Knowledge Capital, Technology Adoption and Environmental Policies:

Evidence from the US Automobile Industry

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Camp Resources XXII

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Motivation

Sufficient innovation and adoption of energy efficiency technologies are important

- Greenhouse gas emissions ↓
- Transportation sector: 27% of the total US GHG (EPA, 2011)
- Energy-efficient technologies ⇒ Emissions from vehicles

Automobiles have become increasingly energy-efficient, holding performance characteristics constant over 1986-2006 (Knittel 2012)

Despite the recent studies estimating the trend of technology progress, we know little about

- specific technology improvements ⇒ energy efficiency
- the impact of policies ⇒ technology improvements

Research Question and Approach

Research question: What is the impact of gas taxes (proxy for a potential carbon tax) and R&D subsidies in creating incentives for automakers to:

- Accumulate knowledge capital on energy-efficient technologies
- Adopt energy-efficient technologies

To answer, I estimate a structural model to explain automakers' choices of:

- How much to invest in the knowledge stock (stock of patents)
- Which EE technologies to adopt
- Vehicle performance characteristics
- Vehicle price

(the first three) $\Rightarrow$ Affect Fuel efficiency

Given vehicle demand as a function of:

- Fuel Economy
- Vehicle price
- Vehicle performance characteristics

Literature

Quantify the autonomous technological progress by estimating the "fuel efficiency frontier" (Knittel, 2012, Klier and Linn, 2014)

- *Here*: How have "adopting" specific technologies and "developing knowledge capital (patenting)" in engine technology improved fuel efficiency
- *Here*: Quantify incentives and costs of technology adoption and innovation

Test and investigate how environmental policies spur innovation (patenting activities) (Aghion et. al 2014, Popp, 2002)

- *Here*: Effects of induced innovation on fuel efficiency improvement

Impact of gas taxes on fuel economy (as opposed to local pollution).

- Consumer-oriented literature examining effects on miles driven as well as vehicle choice
- Supply responses to gas taxes (Bento et. al. 2009)
- *Here*: by changing products offered through the channel of endogenous technological change

Model

Nested Logit model of new cars demand

$$\ln s_h - \ln s_0 = \alpha_p \ln p_h + \alpha_g \ln \underbrace{(fp \cdot g_h)}_{\text{fuel price} \times \text{fuel efficiency(1/mpg)}} + \alpha_x x_h + \sigma_{seg} \ln s_{h|seg} + \xi_j$$

- s_h - market share of model h
- $g_h = \frac{1}{mpg}$ - fuel efficiency (fuel consumption rate: gallon/mile)
- x_h - performance characteristics. e.g. horsepower-to-weight, weight

Automakers' two-stage choice problem

$$\Pi_f(p_h, x_h, a_h, i) = \max_p \left\{ \max_{x,a,i} \left[\sum_h (p_h - \underbrace{c_h(\overset{+}{x_h}, \overset{+}{a_h}, \overset{-}{i})}_{\text{MC of Prod}}) \cdot s_h(\mathbf{p}, \underbrace{\mathbf{g}}_{g_h = g(\overset{+}{x_h}, \overset{-}{a_h}, \overset{-}{i})}, \mathbf{x}) \cdot M - \underbrace{H(\overset{+}{i})}_{\text{R\&D Cost}} \right] \right\}$$

- a_h - technology adoption (e.g. 5-speed gear)
- i - innovation (stock of patents) for firm f
- M - market size

Estimation

Parameters in marginal cost function $c_h(\cdot)$ are identified by equating MR=MC

- Estimate $\hat{c}_h = c_h(x_h, a_h, i)$, where $\hat{c}_h$ is solved from FOC-p:

$$s_j + \sum_h (p_h - \hat{c}_h) \times \frac{\partial s_h}{\partial p_j}(\alpha) = 0$$

