The Costs of Variety

About Productivity of Differentiated Capital Inputs

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Context

- **Productivity**: how much one can produce using a fixed set of inputs.
  - ↪ typically: firms with the same inputs produce different output

$$Y = F(K, L) \cdot \exp\{\omega\}$$

  - ↪ huge dispersion in ω: $q_{90}/q_{10} \approx 3.5$ (Dhrymes, 1991; Fox and Smeets, 2011)

- Input **heterogeneity**: does $K = K$ necessarily?
  - ↪ possibly diverse contributions to production: experienced labor, distinct machines, ...
  - ↪ literature: more on labor heterogeneity, measuring capital heterogeneity difficult

- A possibly important source of **capital** heterogeneity: horizontal differentiation.

Horizontal Capital Input Differentiation

- Goods of **same purpose** but **different make** often used as production inputs.
  - ↪ fleets of vehicles, manufacturing machinery, software
- **Economies of unification**: gains from standarization & specialization.
  - ↪ a unit of a differentiated input may perform better with more units of the same *kind*
  - ↪ a unit of a non-differentiated input may perform better with less variety
- Differentiated capital inputs **prevalent** across industries – implications:
  - ↪ methodology: neglecting heterogeneity underestimates role of K, overestimates ω
  - ↪ policy: variety as a friction: resource misallocation, inefficiency
- **Today**: (causal) impacts of **variety** in differentiated capital on inputs' productivity.

Application: Fleets of Municipal Buses

- **Urban transport industry** excellent to study capital input heterogeneity.
  - ↪ buses are differentiated products
  - ↪ buses are the capital: can abstract from other forms of heterogeneity
- **Unique dataset** on Polish municipal bus operators & their fleets.
  - ↪ lots of variation in fleet composition: fleet renewal via public procurement
  - ↪ bus-level and firm-level measures of performance

Research Questions & Answers

- What is **capital input differentiation**?
  - ↪ unification along manufacturers' identity matters: bus & engine producer, generation
  - ↪ unification along objective features doesn't matter: size, drive, engine displacement
- What is its **importance**?
  - ↪ same bus is more utilized (3-10%) in a fleet with more buses of the same kind
  - ↪ work in progress: more unified fleets require less mechanics, drivers
- **Reduced form** approach – no stand on the source of variety in fleets.
  - ↪ benefits of variety: insurance against recalls, seller's market power, ...
  - ↪ effects of variety on inputs' performance consistently negative

Contributions

- **capital input heterogeneity**.
  - ↪ quality (Griliches, 1957; Griliches and Mairesse, 1995; Bartelsman and Doms, 2000; Fox and Smeets, 2011). new: extend this approach because (1) we control for unobserved bus quality (2) even if all buses were of the same quality, the differentiation would still induce the friction
  - ↪ quality & variety proxied by monetary value (Fox and Smeets, 2011; De Roux, Eslava, Franco, and Verhoogen, 2021). new: extend this approach because even if every bus was worth the same, the differentiation would still induce the friction
  - ↪ vintage (Whelan, 2002). new: extend this approach because (1) we control for bus vintage (2) even if all buses were of the same age, the differentiation would still induce the friction
- **measurement error in capital** – literature typically agnostic about its sources (Collard-Wexler and De Loecker, 2016; Kim, Petrin, and Song, 2016).
  - ↪ new: a detailed causal characterization of a prevalent source of measurement error
- **fleet commonality** in transport literature (De Borges Pan and Espirito Santo Jr, 2004; Brüggen and Klose, 2010; Zou, Yu, and Dresner, 2015; Merkert, 2023; Agrawal, 2024).
  - ↪ new: first to provide causal evidence, both firm- and vehicle-level performance

Theoretical Background

Production with Input Differentiation

- A production function with differentiated (κ) and non-differentiated (ℓ) inputs.

$$y = F(\kappa, \ell)$$

  $\hookrightarrow$ standard assumptions: concave in both arguments.

- κ is an aggregator of J low-level differentiated inputs with gains from unification.

