

Global Policy Spillovers: How Environmental Policies Propagate through Product Attributes*

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Abstract

In a globalized economy, a country's domestic policies can generate global spillovers when it affects the products designed and manufactured by multinational firms. Standard economic analyses typically abstract from this channel, potentially leading to an understatement of policy impacts. We study this phenomenon in the context of environmental regulation in the automobile market. We provide empirical evidence that a fuel economy subsidy in Japan led to significant improvements in the fuel economy of vehicles sold in the U.S., thereby generating additional environmental benefits. We then develop a model of multinational automobile markets that features cross-market cost complementarity to model global spillovers. Using the model estimated for Japan and the U.S., we conduct counterfactual policy simulations to quantify the environmental benefits and welfare effects of policy in one country that causes global spillovers. Accounting for these spillovers is substantive in our case: a majority of greenhouse gas emissions reductions from the Japanese policy occurred in the United States.

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1 Introduction

How should we evaluate policies in one jurisdiction that affect products sold in many places? Standard economic analysis typically focuses on domestic outcomes when evaluating policy, but in a world where multinational firms design global products, policies in one country can propagate to markets worldwide by inducing changes in a product's attributes. This channel, which we call *attribute propagation*, represents a potentially significant but understudied mechanism through which domestic policies generate international effects. Accounting for attribute propagation has the potential to fundamentally alter the evaluation of environmental policies, safety regulations, antitrust remedies, and other policies because conventional economic analyses may substantially underestimate the full impacts of policies when attribute propagation is ignored.

In this paper, we study attribute propagation in the context of automobile environmental policy, highlighting a linkage between the Japanese and U.S. auto markets. Our goal is to develop empirical methods to measure and quantify attribute propagation and assess its significance for evaluating policy. Our estimates suggest that global spillovers, in the form of attribute propagation, are first order in our context: quite substantial in this context: a majority of the greenhouse gas emissions changes induced by an environmental subsidy in Japan occurred in the United States.

The automobile sector and environmental policy provide a natural setting in which to study such spillovers, but attribute propagation can arise in many other contexts, triggered by factors including safety regulations, antitrust rules, or just differences in consumer preferences. For example, the European Union's 2022 directive requiring USB-C charging ports led Apple to adopt USB-C globally for subsequent iPhone models, rather than maintaining separate Lightning and USB-C versions. Similarly, pharmaceutical firms frequently comply with the stringent guidelines of the International Council for Harmonisation worldwide in order to access major markets, even when selling in countries with less demanding regulatory requirements. In aviation, manufacturers such as Boeing and Airbus design aircraft to meet both Federal Aviation Administration and European Aviation Safety Agency standards simultaneously, and then market these designs globally. Likewise, the European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals directive has become a de facto global standard, with firms adopting E.U. chemical regulations across their entire product lines to ensure access to the European market.

Each of these examples illustrates how policies in one jurisdiction can propagate through firms' global product-design decisions, generating spillovers that extend well beyond the regulating authority's borders.

Our findings suggest that evaluating only domestic effects in such settings is likely to miss a substantial share of the total policy impact.

Our analysis begins with a difference-in-differences (DID) design that exploits variation generated by a Japanese fuel-economy subsidy introduced in 2009. The policy created strong incentives for firms to improve the fuel economy of models sold in Japan. We leverage the fact that while many models sold in Japan are also marketed abroad (e.g., in both Japan and the United States), multinational Japanese automakers also produce vehicles for foreign markets that are not sold in Japan. This feature allows us to construct treatment and control groups within the U.S. automobile market, where the former may be affected by the Japanese subsidy through attribute propagation. We show that the treatment and control groups have similar observable characteristics and exhibit parallel pre-trends in fuel economy prior to the policy's introduction.

The DID analysis provides statistical evidence that the Japanese fuel-economy subsidy propagated to the U.S. market. Specifically, the subsidy led to an 8.65% improvement in the fuel economy of related vehicles sold in the United States. We estimate that the direct effect of the policy in the Japanese market was a 25.2% improvement in fuel economy. Taken together, these results imply a substantial but incomplete “pass-through” of fuel-economy gains from Japan to the U.S. market.

Importantly, these estimates do not imply that the policy's environmental impact in the United States is 0.34 ($= 8.65 / 25.2$) of its impact in Japan, because environmental externalities depend not only on fuel-economy improvements but also on sales volumes and vehicle miles traveled, which is much higher in the U.S. To evaluate the policy's environmental impact in each country, we quantify the *spillover multiplier of environmental impacts* as the ratio of the Japanese policy's effect on CO₂ reductions in Japan and the United States to its domestic effect. We find that this spillover multiplier equals 6.72, implying that the Japanese policy's environmental impact abroad substantially exceeds its domestic impact. That is, the total CO₂ reduction is 6.7 times larger than the Japanese domestic CO₂ reduction.

The DID design does not capture potential indirect equilibrium effects: vehicles in the US that are not affected directly by the policy may adjust their fuel economy in response to changes in the fuel economy of competing vehicles. To account for these equilibrium effects, the second part of our paper develops a structural model of multinational vehicle markets with global spillovers. The model features two markets served by a mix of multinational products and products sold in a single location, in which firms choose vehicle fuel economy and prices under Nash–Bertrand competition.

Our model links the two markets through firms' cost functions. In particular, the cost function includes

a fixed cost of improving fuel economy. We allow for cross-market complementarity in these fixed costs through an interaction term: i.e., an improvement in fuel economy in Japan for a particular model lowers the redesign cost of improving fuel economy in the U.S. for the same model.

We then estimate the model following the tradition of [Berry, Levinsohn and Pakes \(1995\)](#) and the approach of [Fan \(2013\)](#) and [Barwick, Kwon and Li \(2024a\)](#) for identifying the slope of the fixed cost of adjusting product attributes. We estimate the automobile demand system separately for Japan and the United States to allow for differences in consumer preferences across the two markets. We then recover marginal costs and marginal fixed costs using the first-order conditions implied by automakers' profit maximization. We find statistical evidence of economies of scope in fuel economy across markets for a given vehicle model.

Finally, we use the model and estimated parameters to conduct a counterfactual simulation in which we remove the fuel-economy subsidy policy and compute a new equilibrium. Our simulation results align with the headline finding on attribute propagation: many of the environmental benefits of the policy arise in the U.S. market. In the US, our simulation predicts that vehicles not directly affected by the subsidy would reduce fuel economy in response to competitors' adjustments, generating negative indirect equilibrium effects on CO₂ emissions. With this indirect equilibrium effect, the spillover multiplier becomes 2.78. Even after taking into account equilibrium effects, the Japanese policy's environmental impact abroad substantially exceeds its domestic impact.

Our findings indicate that incorporating indirect equilibrium effects underscores the importance of global spillovers. Although the Japanese subsidy reduces CO₂ emissions in both Japan and the United States, the resulting emissions reductions in the United States can be substantially larger than the domestic reductions in Japan. Consequently, abstracting from global spillover effects could lead to a substantial understatement of the policy's environmental impacts.

Related literature and our contributions—Our study contributes to literatures on cross-jurisdictional policy effects by providing the first rigorous empirical evidence, with causal identification, of how environmental policies in one jurisdiction propagate to others through multinational firms' product design decisions.

A rich literature has identified several mechanisms through which policy in one location can generate effects beyond its borders. First, policy can cause shifts in the location of production. In environmental economics, this relates to the pollution haven hypothesis, which posits that tightening environmental regulation in one location can shift dirty activities to other markets ([Levinson and Taylor, 2008](#); [Copeland, 2008](#)). A related literature considers how policy can induce trade in products ([Davis and Kahn, 2010](#)) and end of life

treatment (Tanaka, Teshima and Verhoogen, 2022), rather than production per se.

Second, if local policy accelerates learning by doing or enables scale economies, this can affect additional markets through prices. This mechanism has been documented in electric vehicle batteries (Barwick, Kwon, Li and Zahur, 2024b; Head, Mayer, Melitz and Yang, 2025), semiconductors (Goldberg, Juhász, Lane, Lo Forte and Thurk, 2024) and clean energy technologies (Gerarden, 2023).

Third, policies can propagate across jurisdictions through regulatory convergence: policy in one location can trigger follow on policy in other locations. This is often referred to as the “California effect” after (Vogel, 1995), which provides several examples of how California’s environmental policies led other jurisdictions to adopt tighter standards.

Fourth, and most relevant to our study, policies in jurisdictions with large markets can set de facto product standards that extend beyond their borders. An influential literature in political science and law—including work on both the “California effect” Vogel (1995) and “Brussels effect” (Bradford, 2020)—has theorized that firms may find it cost effective to design products to meet the strictest standards they face and then sell these products globally, rather than maintain separate production lines for different markets.

This literature has identified prominent examples using case studies and qualitative analysis, including automobiles that were designed to meet California’s stricter tailpipe emissions standards and sold in other states (Vogel, 1995). In spite of prior discussion, our use of quasi-experimental and structural methods to quantify these spillovers is new to the environmental literature. We are the first paper that we know of to conceptualize and calculate a spillover multiplier of environmental effects.

