcomes at 2006 base level, and other columns show the deviation from the base level. Because my estimates are based on the period 1986—2006 during which the Corporate Average Fuel Economy standard has been flat, my simulations imply policy effects had the regulatory constraints unchanged.

[Insert Table 1 Here]

I find that gasoline taxes have substantial effects in inducing firms to adopt fuel-saving technologies. Column 2 of Table 1 considers raising gasoline prices via taxes by 1 dollar per gallon in the 2006 market. This would cause the 2006 fleet to be 0.47 miles/gallon more fuel efficient, mostly via increasing adoption of

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[7] I address the endogeneity of prices and product characteristics by constructing instrumental variables (IVs) from a set of plausible exogenous choices: longer-run characteristics (e.g., drivetrain choices) similar to Whitefoot et al (2013); grandfathered technologies (e.g. carburetor fuel delivery and 5 gear transmission); cross-category patents (e.g. hybrid and electric engine patents); and patents spillovers.

[8] The welfare exercises exclude tax revenue recycling options from gasoline taxes and fiscal costs from raising R&D subsidies. I also exclude environmental benefit from the policy change in Table 1.

fuel-saving technologies and also via carmakers' pricing strategies. The implied reduction in carbon emissions is comparable to taking 200 thousand new cars in the 2006 model-year off the road per year.

In Column 3, I simulate the effect of an R&D subsidy that would reduce the marginal cost of technology adoption $dc_h(x_h, a_h, i_f)/da_h$ by 30 dollars for each technology adopted in 2006. This only would cause fuel economy to increase by 0.05 miles per gallon. Without an increase in demand for fuel-efficient vehicles, some of the cost reduction benefits cause carmakers to improve their performance characteristics which lower the fuel efficiency.

Column 4 shows the effect of an R&D subsidy that would reduce the marginal cost of developing fuel-saving patents $dH_f(i_f)/di_f$ by by 25 percent in 2006. This subsidy would have raised fuel efficiency only by 0.06 miles/gallon in 2006 but would have increased variable profits by $1.2 billion over all firms that year by incentivizing patent development. The increase in knowledge capital drives down the cost to produce a car[9], and drives up producer surplus. Unfortunately the benefits are not passed to consumers in the form of lower vehicle prices in average.

Using this medium-run endogenous product choice model, I find that gasoline taxes are effective in encouraging technology adoption which leads to improvements in fuel efficiency. R&D subsidies for technology adoption have a small effect on fuel efficiency improvements. In contrast, R&D subsidies on fuel-saving patents have a small effect on technology adoption and fuel efficiency, but the induced increase in fuel-saving patents would drive down the cost of producing a vehicle.

V. Future Work

The present model considers several environmental policies on fuel consumption. This model can inform other policy options such as tax credits and feebate which may provide different incentives for technology adoption and R&D and affect welfare in different ways. My model also allows me to study effects of vehicle market competition, and to analyze policies' distributional effects across different vehicles. In addition, I plan to explore alternative ways to incorporate regulatory constraints faced by automakers.

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[9] The equilibrium cost reduction is not as much as the partial equilibrium cost reduction effect showed in section III. The increase in knowledge capital encourages marginally more technology adoption due to lower marginal cost.

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Table

Table 1— Effects of Environmental Policies

	Base	Gas tax increases by $1/gal.	An R&D subsidy to reduce marginal cost of technology adoption by $30	An R&D subsidy to reduce marginal cost of patent development by 10 percent
Panel A. Equilibrium choices [a]				
p: Prices (2006 USD)	35,435	-46	99	87
x: Performance characteristics (log)				
Weight	1.35	-0.001	0.001	0.001
Horsepower-to-weight	-2.81	0	0.001	0.001
a: Technology adoption rate (percent)				
5 Gear transmission	42.4	0	-0.1	-0.02
Variable valve timing	58.8	1.3	0.5	0.1
Multiple valves	77.6	0.2	0.4	0.1
Multiport fuel injection	100.0	0.1	0.1	0.1
i: Knowledge capital (number of patents per firm)	32.9	0.9	0	3.7
Panel B. Fuel economy				
2006 fleet average (miles/gallon) [a]	20.54	0.47	0.05	0.06
Panel C. Welfare (Billion 2006 USD)				
Consumer surplus	-	-0.6	0.4	0.4
Variable profits	141.2	4.1	1.1	1.2

Notes: Simulations are based on 2006 new car market. All simulation numbers show the changes in equilibrium choices, fuel economy, and welfare effects.

[a] Panel A shows equilibrium choices using the unweighted average. The column 2 – 4 shows changes in equilibrium choices

[b] Fuel economy miles per gallon is computed using inverse fuel consumption rate, i.e. 1/gallons per mile. The 2006 fleet average fuel economy is weighted by sales using the harmonic average.