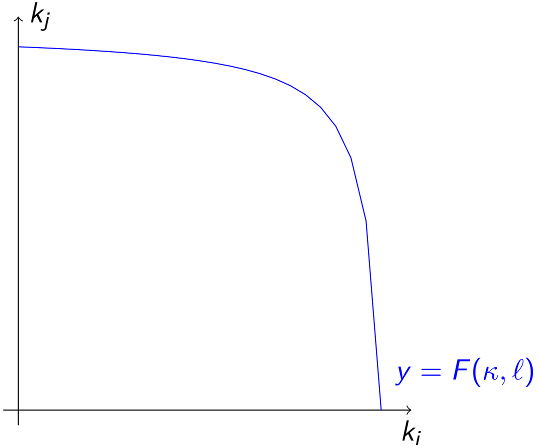
$$\kappa \equiv \kappa(k_1, .., k_J)$$

  $\hookrightarrow$ $\frac{\partial \kappa}{\partial k_i}(k_1, .., k_J) > 0$
  $\hookrightarrow$ $\frac{\partial^2 \kappa}{\partial k_i^2}(k_1, .., k_J) > 0$
  $\hookrightarrow$ $\frac{\partial^2 \kappa}{\partial k_i \partial k_j}(k_1, .., k_J) \leq 0$

- Suppose the firm is cost minimizer.

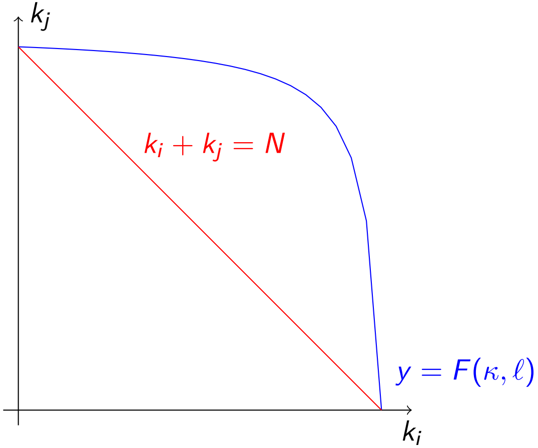
Optimal Choice of Differentiated Inputs is Unification

- Our assumptions imply that the **isoquant** in (k_i, k_j) space is **concave**.



Optimal Choice of Differentiated Inputs is Unification

- **Unify** the differentated input to produce y with the lowest number of inputs N.
  - ↪ higher productivity of a unit of input

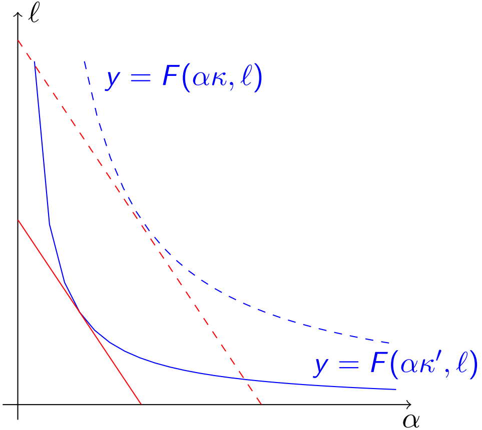


Production with Input Differentiation and Choice Rigidities

- Two firms minimize costs given the same target production level $\bar{y}$.
  - ↪ same quantity of capital inputs: $N = \sum_{i=1}^{J} k_i$
  - ↪ different efficiency: $\kappa' \equiv \kappa(k') > \kappa(k) \equiv \kappa$
- **Rigidities** in adjusting the differentiated input.
  - ↪ can only multiply each k_i by a factor $\alpha > 0$, cannot adjust the structure
  - ↪ consistent with our application: small purchases of buses do not alter fleet structure
- The firms' choice: choose a cost-minimizing combination of α and ℓ.

Inefficient Differentiated Input Decreases Efficiency of Other Inputs

- Less efficient firm needs **more units of both inputs** to attain production level y.