The paper closest to ours is Sabal (2024), and the related work in Castro-Vincenzi, Menagual, Morales and Sabal (2024), which addresses related issues, though with a different methodology and a different set of questions. Sabal (2024) develops a model of the global car industry where policy in one location can influence other markets through a form of attribute propagation, but this occurs entirely through product entry. In order to achieve computational tractability, Sabal (2024) uses a highly aggregated unit of observation for a vehicle and holds attributes fixed within each vehicle type. In our context, we see no evidence of differential product entry in response to the Japanese policy, but instead quantify attribute propagation through modifications to existing models when looking at more granular definitions of a vehicle. Moreover, Sabal (2024) does not consider environmental outcomes or quantify environmental spillovers. As such, we view the two papers as complementary—we answer different questions using different modeling assumptions. Outside of environment, the closest paper we know of is Peukert, Bechtold, Batikas and Kretschmer (2022), which uses

difference-in-differences methods to show that non-E.U. websites substantially reduced third-party tracking after introduction of the European General Data Protection Regulation.

Our paper establishes the importance of attribute propagation in one particular setting, and it provides a methodology that others could follow. Our methodology could be used to study not just policy shocks, but also how preference shocks, or simply preference differences, in one location spillover into other locations through embodied attributes. In terms of policy analysis, ignoring attribute propagation would substantially underestimate the environmental benefits of the Japanese policy. We do not know if the Japanese government thought about these spillover effects when designing the policy, but we do believe this motive sometimes animate policy. The State of California, for example, often pursues an environmental leadership role where it hopes to accelerate the deployment of a low carbon product, like electric vehicles or clean trucks, that would be sold outside the state.

2 Background and Data

2.1 Japanese government's subsidy for fuel-efficient cars

Starting in 2009, the Japanese government provided a subsidy for consumers purchasing a new car with fuel economy in excess of the fuel economy target. There are three unique features of this policy that will help our empirical analysis. First, the subsidy ranged approximately between \$700 and \$1,500, which was a significant amount for consumers (about 5 to 10% of an average new car price).

Second, this subsidy was based on each vehicle's own fuel economy, rather than a corporate average fuel economy. A model was qualified for the subsidy if the model's fuel economy was above the fuel economy target given the model's weight. This allows us to exploit variation at the model level rather than at the corporate level.

Third, because the fuel economy target was designed as a step function of weight, the policy created variation across models in the difficulty of meeting the fuel economy target. For example, if a model's combination of fuel economy and weight before the policy was enacted (i.e., the pre-policy period) was already close to the target, the model would be able to qualify for the subsidy with small changes in its product attributes. In contrast, if a model was located far from the target function, it would need relatively larger changes in its product attributes in order to qualify for the consumer subsidy.

Fourth, many models sold in the US market were also possibly affected by Japan's policy because they

were sold in both countries, whereas there were many other models in the US market that were not sold in Japan. This provides another source of variation to conduct difference-in-differences (DID) estimation. We take advantage of these four features to analyze data with three empirical methods.

2.2 Potential global spillover effects

Our question is whether Japan’s fuel-economy subsidy policy generated global spillover effects through products sold by multinational firms. Before we begin with empirical analysis, it is helpful to see key descriptive statistics in the Japanese and global car markets to hypothesize which automakers are more likely to generate global spillover effects than others.

Figure 1 shows the market shares for new car sales in the Japanese car market in 2012 (Panel A). The top 10 were all Japanese automakers, and about 80% of new car sales were from Japanese firms. In contrast, while American firms sold a variety of cars in Japan, their sales quantities were extremely small; they are part of “other” firms in the figure. These statistics imply that qualifying for the fuel-economy subsidy was likely to be important for Japanese firms but not for American firms—it is unlikely to make sense for American firms to incur fixed costs to change their car designs to qualify for the subsidy as their sales quantities were low.

Panel B of Figure 1 illustrates the extent to which the Japanese market is important for each automaker relative to their worldwide sales. This figure shows again that Japan is a key market for Japanese firms but not for American firms. In addition, this figure suggests that for most of the major Japanese firms, such as Toyota, Honda, Nissan, Suzuki, Subaru, and Mitsubishi, Japan is a major market but Japan’s share relative to these firms’ worldwide sales are around 15-20%, which implies that these firms have high sales quantities in the rest of the world.

Overall, these descriptive statistics suggest that the global spillover effects can be heterogeneous among automakers, depending on their market share in Japan and the rest of the world. We provide our empirical analysis in Section 3.1 to test this hypothesis.

2.3 Data

We use three primary datasets. The first dataset records car specifications data from Japan and the United States. The Japanese and U.S. data sources for the specifications datasets are Car Sensor and Wards Auto

data, respectively. The second dataset is monthly car sales quantity data from Marklines. The third dataset is monthly car production data from Marklines. Our datasets covers all car models sold in Japan and the United States between the 2003 and 2019 model years.

3 Difference-in-Differences Analysis

In this section, we use a difference-in-differences (DID) analysis to investigate whether the fuel-economy subsidy in Japan described in Section 2.1 generated global spillover effects through international car markets. Our main focus is on the US car market, although we find similar results in other countries, which we show in the Appendix.¹

We begin by presenting evidence of the Japanese subsidy’s spillover effects on fuel economy in the US car market in Section 3.1. We then investigate potential threats to the identification in Section 3.2, the underlying drivers of these spillover effects in Section 3.3, followed by an analysis of potential spillovers on other product attributes in Section 3.4 and on product entry and exit in Section 3.5.

3.1 Global Spillover Effects on Fuel Economy

During our sample period from 2003 to 2018, we observe that many vehicle models sold in the U.S. market by Japanese automakers were also offered in Japan, while many others were not. We exploit this variation to construct treatment and control groups for evaluating the impact of the Japanese subsidy, which was introduced in the 2010 model year. Using model year 2009 as the pre-policy baseline, we define the treated group as consisting of models sold in both the U.S. and Japan, and the control group as models sold in the U.S. but not in Japan.

Table 1 reports summary statistics of vehicle characteristics in 2009 for the treated and control groups for Japanese vehicles sold in the U.S. market. While the average vehicle price is slightly higher for the treated group, the difference is not statistically significant. Other characteristics are similar on average, and the differences are statistically insignificant across the two groups.

Our hypothesis is that, if the Japanese subsidy policy generated an international spillover effect on fuel economy, we would expect to observe an improvement in fuel economy for the treated group relative to the control group in the U.S. market. Our DID design is likely to yield a lower bound of the international

¹Table A.4 reports the DID results for Germany and India, which are similar to the findings for the United States presented in this section.

spillover effect if there was also a within-firm technological spillover—where innovations adopted for models affected by the subsidy may be shared across untreated models within the same firm. If this was the case, it could lead to improvements in fuel economy even among the control group. Such within-firm spillovers would attenuate the estimated difference between the treated and control groups, thus making our estimates a lower bound of the international spillover effect.

Figure 2 presents the time trends of sales-weighted average log fuel economy in the U.S. market for vehicles sold by Japanese automakers. The figure indicates that the treated models—defined as those sold in both the U.S. and Japanese markets—and the control models—those sold in the U.S. but not in Japan—exhibited similar trends during the pre-policy period, spanning from 2003 to 2009. These parallel pre-trends include a decline in average fuel economy in 2008, which reflects a market-wide phenomenon driven by falling gasoline prices during that year.²

Following the introduction of the subsidy policy in 2009, fuel economy began to diverge between the treated and control groups, with the treated group exhibiting an increase of approximately 0.1 log points (roughly 10%) relative to the control group. The figure further suggests that the improvement in fuel economy for the treated group did not occur entirely in the immediate aftermath of the policy’s implementation. Rather, the response appears to involve both short-run and medium- to long-run adjustments. This pattern is consistent with the typical product development cycle in the automobile industry, where major specification changes to a vehicle model occur only every few years. As such, some of the automakers’ responses to the subsidy policy likely materialized with a delay.

While the graphical analysis provides a visual representation of the raw data trends, it does not account for potential confounding factors. To obtain DID estimates with controls, we estimate the following equation using ordinary least squares (OLS). The dataset comprises all vehicles sold by Japanese automakers in the U.S. market from 2003 to 2018, at the model-year (t) and model-by-trim (j) level:

$$\ln e_{jt} = \alpha D_{jt} + \theta_j + \lambda_t + \epsilon_{jt}, \quad (1)$$

where e_{jt} denotes the fuel economy, measured in miles per gallon (MPG), for vehicle trim i in model-year t . The treatment indicator D_{jt} equals 1 if the model is also sold in Japan and the model-year t is after the introduction of the Japanese subsidy. The specification includes model fixed effects (θ_j) to control for time-

²It is well established that lower gasoline prices tend to reduce average fuel economy, as consumers typically respond to contemporaneous fuel prices when making vehicle purchase decisions.

invariant heterogeneity across vehicle models and year fixed effects (λ_t) to account for common shocks over time. In Section 3.2, we also include year fixed effects interacted with a truck–car indicator and year fixed effects interacted with firm indicators to assess robustness. Standard errors are clustered at the model level to address serial correlation.

Table 2 reports the OLS estimates of Equation (1) for Japanese vehicles sold in the U.S. market. The difference-in-differences estimates in column 1 indicate that the Japanese subsidy policy generated an international spillover effect on fuel economy in the *U.S. market*, increasing fuel economy by 0.073 log points (7.57 percent).

In Table A.1, we replicate the same DID estimation for *American vehicles* in the U.S. market. As discussed in Section 2.2, although American automakers do sell a range of models in both Japan and the U.S., their sales volumes in the Japanese market are very low. Consequently, we hypothesize that American automakers have limited incentive to respond to the Japanese subsidy. The empirical results in Table A.1 support this prediction: we find economically and statistically insignificant effects on fuel economy for vehicles produced by American automakers.