Parameters in R&D cost function $h(i)$ are identified by equating

- MC(i) = Aggregated MR(i)
- Estimate $\hat{h}(i) = h(i)$, where $\hat{h}(i)$ is solved from FOC-i:

$$\hat{h}(i) = \left[\sum_h \left(\frac{\partial p_h}{\partial i} - \frac{\partial c_h}{\partial i} \right) s_h + \sum_h (p_h - c_h) \left(\sum_k \frac{\partial s_h}{\partial g_k} \frac{\partial g_k}{\partial i} + \sum_k \frac{\partial s_h}{\partial p_k} \frac{\partial p_k}{\partial i} \right) \right] M$$

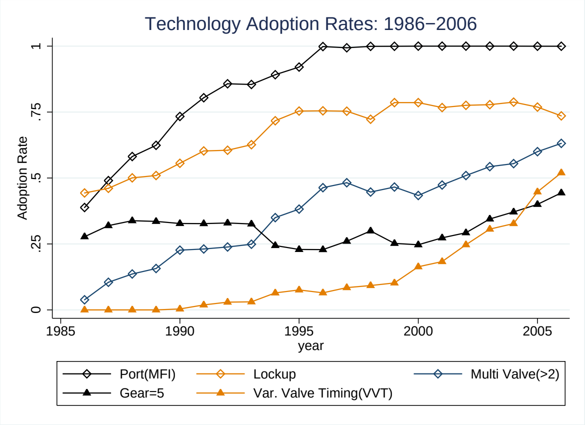
Estimate the model using Generalized Methods of Moments

Follow Fan (2013) and Villas-Boas (2007) to computes gradients $\partial p_k / \partial i$

Data: 1986-2006

- Vehicle characteristics, technology adoption, and sales data at model level
  - Source: EPA Fuel Economy Trend, EPA Fuel Economy Guide, Ward's Auto

- Specific fuel efficient technologies adopted $a \in [0, 1]$
  - e.g. install 5-speed gear box, multiple valves per cylinder, variable valve timing, etc.
  - Aggregate to model level. (e.g. $a_{h,vvt} = 28.6\%$ for Toyota Accord 2003)



Data: 1986-2006

- Stock of knowledge = Stock of patents related to *all* engine and powertrain technologies
  - e.g. "F02B: Internal-combustion piston engines; combustion engines in general"
  - e.g. File a patent on turbocharging, fuel injection apparatus, etc.
  - Varies at firm level
  - Source: OECD Triadic Patent Family Database

- Clarification: Technology adoption $\neq$ Adopting a patent

Model: Revisit

Nested Logit model of new cars demand

$$\ln s_h - \ln s_0 = \alpha_p \ln p_h + \alpha_g \ln \underbrace{(fp \cdot g_h)}_{\text{fuel price} \times \text{fuel efficiency(1/mpg)}} + \alpha_x x_h + \sigma_{seg} \ln s_{h|seg} + \xi_j$$

- s_h - market share
- g_h - fuel efficiency (fuel consumption rate: gallon/mile)

Automakers' Two-stage Choice Problem

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- a_h - technology adoption (e.g. 5-speed gear)
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Estimation Results: Demand

Demand Side Market Share: $\ln s_h - \ln s_0 = \alpha_p p_h + \alpha_g fp \cdot g_h + \alpha_x x_h + \sigma_{seg} \ln s_{h|seg} + \phi_{mt} + \xi_j$

Parameters		Estimates	Standard Errors
α_p: Price Semi-Elas	Veh. Price, \$10k	-0.553***	(0.114)
α_g: Fuel Economy	Dollar/Mile	-17.794***	(6.368)
α_x: Veh. Performance Char.	ln(Weight)	1.716***	(0.448)
	ln(Horsepower/Weight)	1.058***	(0.337)
σ_{seg}: Segment Similarity	ln(share|seg)	0.490***	(0.089)
	Make by Year FE	Yes	

Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

- Own-elasticity of fuel economy $fp \cdot g_h$: -2.05 $\Rightarrow$ Potential Gas Taxes (or Carbon Pricing)
- Own-product elasticity of demand -3.48 $\Rightarrow$ Potential Policies that affect MC