- In the remainder of the paper, we provide extensive evidence on these patterns.
  - ↪ **today**: isoquants in the space of differentiated inputs
  - ↪ **work in progress**: isoquants in the space of aggregate inputs

Data & Market Environment

Data Sources

- **Fleet Data** – a list of buses owned by the operators (2005-2023).
  - ↪ year of purchase and scrapping/resale, previous owners
  - ↪ sources: scraping `phototrans.eu`, online bus gallery
- **Odometer Data** – averaged yearly mileage of a bus (2014-2023).
  - ↪ requirement to collect mileage data on periodic maintenance since 2014
  - ↪ sources: scraped from official registry
  - ↪ coverage below 100% but satisfactory
- **IGKM Data** – firm performance indicators (2008-2022).
  - ↪ IGKM: a co-operative of transit companies to share data and experiences
  - ↪ direct measures of costs and performance
  - ↪ yearly survey, some attrition and measurement error

Market Environment

- 164 **public bus operators** in Poland owned by city authorities.
  - ↪ serve routes on city's request: incentives consistent with cost minimization
  - ↪ 90% market share in municipal bus services
  - ↪ own, maintain & repair utilized buses
- Cities' demand for routes constant in time: bus purchases towards **fleet renewal**.
  - ↪ new buses arrive in depot on average once per $2^1/_2$ years
- Perfect **fleet unification impossible**.
  - ↪ limited discretion in procurement: auctions with favoritism (Premik, 2024)
  - ↪ bus producers' specialization, market entry & exit, evolution of technology

What is Variety?

- Aspects related to **producers' identity** – own technological solutions.
  - ↪ bus producer, generation, engine brand, engine family
- Aspects related to objective features – related to **bus purpose**.
  - ↪ drive, engine displacement, size, floor

Buses of the same Brand

Buses of the same Generation

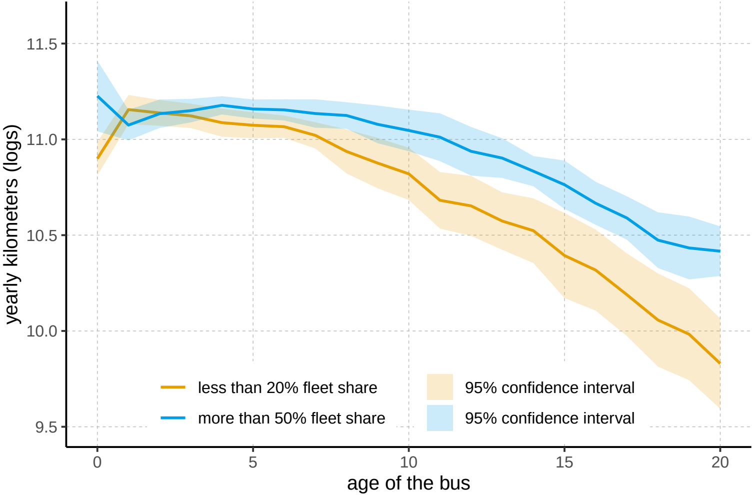
Buses of the same Generation and Size

Fleet Unification Patterns, 2014-2023

	market				fleet			
	#	share (highest)	share (2nd highest)	hhi	#	share (highest)	share (2nd highest)	hhi
brand	28.6	.43	.17	.25	3.4	.65	.21	.55
generation	71.6	.3	.12	.13	5.4	.52	.2	.41
engine brand	20.4	.3	.24	.2	3.6	.62	.22	.52
engine family	62.1	.21	.14	.09	5.4	.52	.2	.41
drive	5.9	.89	.05	.8	1.6	.93	.07	.9
displacement	5	.33	.31	.29	2.8	.67	.23	.58
size	5	.54	.3	.39	2.6	.74	.19	.65
floor	3	.86	.08	.76	2.1	.84	.12	.78
all types	267.7	.1	.09	.03	8.8	.42	.17	.32

Note: The table presents the summary statistics regarding bus differentiation averaged over operators and years.

Bus Utilization in Life-Cycle by Generations' Fleet Share



The Costs of Variety

- **Raw data** trend suggest underutilization of buses of less represented types.
- Now we move to show that this relation is **causal**.