3.2 Potential Threats to Identification

The identification assumption underlying the DID estimation is the parallel trends assumption—namely, that in the absence of the Japanese subsidy policy, trends in fuel economy would have evolved similarly for the treated and control groups. A potential threat to this assumption is the presence of a confounding factor in the U.S. market that varies over time and differentially affects the treated and control groups.

Several things happened in the US auto market around this time. The Cash for Clunkers program was initiated as a stimulus program. Transactions were eligible for this subsidy only if they met minimum fuel economy requirements. This might have created an incentive to improve fuel economy. However, this would have affected both our treatment and control group, and the program was so short-lived (two months) that automakers had limited ability to respond by modifying and certifying a new configuration.

U.S. fuel-economy standards (Corporate Average Fuel Economy, or CAFE) also changed in this time period. The law was changed in 2009, but changes in the standard did not take effect until 2012. Nevertheless, because there is some banking and borrowing allowed, automakers could have responded to the new law earlier than 2012. The 2009 reform to CAFE also introduced credit trading across firms. The Japanese automakers, particularly in the passenger car segment, were operating well above the standard, so changes

in the standard would have little direct effect on them. However, trading meant that they could potentially monetize improvements in fuel economy by selling credits to other automakers, after 2009.

A tighter future fuel-economy standard and the availability of credit trading would have increased the incentives to improve fuel-economy today, but this should have a similar effect on treatment and control for Japanese vehicles. Even so, our identification strategy could be threatened if the effect of these reforms was different across the two sets of vehicles. The main reason we can think of why this would be true was if the control vehicles were skewed towards the truck segment (which includes SUVs and vans), where the Japanese companies had far less head room relative to the standard. In other words, prior to the advent of credit trading, fuel-economy standards were creating a shadow price on fuel economy improvements among Japanese trucks, but not among Japanese passenger cars.

To address this concern, we include interactions between time fixed effects interacted with car/truck indicator to allow for vehicle-type-specific time trends (columns 2 and 3). In column 3, we also add time fixed effects interacted firms indicators to allow for automaker-specific time trends. The results of these specifications are presented in column 2 and 3 of Table 2. The estimated treatment effect remains largely unchanged, providing further support for the validity of our identification strategy.

3.3 What Drives the Spillover Effects?

Beyond estimating the average treatment effect, we explore two potential sources of heterogeneity in the spillover effects. First, our data in the pre-subsidy period reveal that some vehicle models exhibited similar fuel economy within a model across the U.S. and Japanese markets, while others showed considerable differences in fuel economy between the two countries, despite being sold under the same model name. This suggests that the degree of product differentiation within a model across the two markets was heterogeneous in the baseline period.

We hypothesize that this pre-existing cross-market product differentiation may influence the magnitude of the international spillover effect. Specifically, less-differentiated models (i.e., those with similar fuel economy across markets) were likely designed and manufactured for the two markets. In contrast, more-differentiated models (i.e., those with greater fuel economy differences) were likely tailored separately for each market. Based on this reasoning, we expect that the spillover effects are larger for models with less pre-existing product differentiation.

We empirically test this prediction in column 4 of Table 2 by interacting the treatment variable, D_{jt}

in equation (1), with a measure of cross-market product differentiation. For each vehicle model in 2009, we calculate the average fuel economy separately for the U.S. and Japanese markets, and then compute the absolute value of the log difference between the two. We find that the interaction term is negative and statistically significant, indicating that models with higher levels of pre-existing product differentiation across markets exhibit smaller spillover effects. This finding is consistent with our theoretical prediction.

3.4 Potential Impacts on Other Product Attributes

The analysis thus far has focused on the spillover effects of the Japanese subsidy policy on fuel economy in the U.S. market. We can extend our DID framework in equation (1) to examine whether the policy also had spillover effects on other product attributes. In Table A.2, we apply our primary DID specification—reported in column 3 of Table 2 to estimate treatment effects on additional vehicle characteristics in the U.S. market. We do not find statistically significant effects on product attributes other than fuel economy, suggesting that automakers’ responses were primarily to improve fuel economy directly.

3.5 Potential Impacts on Product Entry and Exit

Recent studies in the international trade literature emphasize that firms, including automakers, may respond to policy shocks through adjustments in product entry and exit (Sabal, 2024). In our context, however, such a response is less likely because the Japanese subsidy policy targeted a single product attribute: fuel economy. As a result, automakers may have found it more cost-effective to adjust the fuel economy of existing models rather than engage in more costly product entry or exit decisions.

Nevertheless, we empirically test whether the Japanese subsidy policy affected product entry and exit behavior. For each model-year, we identify product entries and exits to calculate net entry counts, which we then plot separately for the treated and control groups in Figure A.1. The net entries are similar between the two groups and similar before and after the introduction of the Japanese subsidy policy. Thus, there is an absence of evidence that the subsidy differentially influenced net entry between the treatment and control groups.

We also provide statistical evidence in Tables A.3 by estimating DID regressions. The DID estimates indicate that the Japanese subsidy policy did not have statistically significant effects on net entry, entry, or exit, further supporting the view that automakers were likely to focus on adjusting the fuel economy of

existing models in response to this policy.

3.6 Direct Policy Effects in the Japanese Market

A natural question is how large the spillover effect is relative to the policy’s direct effect in the Japanese market. We lack a natural treatment and control group that are both within Japan—all vehicles were potentially eligible for the subsidy.

Instead, we use the same treatment and control group as in our main analysis, but for the treated vehicles we examine their fuel economy in *Japan*. This provides a DID for fuel economy in Japan, where the identifying assumption is that, absent the policy, the fuel economy of the treated cars in Japan would have tracked the fuel economy of the control in the U.S. Practically, this is the same as estimating Equation (1), on the same sample, but using Japanese fuel economy for the treated observations.

We have two possible predictions. One is *complete spillover*, in which automakers make identical fuel economy improvements in Japan and the United States. Under this scenario, the direct treatment effect on fuel economy in Japan would be similar to the spillover effect on fuel economy in the United States in Section 3.1, where we find an improvement of 0.083 log points (8.65 percent). Another possibility is *partial spillover*, where the direct effect on fuel economy in Japan would be larger than the spillover effect in the United States.

Table 3 provides evidence consistent with partial spillover. Column 3 shows that the direct effect on fuel economy in Japan is a 0.225 log point (25.2 percent) improvement on average, which exceeds the spillover effect estimated for the U.S. market (an 8.65 percent improvement). The resulting spillover-to-direct ratio in terms of fuel economy improvements is therefore 0.34 ($= 8.65 / 25.2$). However, this ratio alone does not capture the relative environmental impacts, as it does not account for differences in reduced externalities, which we examine in the next section.

3.7 Policy Implications: Spillover Multiplier of Environmental Impacts

The DID estimation results indicate that the Japanese policy’s direct effect was a 25.2 percent improvement in fuel economy in Japan, whereas the spillover effect in the U.S. market was a 8.65 percent improvement.

Importantly, these estimates do not imply that the policy’s environmental impact in the United States is 0.34 ($= 8.65 / 25.2$) of its impact in Japan, as environmental externalities depend not only on fuel economy

improvements but also on sales volumes and vehicle miles traveled. First, the U.S. automobile market is substantially larger than that of Japan. Therefore, more vehicles in the US can be affected by the policy. Second, U.S. drivers travel substantially more miles per vehicle than Japanese drivers, resulting in more gasoline consumption per vehicle. The average annual miles traveled per vehicle are 14,489 in the United States and 4,181 in Japan. As a result, a given improvement in fuel economy may generate a larger reduction in environmental externalities in the United States.

To evaluate the policy's environmental impact in each country, we take the following steps. Our DID estimates provide the percentage change in fuel economy (miles per gallon) for affected vehicles. We convert these estimates into changes in gasoline consumption per mile (gallons per mile) and multiply them by the average annual miles driven per vehicle in each country to obtain the reduction in gasoline consumption.³ We then translate the reduction in gasoline consumption into metric tons of CO₂ emissions avoided.

We define the *spillover multiplier* of environmental impacts (ρ) as follows:

$$\begin{aligned}
 \rho &\equiv \frac{\text{Japanese policy's environmental impacts in Japan and the U.S.}}{\text{Japanese policy's environmental impacts in Japan}} \\
 &= 1 + \frac{\Delta \text{Externality per vehicle}_{US} \times Q_{US}}{\Delta \text{Externality per vehicle}_{JP} \times Q_{JP}} \\
 &= 1 + \frac{0.43 \text{ tons of CO}_2 \times 5,395,182}{0.20 \text{ tons of CO}_2 \times 2,074,181} \\
 &= 1 + \frac{2,351,186 \text{ tons of CO}_2 \text{ per year}}{411,203 \text{ tons of CO}_2 \text{ per year}} \\
 &= 6.72,
 \end{aligned} \tag{2}$$

where $\Delta \text{Externality per vehicle}$ denotes the policy-induced change in CO₂ emissions per vehicle, and Q denotes the quantity of affected vehicles. $\Delta \text{Externality per vehicle}$ is larger in the United States foremost because average annual miles traveled per vehicle are higher. Moreover, Q is larger in the United States because the affected models—those sold in both countries—have higher total sales in the U.S. market.