Estimation Results: Supply

Parameters		Estimates	SE	Parameters		Estimates	SE
A. Marginal Cost of Production ($10k)				***B. Fuel Efficiency Technology Frontier:***			
$\hat{c}_h(x_h, a_h, i) = \gamma_0 + \gamma_x x_h + \gamma_a a_h + \gamma_i ki + \nu_h$				$g_h(x_h, a_h, i) = \exp\{\theta_0 + \theta_x x_h + \theta_a a_h + \theta_i ki\} + \varepsilon_h$			
γ_x : Performance	ln(Weight)	3.509***	(0.451)	θx :	ln(Weight)	0.497***	(0.010)
	ln(Hp/Weight)	1.025*	(0.567)		ln(Hp/Weight)	0.241***	(0.008)
γ_a: Tech. Adopt.	5 Gear Trans.	1.454***	(0.212)	θ_a:	5 Gear Trans.	-0.072***	(0.005)
	Var. Valve Timing	0.629	(0.364)		Var. Valve Timing	-0.045***	(0.005)
	Multi. Valve	0.438***	(0.195)		Multi. Valve	-0.087***	(0.004)
	Port (MFI)	0.404***	(0.128)		Port (MFI)	-0.085***	(0.005)
γ_i: Knowledge	*ki*: Knowl. Stock	-0.070***	(0.020)	θ_i:	*ki*: Knowl. Stock	-0.009***	(0.001)
	Seg, Year FE	Yes			Seg, Make FE	Yes	
C. Marginal Cost of Knoweldge Capital (\$Brillion) $\hat{h}(i) = \lambda_1 + \lambda_2 i + u$							
λ_1:	Constant	0.467***	(0.060)				
λ_2: Knowledge	*i*: Knowl. Flow	0.395***	(0.052)				
λ_3:	Japanese Mfr.	-0.352***	(0.063)				
λ_4:	US Mfr.	1.386***	(0.080)				
	Time Trend	Yes					

Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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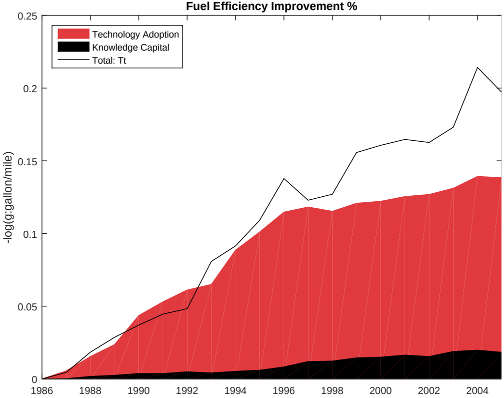
Estimation Results: Tech. Adopt. v.s. Knowledge Cap.

Adopting EE technologies has sizable effects in fuel efficiency improvement

- 12% of efficiency improvement over 1986-2006, holding performance x constant
- 10 times larger than that from knowledge accumulation
- Fuel economy frontier $g(x,a,i) = \exp\{\theta_0 + \theta_x x + \underbrace{\theta_a a} + \underbrace{\theta_i i}\} + \varepsilon$

  Conventional frontier $g(x,T_t) = \exp\{\theta_0 + \theta_x x + \underbrace{T_t}\} + \varepsilon$
- Plot $-\ln(g) \equiv \ln(\text{miles/gallon})$ against $\theta_a a$, $\theta_i i$ and T_t



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100 additional patents
-> $700 MC savings/vehicle ($392 Million)
-> 0.9% Fuel Efficiency Improvement (Raise Rev. $235 Million)
-> $660 Million R&D Cost

Preliminary Simulation Results

1. A \$0.5/gallon increase in gas tax on vehicle market in 1986

		Scenario I. Choose p	Scenario II. Choose p,a,i	
		Choices	Choices	EE Improvement (%) $-\ln(g) \equiv \ln(\text{mile/gallon})$
p: Price		\$60↑	\$181 ↑	
a: Tech. Adopt Rate	5 Gear Trans.		0.7% ↓	⇒ 0.38 ↑
	Var. Valve Timing		3.2% ↑	
	Multi. Valve		1.6% ↑	
	Port (MFI)		1.7% ↑	
i: Effort in Knowledge Capital			10 Patents ↑	⇒ 0.09 ↑