Identification

Conceptual Framework

- We are interested in the following equation:

$$y_{ijt} = \gamma d_{ijt} + x'_{ijt}\beta + \mu_{ijt} + \varepsilon_{ijt} \tag{1}$$

  - ↪ y_{ijt} – performance of bus i in fleet j at year t
  - ↪ d_{ijt} – measure of how similar i is to the rest of the fleet
  - ↪ x_{ijt} – observed systematic drivers of performance
  - ↪ μ_{ijt} – unobserved systematic drivers of performance
  - ↪ ε_{ijt} – idiosyncratic componenent

- **Measurement**.
  - ↪ y_{ijt} – log yearly mileage
  - ↪ d_{ijt} – fraction of buses *similar* to i

Conceptual Framework

- We are interested in the following equation:

$$y_{ijt} = \gamma d_{ijt} + x'_{ijt}\beta + \mu_{ijt} + \varepsilon_{ijt} \tag{2}$$

- **Tasks**.
  - ↪ estimate d_{ijt} – which aspects of variety matter?
  - ↪ estimate γ – how strong the effects are?

- **Endogeneity**: it is likely that $\mathbb{E}[d_{ijt}\mu_{ijt}] \neq 0$.
  - ↪ if bus i is *good* for j $\rightarrow$ drives more miles
  - ↪ if bus i is *good* for j $\rightarrow$ more of the same kind is purchased

Identification

- **General idea**: $\nearrow$ in a number of buses of specific type $\rightarrow$ $\nearrow$ utilization of incumbent buses of this type reflecting the economies of unification.
- **Identify** γ by comparing Δy_{ijt} between buses of this type and others in the fleet.
  $\hookrightarrow$ need to be careful on what we are comparing

Identification

- Define **class** as a known subset of a fleet.
  - ↪ notation: write $class(i)$ if bus i belongs there
- Partition class into mutually exclusive **subclasses**.
  - ↪ notation: for buses i and i':

$$subclass(i), subclass(i') \subset class(\cdot), \quad \begin{cases} subclass(i) \cap subclass(i') = \emptyset & \text{or} \\ subclass(i) = subclass(i') \end{cases}$$

- **Identifying assumption**: μ's vary only on the class-level.

$$\mu_{ijt} = \mu_{class(i)jt}$$

  - ↪ strategy: compare Δy_{ijt} between subclasses of the same class s.t. $\Delta\mu_{ijt}$ cancels out

Stacked DiD Approach

- Define **event**: new vehicles of $class(i)$ and $subclass(i)$ introduced to the fleet.
  - ↪ vehicles in $subclass(i') \subset class(i)$ not introduced at the event: a valid control group
- For each event: a **random sample** of pre- and post- introduction y_{ijt}, d_{ijt}, and x_{ijt}.
  - ↪ all already existing buses in $class(i)$
  - ↪ $d_{hjt} = d_{subclass(h)jt}$ for each $h \in class(i)$
- **Stack** event samples in the spirit of Cengiz, Dube, Lindner, and Zipperer (2019).
  - ↪ time centered around the introduction period: $s \in ..., -1, 0, 1, ...$

Estimating Equation

$$y_{ijs} = \begin{cases} \quad \beta_0 + \beta_1 \mathbf{1}[s > 0] + \beta_2 \mathbf{1}[i \text{ treated}] & \text{nuisance parameters} \\ + \quad \gamma \mathbf{1}[s > 0 \,\&\, i \text{ treated}] & \text{effect of interest} \\ + \quad \lambda_{ijs}^{\text{age}} & \text{vintage trends} \\ + \quad \lambda_{js}^{\text{event}} & \text{event-time fixed effect:}\mu \\ + \quad \lambda_{i}^{\text{bus}} & \text{unobserved bus quality} \\ + \quad \varepsilon_{ijs} & \text{idiosyncratic term} \end{cases}$$

Results

Empirical Strategy

- Which aspects of bus differentiation have a causal impact on bus utilization?
  - ↪ various combinations of class and subclass definition
- Characterize effects of unification on performance by varying specification of d_{ijt}.
  - ↪ causal effects: dummy indicating introductions
  - ↪ dynamic causal effects: dummies indicating periods pre- and post- introductions
  - ↪ continuous causal effects: number of buses introduced as a fraction of fleet
- Additional controls.
  - ↪ life cycle shocks: vintage (age) dummies
  - ↪ unobserved quality: bus fixed effects
  - ↪ μs & initial fleet shares: event dummies interacted with time