The spillover ratio of environmental impacts (ρ) is greater than one, implying that the Japanese policy's environmental impact abroad *exceeds* its domestic impact. This finding carries important policy implications. Standard analyses of environmental policies often focus exclusively on domestic effects, potentially

³We abstract from a potential rebound effect—drivers may increase vehicle usage when fuel economy improves. This extension could be incorporated, but if proportional rebound effects are identical across the two countries, they cancel out in Equation 2 and have no impact on ρ .

leading to a substantial understatement of overall policy impacts.

There is one important limitation in our calculation of ρ based on the DID estimates. The calculation above focuses only on vehicles directly affected by the spillover effects of the fuel economy subsidy. What may be missing are potential equilibrium effects: vehicles that are not directly affected by the global spillover may nevertheless adjust their fuel economy in response to competitors' changes. In the next section, we develop a model of multinational automobile markets with global policy spillovers to incorporate these equilibrium effects into the calculation of ρ .

4 A Model of Multinational Car Markets with Global Policy Spillovers

Our model has two goals. First, we aim to model and estimate a potential mechanism of global policy spillovers. To do so, we extend a standard differentiated-product market model [Berry, Levinsohn and Pakes \(1995\)](#) to incorporate firms selling products in multinational markets and incorporate firms' endogenous attribute choices. This allows us to estimate potential cross-market links in revenues and costs.

The second objective of our model is to investigate the welfare implications of the global policy spillover effect. The equilibrium model allows us to examine the welfare implications of the global spillover effects by quantifying consumer surplus, producer surplus, and environmental externalities.

4.1 Demand

We follow [Berry, Levinsohn and Pakes \(1995\)](#) to model a consumer's new car purchase with a random utility model. We estimate demand in Japan and the United States separately, allowing the demand systems to differ between the markets.

We use p_{jc} to denote price for product j in market c and x_{jc} for a vector of product characteristics for product j in market c . Conditional indirect utility of consumer i who purchases product j can be written by: $u_{ijc} = \beta_i x_{jc} + \alpha_i p_{jc} + \xi_{jc} + \epsilon_{ijc}$, where ξ_{jc} is unobserved factors at the market-product level and ϵ_{ijc} is unobserved factors at the market-product-consumer level. We assume ϵ_{ijc} is distributed type-I extreme value. The market share for product j in country c is:

$$s_{jc} = \int \frac{\exp(\beta_i x_{jc} + \alpha_i p_{jc} + \xi_{jc})}{\sum_{j'=0}^J \exp(\beta_i x_{j'c} + \alpha_i p_{j'c} + \xi_{j'c})} f(\mu_i) d\mu_i, \quad (3)$$

where $f(\mu_i)$ is the distribution of random-coefficients. The outside option is not to buy product $j = 1, \dots, J$. This market share is usually unobservable from a dataset. A typical approach is to assume that s_{0c} is the number of consumers (households) in market c that did not buy any product j .

We begin by estimating demand using the standard logit model without random coefficients. In this specification, the preference parameters do not vary across consumers, allowing Equation (3) to be written in linear form as $\ln s_j - \ln s_0 = \beta x_{jc} + \alpha p_{jc} + \xi_{jc}$. An advantage of this approach is that it can be consistently estimated using linear instrumental variables methods with valid instruments. A key limitation, however, is that the standard logit model imposes restrictive substitution patterns through the Independence of Irrelevant Alternatives (IIA) assumption.

To address the issue with the IIA, we use a random-coefficient logit approach for our main specification. We allow heterogeneity in α with a log-normal distribution. An advantage of this approach is that it allows for flexible substitution patterns, less restrictive price elasticities, and heterogeneous consumer tastes. A key challenge is that nonlinear GMM estimation requires numerical simulation and does not guarantee convergence to a unique global optimum; therefore, careful implementation is necessary to obtain globally optimal estimates (Knittel and Metaxoglou, 2013; Conlon and Gortmaker, 2020).

4.2 Supply and Equilibrium

We describe the operating profit of multinational, multi-product firm f in each market as follows:

$$\begin{aligned} \text{Japan: } \pi_f &= \sum_{j \in J_f} [(p_j - c_j(e_j, x_j)) \cdot q_j(p_j - \tau_j(e_j), e_j, x_j)] \\ \text{US: } \tilde{\pi}_f &= \sum_{j \in \tilde{J}_f} [(\tilde{p}_j - \tilde{c}_j(\tilde{e}_j, \tilde{x}_j)) \cdot \tilde{q}_j(\tilde{p}_j, \tilde{e}_j, \tilde{x}_j)], \end{aligned} \quad (4)$$

where J_f denotes the set of cars sold by firm f ; p_j is the price of car j ; c_j is its marginal cost; e_j denotes fuel economy; x_j is a vector of other product attributes; q_j represents demand; and $\tau_j(e_j)$ is the fuel-economy subsidy in Japan. We use tildes to denote the corresponding variables in the U.S. market.

Firm f maximizes the joint profit from the two markets, with respect to prices and fuel economy:

$$\max_{p, e, \tilde{p}, \tilde{e}} \pi_f = \pi(p, e, x) + \tilde{\pi}(\tilde{p}, \tilde{e}, \tilde{x}) - \sum_{j \in J_f} FC(e_j, \tilde{e}_j), \quad (5)$$

where p , e , \tilde{p} , and \tilde{e} are vectors of prices and fuel economy for all products. The function $FC(e_j, \tilde{e}_j)$ denotes the fixed cost of changing fuel economy, which we allow to depend on both e_j and \tilde{e}_j . In Section 5.3, we describe how we model this fixed cost to allow for cross-market complementarity.

Equation 5 implies that, in equilibrium, four first-order conditions—with respect to $(p_j, e_j, \tilde{p}_j, \tilde{e}_j)$ —must be satisfied for each product j :

$$q_j + \sum_{k \in J_f} \left[(p_k - c_k) \frac{\partial q_k}{\partial p_j} \right] = 0, \quad (6)$$

$$-\frac{\partial c_j}{\partial e_j} q_j + (p_j - c_j) \left(\frac{\partial q_j}{\partial e_j} - \frac{\partial q_j}{\partial (p_j - \tau_j)} \frac{\partial \tau_j}{\partial e_j} \right) + \sum_{k \neq j \in J_f} \left[(p_k - c_k) \frac{\partial q_k}{\partial e_j} \right] = \frac{\partial FC(e_j, \tilde{e}_j)}{\partial e_j}. \quad (7)$$

$$\tilde{q}_j + \sum_{k \in \tilde{J}_f} \left[(\tilde{p}_k - \tilde{c}_k) \frac{\partial \tilde{q}_k}{\partial \tilde{p}_j} \right] = 0, \quad (8)$$

$$-\frac{\partial \tilde{c}_j}{\partial \tilde{e}_j} \tilde{q}_j + \sum_{k \in \tilde{J}_f} \left[(\tilde{p}_k - \tilde{c}_k) \frac{\partial \tilde{q}_k}{\partial \tilde{e}_j} \right] = \frac{\partial FC(e_j, \tilde{e}_j)}{\partial \tilde{e}_j}, \quad (9)$$

Equations (6) and (8) are the first-order conditions with respect to prices, which are standard in the literature on differentiated product markets. For each firm f in each market, these conditions yield a system of J_f equations in J_f unknown marginal costs, allowing us to recover marginal costs given demand estimates.

Equations (7) and (9) are the first-order conditions with respect to fuel economy.⁴ The left-hand side of Equation (9) represents the net marginal revenue from an increase in fuel economy. $\sum_{k \in \tilde{J}_f} (\tilde{p}_k - \tilde{c}_k) \frac{\partial \tilde{q}_k}{\partial \tilde{e}_j}$ captures the marginal revenue, while $-\frac{\partial \tilde{c}_j}{\partial \tilde{e}_j} \tilde{q}_j$ reflects the increase in marginal cost. This first-order condition therefore implies that firms equate the net marginal revenue with respect to fuel economy—the left-hand side—with the *marginal* fixed cost—the right-hand side—when endogenously choosing the optimal level of fuel economy.

Each element of Equation (9) can be obtained from data or the estimated demand and marginal cost functions. Once we obtain these, we can estimate a function of marginal fixed cost, $\frac{\partial FC(e_j, \tilde{e}_j)}{\partial \tilde{e}_j}$, with a parametric assumption. We will discuss this estimation strategy in Section 5.3.

Compared to Equation (9) for the U.S. market, Equation (7) for the Japanese market includes an additional term, $-\frac{\partial q_j}{\partial (p_j - \tau_j)} \cdot \frac{\partial \tau_j}{\partial e_j}$, for j . This term captures the marginal effect of fuel economy e_j on the subsidy $\tau_j(e_j)$ and the subsidy's effect on demand q_j . This term reflects how a change in e_j influences the level of the subsidy, thereby indirectly affecting consumer demand in Japan.

⁴Our approach follows Fan (2013) in modeling endogenous product attributes, as in her analysis of newspapers.

In Section 5, we use our data and policy-induced variation to estimate the model. We then use the estimated model to conduct counterfactual simulations in Section 6. In these simulations, the four first-order conditions in Equations 8–7 play a central role. To illustrate the mechanism, consider a change in the subsidy τ_j and the resulting new equilibrium. The direct effect of the subsidy change enters only the fuel-economy first-order condition in Japan (Equation 7). However, any induced change in fuel economy in Japan can affect the optimal level of fuel economy in the U.S. (Equation 9) through the marginal fixed cost, provided that e_j and \tilde{e}_j are complements in the marginal fixed cost function. These adjustments in optimal fuel economy then feed into the price first-order conditions in Equations 8 and 6, leading firms to choose new equilibrium levels of both prices and fuel economy.