2. A potential R&D subsidy increase
3. Impact of reducing competition in EE technology improvement
   - Actual merger of Chrysler and Fiat in 2009
   - Rumored merger of Chrysler and GM in 2008

Conclusions

I examine automaker's incentives of innovation and technology adoption

- Main incentive of innovation⇒ production cost reduction
- Main incentive of technology adoption ⇒ raise sales by offering fuel-efficient vehicles

Potential policies

- Gasoline tax on fuel efficiency: sizable improvement through the channel of technology improvement
- Elastic demand w.r.t. price ⇒ Potential policies affect the cost component (R&D subsidies)

Thank you!

Discussions

Channels that are not included in the current framework

- CAFE Standard: allow adjusting p_h to meet CAFE standard
  - 2nd order concern: (almost) no change over 1986-2006
  - Relax the model by allow parameters in c_h to vary by groups such as a CAFE constrained group (3 US), a CAFE unconstrained group (JP and KR), and a fine-paying group
  - Or solve a constrained profit maximization problem by using shadow costs of complying to CAFE estimated in Jacobsen (2012) using data 1997-2001

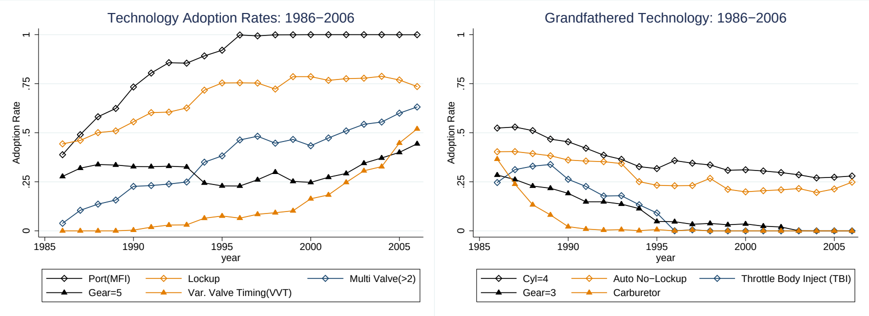
- Future cost savings from current innovations
  - I only allow concurrent cost savings from innovation
  - Benefit from innovation induced by a R&D subsidy or a gas tax would be a conservative estimate

Instruments for $\{p_h, x_h, a_h, i\}$

1. Grandfathered technologies
   - Distance of adoption rates of grandfathered technology from competing models
     $distout(a)_h^{dated} = a_h^{dated} - \sum_{j \notin firm, j \in seg} a_j^{dated}$
   - Distance of adoption rate of grandfathered technology from the same brand
     $distin(a)_h^{dated} = a_h^{dated} - \sum_{j \neq h, j \in firm} a_j^{dated}$
2. Longer-run vehicle characteristics (e.g. drivetrain spec. 4WD/AWD), suggest by Fowlie, et.al. (2013)
   - Distance of LR technology from competing models
     $distout(x)_h^{lr} = x_h^{lr} - \sum_{j \notin firm, j \in seg} x_j^{lr}$
   - Distance of LR technology from the same brand
     $distin(x)_h^{lr} = x_h^{lr} - \sum_{j \neq h, j \in firm} x_j^{lr}$
3. Cumulative innovation from cross-category and innovation spillovers
   - Spillover for regular internal combustion engine
   - Own knowledge for Alternative Fuel Vehicle (AFV) engine
   - Spill over for AFV engine

Instruments and Assumptions

Grandfathered technologies



Assumptions for the demand system

$$\ln s_h - \ln s_0 = \alpha_p \ln p_h + \alpha_g \ln \underbrace{(fp \cdot g_h)} + \alpha_x x_h + \sigma_{seg} \ln s_{h|seg} + \xi_j$$

- All efficiency-related qualities ✓ : picked up by $fp \cdot g_h$
- All performance-related qualities ✓: picked up by x_h
  - ξ_j only includes non-efficiency non-performance related qualities
  - e.g. tastes associated with leather seat and sound system