Results

Causal Effects

Causal Effects: Any Introduction Within a Subclass

	class: brand						
	brand	generation	engine brand	engine family	drive	displacement	size
coef.	—	.053 (.016)***	.052 (.027)*	.027 (.014)*	.095 (.037)**	−.004 (.022)	−.012 (.016)
N		38225	34853	37445	21248	30998	41334
N events		220	140	234	72	197	253
N buses		5168	3503	4965	2858	4224	4913
N brands		7	3	5	5	7	6
N operators		76	52	76	30	73	75
r2		.829	.786	.813	.803	.810	.818

The table presents estimation results of specifications in which the treatment variable is defined as a binary indicator of introduction of buses of a given class. Standard errors clustered at the bus operator level are given in the parentheses. P.vals: $^{***} < .01$, $^{**} < .05$, $^{*} < .1$.

Causal Effects: Any Introduction Within a Subclass

	class: engine brand						
	brand	generation	engine brand	engine family	drive	displacement	size
coef.	.095 (.036)***	.102 (.022)***	—	.032 (.021)	.016 (.057)	.038 (.038)	.006 (.035)
N	5546	18374		21565	4128	19560	20399
N events	67	176		185	31	157	184
N buses	1099	3304		3831	885	3230	3504
N brands	14	11		13	9	13	13
N operators	41	74		66	17	63	70
r2	.793	.838		.832	.830	.822	.832

The table presents estimation results of specifications in which the treatment variable is defined as a binary indicator of introduction of buses of a given class. Standard errors clustered at the bus operator level are given in the parentheses. P.vals:*** $<.01$,** $<.05$,* $<.1$.

Causal Effects: Any Introduction Within a Subclass

	class: drive						
	brand	generation	engine brand	engine family	drive	displacement	size
coef.	.07 (.016)***	.085 (.016)***	.056 (.018)***	.06 (.016)***	—	.027 (.027)	.023 (.018)
N	60259	56246	68065	59193		66113	54350
N events	356	294	387	322		389	350
N buses	7453	7111	7814	7177		7716	7605
N brands	21	20	20	19		19	20
N operators	100	94	105	98		105	104
r2	.826	.821	.821	.817		.824	.833

The table presents estimation results of specifications in which the treatment variable is defined as a binary indicator of introduction of buses of a given class. Standard errors clustered at the bus operator level are given in the parentheses. P.vals: $^{***} < .01$, $^{**} < .05$, $^{*} < .1$.

Causal Effects: Any Introduction Within a Subclass

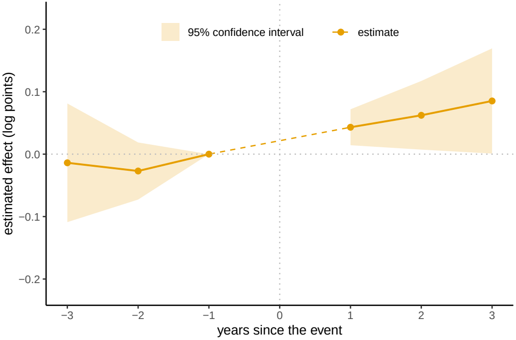
	class: size						
	brand	generation	engine brand	engine family	drive	displacement	size
coef.	.042 (.02)**	.066 (.019)***	.06 (.014)***	.044 (.02)**	.021 (.048)	.002 (.018)	—
N	59504	48939	60173	36872	30634	49465	
N events	344	270	321	249	112	308	
N buses	6800	6054	6840	5482	4045	6121	
N brands	19	18	18	15	16	15	
N operators	88	82	92	82	39	86	
r2	.822	.833	.816	.818	.795	.822	

The table presents estimation results of specifications in which the treatment variable is defined as a binary indicator of introduction of buses of a given class. Standard errors clustered at the bus operator level are given in the parentheses. P.vals: $^{***} < .01, ^{**} < .05, ^{*} < .1$.