4.3 Endogeneity and instruments

The standard BLP estimation considers that firms endogenously choose only p_j , taking other attributes exogenous. This approach is not appropriate in our context because we allow firms to endogenously choose p_j and e_j .

Following [Ito and Sallee \(2018\)](#), we use a unique feature of the Japanese subsidy to create an instrumental variable for e_j . To be qualified for the subsidy, e_j needed to be above the target. As shown in Figure A.2, the fuel-economy target was a non-linear step function. This created variation in easiness/difficulties to qualify for the subsidy so that it created a policy-induced change in e_j in policy period. Recall that the subsidy was introduced in 2009. We create $\Delta e_j = e_j^{\text{target}} - e_{j,2008}$ as an instrument for e_j .

Figure A.2 visually shows the policy induced variation. We construct panel data of car models by linking cars sold in 2008 (before the policy change) and 2012 (three years after the policy introduction). Each dot in the figure shows a car's starting values of fuel economy and weight in 2008. For the cars that qualified for the new subsidy in 2012, we also show vectors connecting each car's starting position in 2008 to its final position in 2012.

This figure provides several useful results. First, many of the cars that gained the subsidy were redesigned in a way that they were just above the subsidy cutoff. Second, cars that started closer to the new standard were more likely to get the subsidy; that is, the “distance” to the subsidy cutoff explains most of the variation in which cars obtained the subsidy.

5 Estimation of the Model

In this section, we estimate the model presented in Section 4. We begin by estimating demand in Section 5.1, followed by the estimation of marginal costs in Section 5.2, and marginal fixed costs in Section 5.3. We then use the estimated model to conduct counterfactual policy simulations in Section 6.

5.1 Demand Estimation Results

Table 4 reports the demand estimation results for Japan and the United States, with the standard logit estimates shown in columns 1–2 and the random-coefficients logit estimates shown in columns 3–4.

In both markets, consumers value fuel economy, horsepower, and lower prices. The parameter σ represents the standard deviation of the log-normal random coefficient on price and indicates substantial unobserved heterogeneity in price sensitivity. Figure A.3 illustrates the implied distribution of the price coefficient to visualize this heterogeneity in price elasticity.

Overall, the demand estimates suggest that preference parameters are broadly similar across the two markets. One notable exception is the coefficient on fuel economy. Our results indicate that consumers in the United States place slightly greater value on fuel economy than consumers in Japan, potentially because U.S. drivers travel substantially more miles than Japanese drivers, as discussed in Section 3.7.

5.2 Marginal Cost Estimation Results

As discussed in Section 4.2, the first order conditions with respect to prices in Equations (8) and (6) yield a system of J_f equations in J_f unknown marginal costs for firm f , allowing us to recover the marginal costs (c_j) given the estimated demand system.

We regress the recovered marginal costs c_j on product attributes to estimate the marginal cost function. We estimate it separately for each market to allow for cross-market heterogeneity.

Table 5 reports the marginal cost estimation results for each market, with and without firm fixed effects. The estimated coefficient on horsepower is similar across the two countries, while the coefficient on fuel economy is larger in the United States. This pattern suggests that a unit increase in fuel economy leads, on average, to a larger increase in marginal cost in the United States than in Japan.

5.3 Marginal Fixed Cost Estimation Results

Our approach builds on the estimation of marginal fixed costs with respect to endogenous product attributes in [Fan \(2013\)](#) and [Barwick, Kwon and Li \(2024a\)](#). Our approach extends this method to incorporate cross-market complementarity in the marginal fixed cost.

Firm j 's first order conditions with respect to fuel economy—Equations (9) and (7)—provides an estimate of the *marginal* fixed cost with respect to an improvement in fuel economy, $\frac{\partial FC(e_j, \tilde{e}_j)}{\partial e_j}$ and $\frac{\partial FC(e_j, \tilde{e}_j)}{\partial \tilde{e}_j}$. The left-hand sides of these equations can be calculated by data and estimates from the demand and marginal cost estimation. Then we can estimate the marginal fixed cost function with a parametric functional form assumption.

Consider that firms face the following fixed cost function for improving fuel economy:

$$FC(e_j, \tilde{e}_j) = \gamma + \gamma_0 e_j + \gamma_1 e_j^2 + \gamma_0' \tilde{e}_j + \gamma_1' \tilde{e}_j^2 + \gamma_2 e_j \tilde{e}_j \quad (10)$$

where e_j and \tilde{e}_j denote fuel economy in Japan and the United States, respectively. This specification implies that firms incur a quadratic cost when improving fuel economy. The final term γ_2 captures a potential cost complementarity between fuel economy choices in Japan and the United States.

Recall that Equations (9) and (7) characterize the *marginal* fixed costs, rather than the fixed cost itself. We therefore take derivatives with respect to fuel economy in Japan (e_j) and in the United States (\tilde{e}_j):

$$\frac{\partial FC(e_j, \tilde{e}_j)}{\partial e_j} = \gamma_0 + 2\gamma_1 e_j + \gamma_2 \tilde{e}_j \quad (11)$$

$$\frac{\partial FC(e_j, \tilde{e}_j)}{\partial \tilde{e}_j} = \gamma_0' + 2\gamma_1' \tilde{e}_j + \gamma_2 e_j \quad (12)$$

We estimate these equations to recover the parameters γ_0 , γ_1 , and γ_2 , controlling for firm fixed effects to capture unobserved heterogeneity across firms. The key parameter of interest is γ_2 , which governs the degree of scope economies in fuel-economy choices. If γ_2 is negative, then an improvement in fuel economy in the U.S. lowers the cost of improving fuel economy in Japan for the same model, and vice-versa. We use the policy-induced instruments discussed in Section 4.3 as instrumental variables for e_j and \tilde{e}_j to address the potential endogeneity of fuel economy choices.

Table 6 reports the marginal fixed-cost estimation results. The negative and statistically significant γ_2 provides evidence of cross-market cost complementarity in firms' fuel-economy choices. For example, a

fuel economy improvement in Japan for vehicle j would reduce the marginal fixed cost of improving fuel economy in the US, and vice versa. Hence, when firms respond to the fuel-economy subsidy in Japan and improve a vehicle model's fuel economy in Japan, the corresponding model in the United States gets a reduction in the marginal fixed cost of improving fuel economy, which could explain a potential mechanism of the global policy spillover effects.

6 Counterfactual Policy Simulation

To investigate the welfare impact of the global policy spillover, we use our structural model in Section 4 and parameter estimates from Section 5 to simulate two scenarios. The first is the actual scenario, where we include the fuel-economy subsidy policy in the Japanese market. The second is a counterfactual scenario, where we remove the fuel-economy subsidy policy and compute a new equilibrium.

6.1 Simulation Algorithm

In our policy simulation, we first introduce a counterfactual policy environment (e.g., removing Japan's fuel economy subsidy). Firms then endogenously choose four variables—prices and fuel economy in Japan (p_j, e_j) and in the United States (\tilde{p}_j, \tilde{e}_j)—by solving the first-order conditions (FOCs) in Equations (8)–(7), yielding a new equilibrium.

Solving the four first-order conditions simultaneously is computationally intensive due to the large number of products produced by multi-product firms and the presence of nonlinear equilibrium conditions, including a random-coefficients demand system. We therefore solve the first-order conditions using the following iterative procedure.

In the first iteration, we initialize the algorithm using the observed values of p_j, e_j, \tilde{p}_j , and \tilde{e}_j from the data. Within the iteration, we treat these values as given and solve the first-order conditions in Equations (8)–(7) separately. For example, we solve Equation (7) with respect to fuel economy in Japan (e_j), holding fixed the other three endogenous variables, p_j, \tilde{p}_j , and \tilde{e}_j . Similarly, we solve Equation (9) with respect to fuel economy in the United States (\tilde{e}_j), holding fixed p_j, \tilde{p}_j , and e_j .

Solving all four first-order conditions in this manner yields an updated set of p_j, e_j, \tilde{p}_j , and \tilde{e}_j . At the end of the iteration, we update the values of these endogenous variables, as well as demand and cost functions, which depend on them.

In the second and subsequent iterations, we repeat this procedure: each first-order condition is solved separately, taking the remaining endogenous variables from the previous iteration as given. At the end of each iteration, we update prices, fuel economy, demand, and costs, and proceed to the next iteration. We continue until the algorithm converges to a new equilibrium.

6.2 Counterfactual Policy Simulation Results

Table 7 reports the counterfactual policy simulation results based on the structural model described in Section 4 and the parameter estimates from Section 5. Column 1 presents the observed equilibrium with the fuel economy subsidy in place in the Japanese market. Column 2 reports the counterfactual equilibrium in which the subsidy is removed. Columns 3 and 4 report the differences between the two scenarios in levels and percentages, respectively.

We report sales-weighted average fuel economy (MPG) separately for all vehicles, vehicles that received the subsidy, and other vehicles in Japan. The subsidized vehicles are those that receive the subsidy in the observed equilibrium. For the United States, we report the results for all vehicles, spillover vehicles, and other vehicles. The spillover vehicles are vehicle models that received the subsidy in Japan and also were sold in the United States. As discussed in Section 3.7, vehicles not directly affected by the subsidy may nevertheless adjust fuel economy in response to competitors' changes, generating indirect equilibrium effects.

For the subsidized vehicles in Japan and spillover vehicles in the United States, we find simulation results that are consistent with our findings from the DID analysis in Sections 3.1 and 3.6. On average, the subsidy in Japan increases fuel economy by 25.65% in Japan, while generating a spillover effect of an 11.15% improvement in the U.S. market.

Indirect equilibrium effects are smaller than direct effects at the per-vehicle level. In Japan, the indirect effect on other vehicles is a 0.1% decline in fuel economy, whereas in the United States the indirect effect is a 1.49% decline. That is, our findings suggest that competing vehicles would slightly reduce fuel economy in response to the fuel-economy subsidy in Japan to differentiate themselves from vehicles that receive the subsidy.

In Japan, these patterns are also reflected in aggregate CO₂ emissions. The overall policy effect is a reduction of 0.51 megaton of CO₂ per year. Most of this reduction comes from the direct effect on affected vehicles, while the indirect effect is positive but small, due to the small market share of other vehicles.

In the United States, although the per-vehicle indirect effect on fuel economy is small, it generates a considerable increase in total emissions because other vehicles account for a large share of the market. We estimate CO₂ reductions of 1.69 megatons per year from spillover vehicles and a CO₂ increase of 0.78 megatons per year from other vehicles, for a total reduction of 0.91 megatons per year.

Accounting for indirect equilibrium effects, the spillover ratio of the policy’s environmental impacts (ρ) is 2.78 ($= 1 + 0.91/0.51$). This finding suggests that accounting for indirect equilibrium effects is important: while the Japanese subsidy policy reduces CO₂ emissions in both Japan and the United States, the resulting reductions in the United States can be partly offset by the indirect equilibrium effect. Nevertheless, qualitatively, our key finding does not change between the DID analysis and finding in this section—while the Japanese subsidy policy reduces CO₂ emissions in both Japan and the United States, the resulting reductions in the United States can be substantially larger than the domestic reductions in Japan, and therefore, abstracting from the global spillover effect could considerably underestimate policy impacts.

7 Conclusion

In a globalized economy, a country’s domestic policies can generate global spillover effects through products designed and manufactured by multinational firms. In this paper, we study this phenomenon, which we label attribute propagation, in the context of environmental regulation in the automobile market. To quantify the significance of attribute propagation for environmental outcomes, we define the spillover multiplier of environmental impacts. Our study contributes novel methods and a first empirical quantification of these effects, which are related to the notion of the California effect (Vogel, 1995) and Brussels effect (Bradford, 2020).

We find that Japan’s fuel economy subsidy led to significant improvements in the fuel economy of vehicles sold in the U.S. market, thereby generating global environmental benefits. We develop a model of multinational automobile markets to examine how cross-market linkages and costs give rise to such global spillovers. Using the estimated model, we conduct counterfactual policy simulations to quantify the environmental benefits and welfare effects of these global policy spillovers, accounting for equilibrium effects, namely how other non-treated vehicles change their fuel economy and prices. Our structural analysis confirms the significance of attribute propagation.

We study one salient and important market and focus on environmental policy and outcomes. Attribute

propagation could have similar significance for other policies or preference shocks. Our paper provides one potential roadmap for studying this phenomenon in other contexts.

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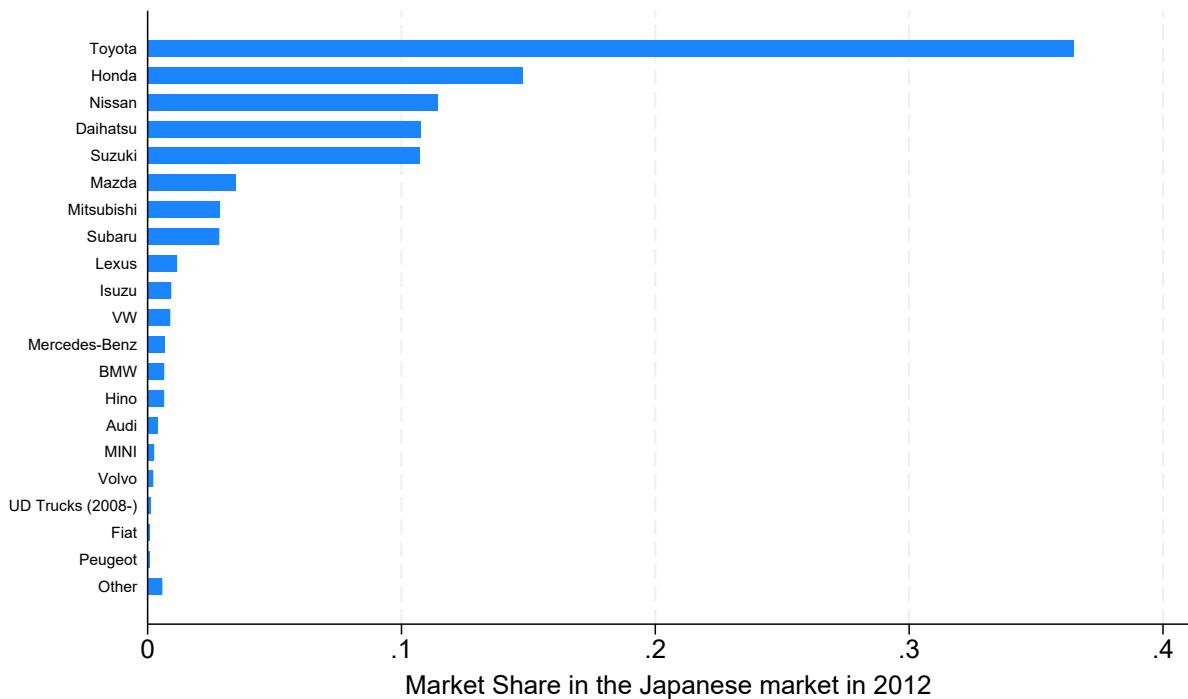
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Figures and Tables

Figure 1: Market Shares

Panel A: Market Share in the Japanese market in 2012



Panel B: Each firm's Japanese market share relative to its worldwide sales

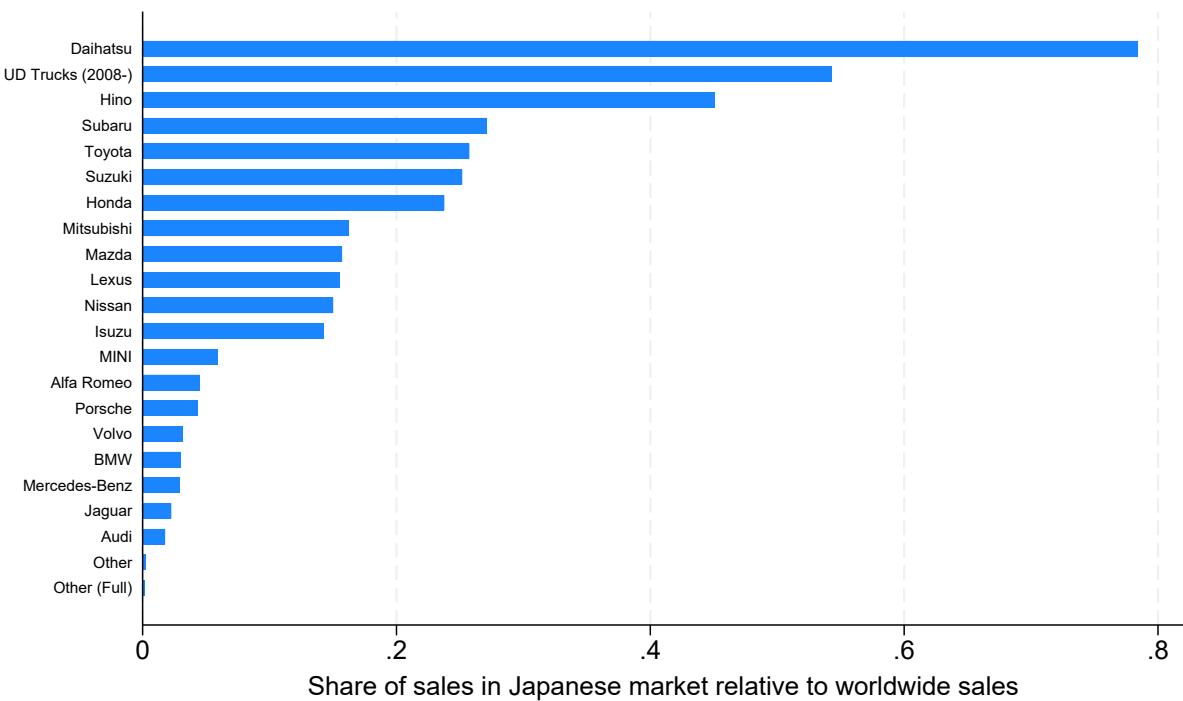
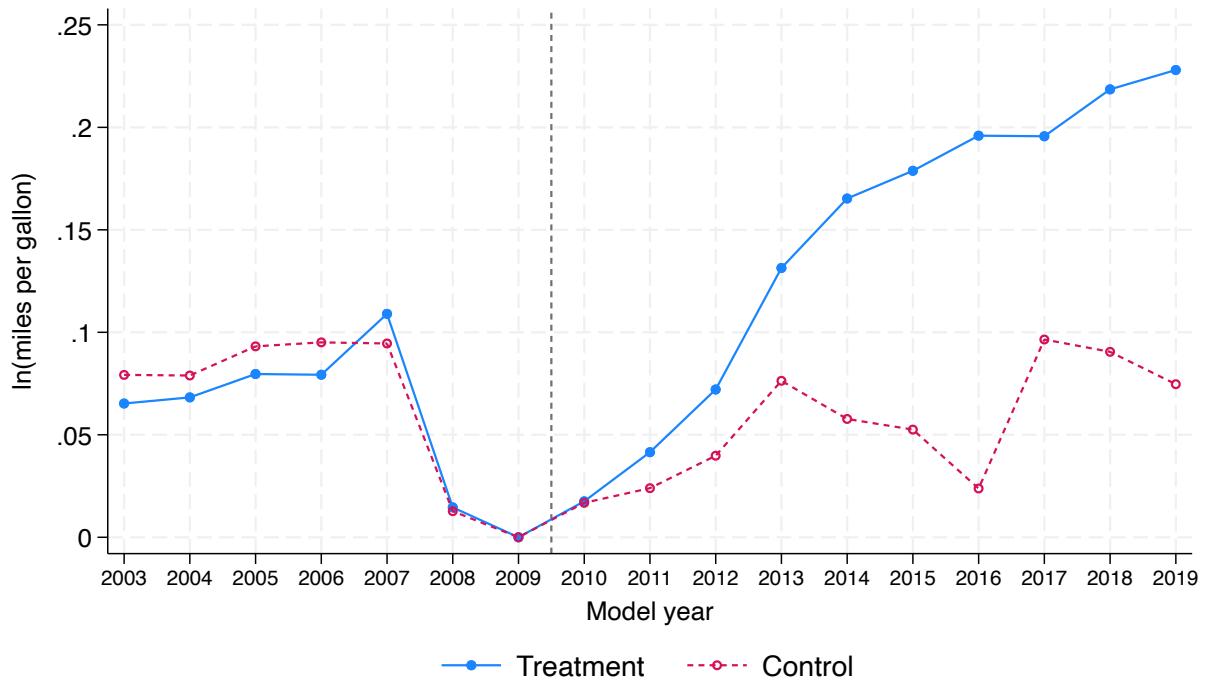