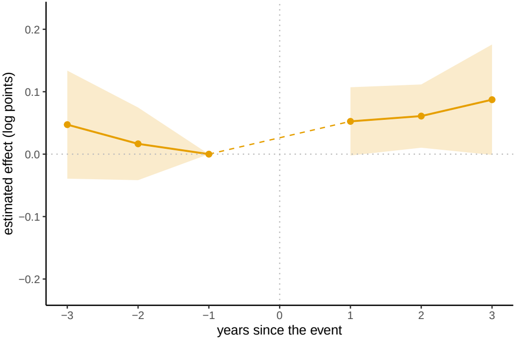
Results

Dynamic Causal Effects

Dynamic Causal Effects. Any Introdution Within a Subclass

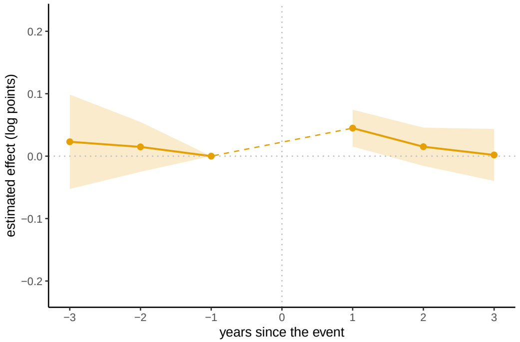


(a) class: brand. subclass: generation.

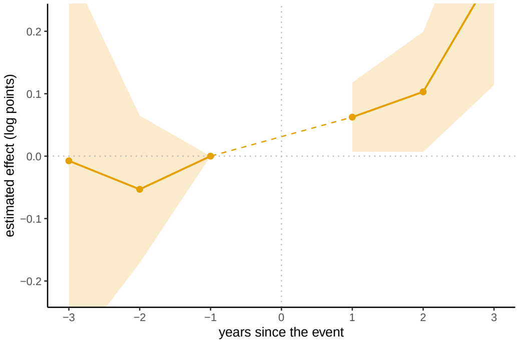


(b) class: brand. subclass: engine brand.

Dynamic Causal Effects: Any Introdution Within a Subclass

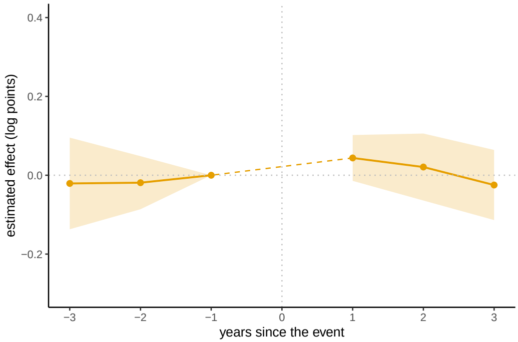


(a) class: brand. subclass: engine family.

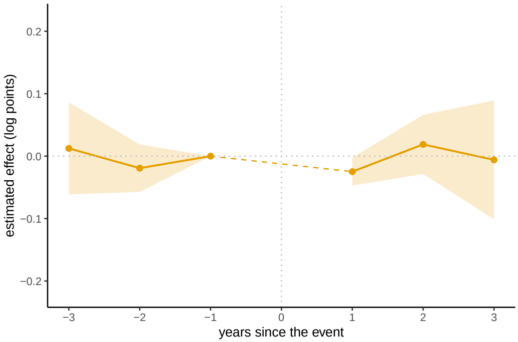


(b) class: brand. subclass: drive.

Dynamic Causal Effects: Any Introdution Within a Subclass



(a) class: brand. subclass: displacement.

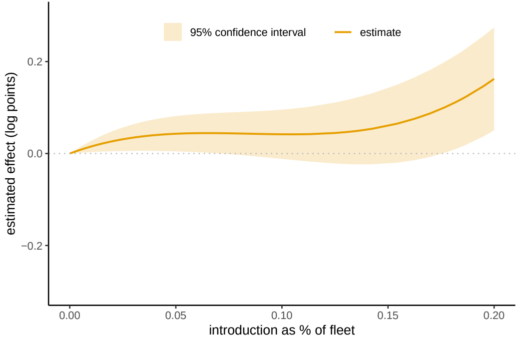


(b) class: brand. subclass: size.

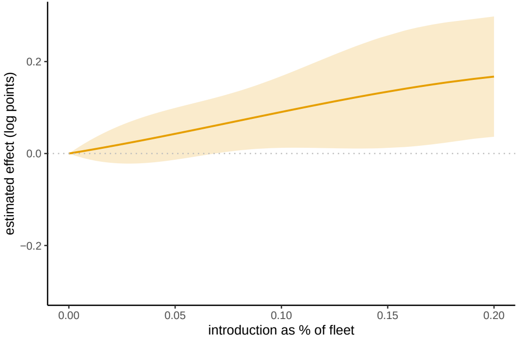
Results

Continuous Causal Effects

Continuous Causal Effects: Introdution Within a Subclass as % of Fleet

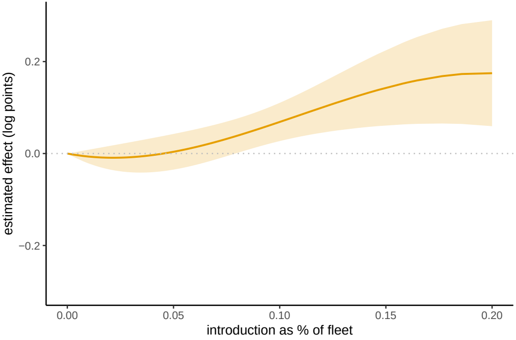


(a) class: brand. subclass: generation.

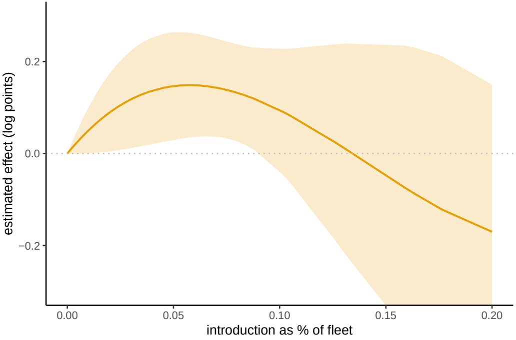


(b) class: brand. subclass: engine brand.

Continuous Causal Effects: Introdution Within a Subclass as % of Fleet

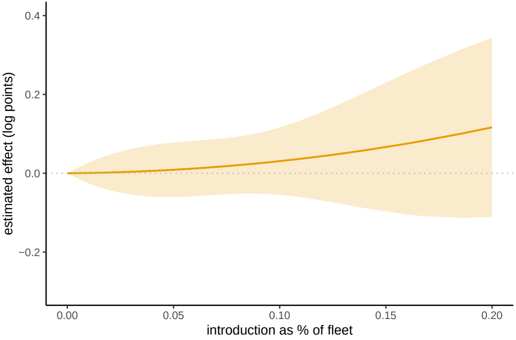


(a) class: brand. subclass: engine family.

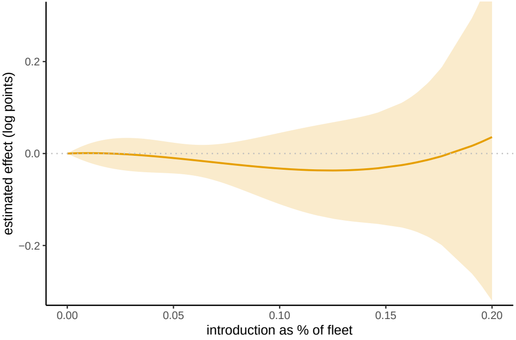


(b) class: brand. subclass: drive.

Continuous Causal Effects: Introdution Within a Subclass as % of Fleet



(a) class: brand. subclass: displacement.



(b) class: brand. subclass: size.

Conclusion

Our Results

- Input differentiation is an important source of capital heterogeneity.
  - ↪ in more unified fleets, buses perform better
  - ↪ in more unified fleets, other inputs perform better (work in progress)
- Differentiation relates mainly to technological differences among the producers.
- Important to account for this source of heterogeneity in structural frameworks.
  - ↪ **next step**: estimation of production functions with input differentiation

Thank you for your attention!

More on this project can be found at www.filippremik.com.

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