Figure 2: Average Fuel Economy of Japanese Vehicles in the US market



Note: Each dot shows the log of fuel economy in the US auto market for each group, normalized at their 2009 level so that it shows the changes in the log of fuel economy relative to 2009. The treatment group includes Japanese automakers' vehicles that were sold in both the United States and Japan. The control group includes Japanese automakers' vehicles that were sold in the United States but not in Japan.

Table 1: Baseline Characteristics of Treatment and Control Groups Prior to the Subsidy

	Treated		Control		Difference		
	Mean	S.D.	Mean	S.D.	Mean	S.E.	p-value
Price (1,000 USD)	35.0	10.4	32.4	9.6	2.7	1.9	0.17
Miles per gallon	18.2	3.2	18.9	3.7	-0.7	1.1	0.55
Horsepower	288.3	65.3	268.1	79.9	20.2	21.7	0.35
Length (feet)	18.3	2.6	17.7	2.3	0.6	1.0	0.57
Width (feet)	6.6	0.6	6.4	0.6	0.2	0.2	0.34
Height (feet)	6.0	0.6	5.9	0.8	1.5	0.1	0.1
Wheelbase (feet)	11.3	2.0	10.8	1.8	0.6	0.8	0.46
Footprint (square feet)	75.3	17.7	69.6	16.2	5.7	7.0	0.42
Weight (1,000 lbs)	5.5	1.5	4.7	1.2	0.8	0.6	0.23

Notes: This table reports summary statistics of vehicle characteristics in 2009, one year prior to the introduction of the Japanese fuel economy subsidy, for Japanese vehicles sold in the U.S. market. The treated group consists of models sold in both the U.S. and Japan, while the control group includes models sold in the U.S. but not in Japan. *S.D.* denotes the standard deviation, *S.E.* refers to the standard error of the difference in means, and the *p*-value corresponds to a test of the null hypothesis that the difference in means between the two groups is equal to zero.

Table 2: Global Spillover Effects of the Japanese Fuel-Economy Subsidy on the US Market

	Dependent variable: log fuel economy			
	(1)	(2)	(3)	(4)
Treated \times Post	0.073 (0.024)	0.090 (0.022)	0.083 (0.026)	0.151 (0.038)
Treated \times Post \times Differentiation				-0.300 (0.090)
N	9,098	9,098	9,098	7,159
Model FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Year \times Truck FE	No	Yes	Yes	Yes
Year \times Make FE	No	No	Yes	Yes

Note: This table shows the OLS regression results of equation (1). The dependent variable is the log of fuel economy (miles per gallon) at the make-model-trim level between model years 2003 and 2019. All regressions are weighted by the average annual sales. Standard errors are clustered at the model level. The data include all vehicles sold by Japanese automakers in the US automobile market.

Table 3: Direct Effects of the Japanese Fuel-Economy Subsidy in Japan

Dependent variable: log fuel economy			
	(1)	(2)	(3)
Treated \times Post	0.203 (0.081)	0.276 (0.125)	0.225 (0.115)
N	12,812	12,810	12,810
Model FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Year \times Truck FE	No	No	Yes
Year \times Make FE	No	Yes	Yes

Note: This table shows the OLS regression results in Section 3.6. The dependent variable is the log of fuel economy (miles per gallon) at the make-model-trim level between model years 2003 and 2019. All regressions are weighted by the average annual sales. Standard errors are clustered at the model level. The data include all vehicles sold by Japanese automakers in the US automobile market.

Table 4: Demand Estimation Results

	Standard logit		Random-coefficient logit	
	Japan	US	Japan	US
Mean Price/Income (USD)	-1.28 (0.496)	-4.81 (0.428)	-13.03 (3.72)	-27.26 (4.28)
Fuel economy (mpg)	0.079 (0.010)	0.117 (0.020)	0.073 (0.015)	0.114 (0.025)
Horsepower	0.012 (0.004)	0.015 (0.003)	0.047 (0.011)	0.023 (0.006)
σ			0.325 (0.098)	0.662 (0.073)
Observations	2142	1469	2142	1469

Note: This table shows the demand estimation results of our structural model in Section 5.1. We estimate random-coefficients on prices with the log-normal distribution and report their means and standard deviations σ .

Table 5: Marginal cost estimation results

	Japan		US	
	(1)	(2)	(3)	(4)
Fuel economy (MPG)	364.82 (52.90)	370.64 (46.16)	470.35 (94.08)	355.11 (82.08)
Horsepower	331.86 (14.65)	318.60 (23.52)	122.40 (14.79)	95.65 (14.40)
Firm FE	No	Yes	No	Yes
Observations	2142	2142	1469	1469

Note: This table shows the marginal cost estimation results described in Section 5.2.

Table 6: Marginal fixed cost estimation results

	(1)	(2)
γ_1	0.195 (0.010)	0.218 (0.019)
γ_2	-0.040 (0.012)	-0.102 (0.019)
Country FE	Yes	Yes
Firm FE \times Country FE	No	Yes
Observations	3611	3611

Note: This table shows the marginal fixed cost estimation results described in Section 5.3.

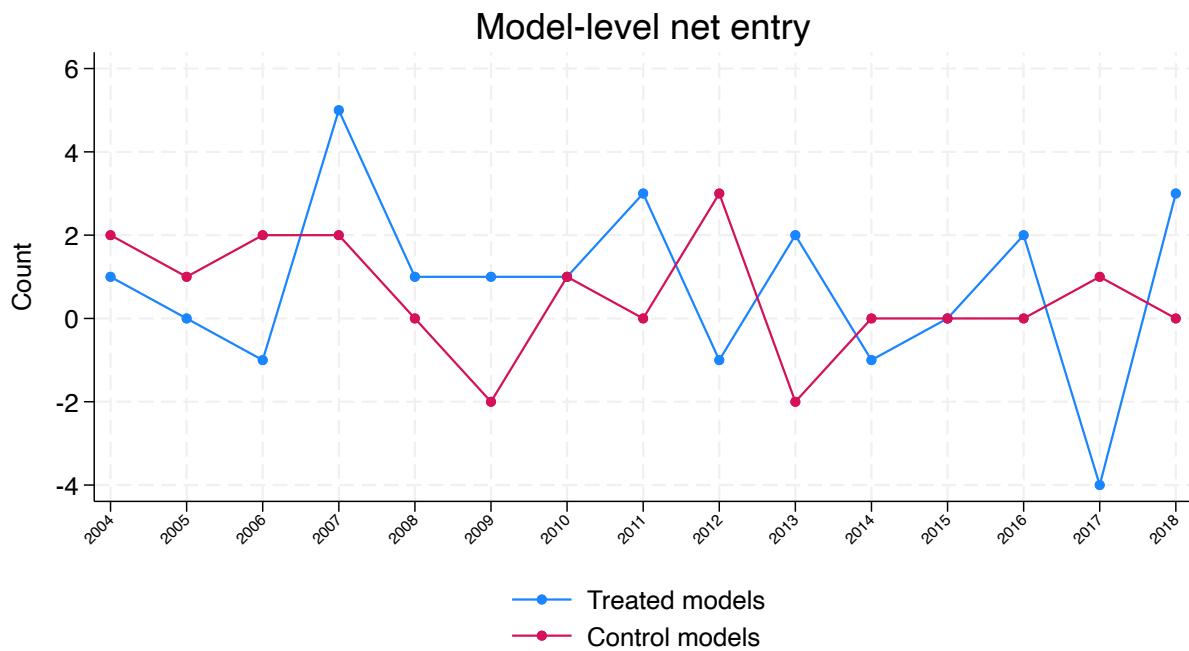
Table 7: Counterfactual Policy Simulation Results

	Actual	Counterfactual (no subsidy in Japan)	Impacts of the subsidy	
			Levels	% changes
Average fuel economy (miles per gallon)				
Japan: All vehicles	49.97	42.07	7.90	18.78
Japan: Subsidized vehicles	56.49	44.96	11.53	25.65
Japan: Others	35.71	35.75	-0.04	-0.10
USA: All vehicles	25.29	24.91	0.38	1.53
USA: Spillover vehicles	28.38	25.54	2.85	11.15
USA: Others	24.35	24.72	-0.37	-1.49
Total CO₂ emissions per year (megatonnes)				
Japan: All vehicles	4.17	4.67	-0.51	-10.90
Japan: Subsidized vehicles	2.43	2.94	-0.51	-17.38
Japan: Others	1.73	1.73	0.00	0.13
USA: All vehicles	65.33	66.25	-0.91	-1.38
USA: Spillover vehicles	13.79	15.48	-1.69	-10.90
USA: Others	51.55	50.77	0.78	1.53

Note: This table shows the counterfactual simulation results described in Section 6.

Appendix Figures

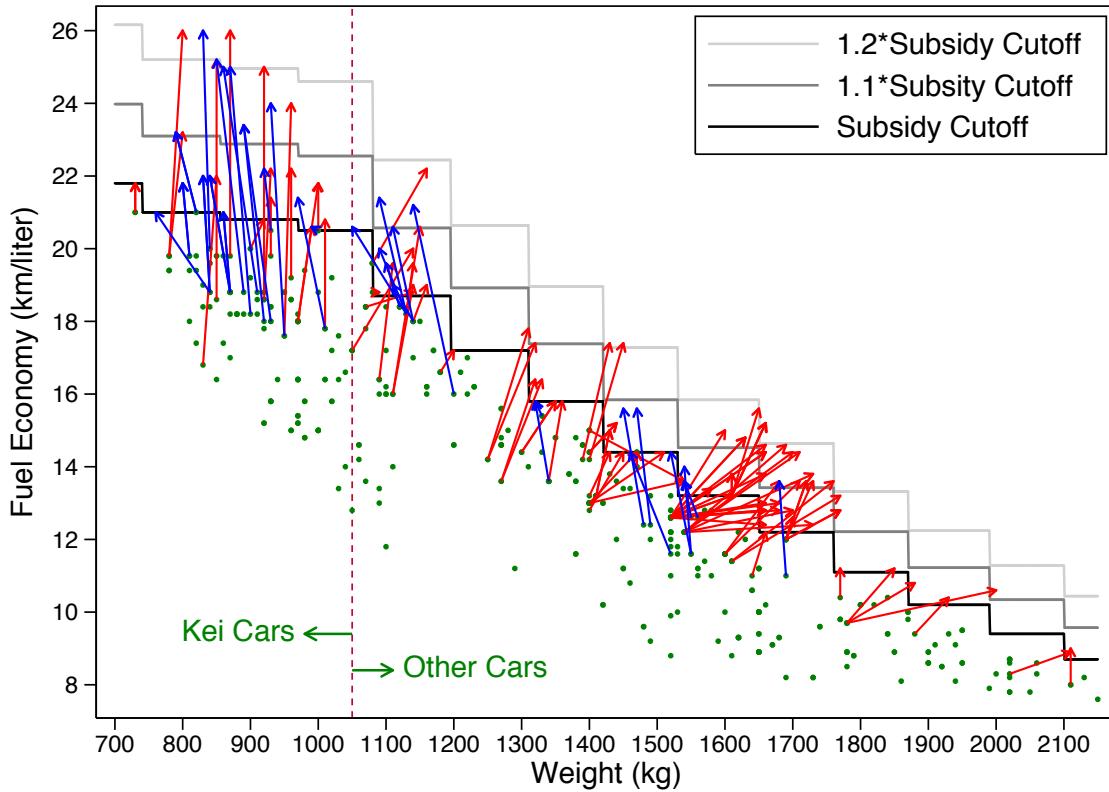
Figure A.1: Net Product Entry



All Japanese models in the US car market.

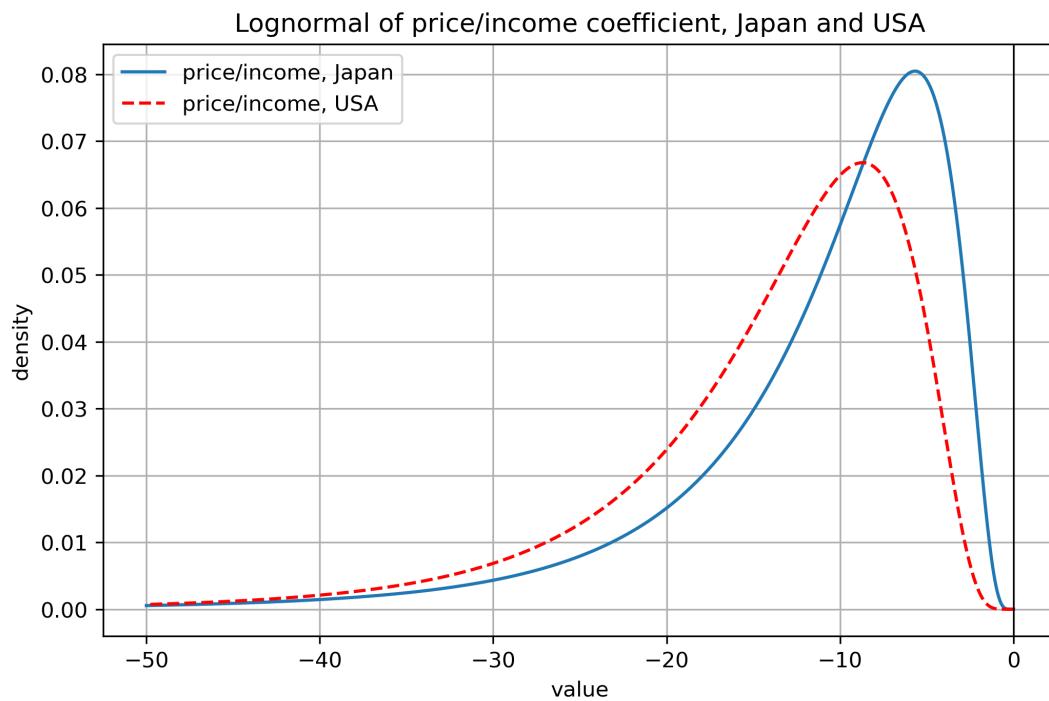
Note: This figure shows the product entry and exit discussed in Section 3.5. For each model-year, we identify product entries and exits to calculate net entry counts, which we then plot separately for the treated and control groups.

Figure A.2: Subsidy take-up



Note: This figure shows the policy induced variation. We construct panel data of car models by linking cars sold in 2008 (before the policy change) and 2012 (three years after the policy introduction). Each dot in the figure shows a car's starting values of fuel economy and weight in 2008. For the cars that qualified for the new subsidy in 2012, we also show vectors connecting each car's starting position in 2008 to its final position in 2012.

Figure A.3: Log-Normal Distribution of Price/Income Coefficients



Note: This figure shows the distributions of price coefficients estimated by the random-coefficient logit model in Section 5.1.

Appendix Tables

Table A.1: International Spillover Effects of Japan's Fuel Economy Subsidy on the US Automobile Market (American cars in the US market)

American cars in the US market. Dependent variable is the log of each attribute.						
	(1) MPG	(2) Horsepower	(3) Price	(4) Wheelbase	(5) Footprint	(6) Weight
Treated \times Post	-0.025 (0.028)	0.051 (0.035)	0.016 (0.023)	-0.003 (0.007)	0.000 (0.009)	-0.007 (0.013)
N	21,567	21,752	21,661	21,762	21,762	21,719

Note: This table shows the OLS regression results of equation (1). The dependent variable is the log of each car attribute at the make-model-trim level between model years 2003 and 2019. All regressions are weighted by the average annual sales. Standard errors are clustered at the model level. Panel A includes vehicles sold by Japanese automakers (Honda, Isuzu, Lexus, Mazda, Mitsubishi, Nissan, Subaru, Suzuki, and Toyota). Panel B includes vehicles sold by American automakers (Buick, Cadillac, Chevrolet, Chrysler, Dodge, Fisker, Ford, GMC, Hummer, Jeep, Lincoln, Mercury, Oldsmobile, Pontiac, Saturn, Tesla, and Wheego). Year by Car or Truck FE

Table A.2: Potential Spillover Effects on Other Product Attributes

Dependent variable is the log of each vehicle characteristic in the US market.						
	(1) MPG	(2) Horsepower	(3) Price	(4) Wheelbase	(5) Footprint	(6) Weight
Treated \times Post	0.083 (0.026)	-0.062 (0.045)	0.001 (0.019)	-0.010 (0.007)	-0.001 (0.008)	-0.006 (0.016)
N	9,098	9,134	9,124	9,134	9,134	9,120

Note: This table shows the OLS regression results of equation (1). The dependent variable is the log of each car attribute at the make-model-trim level between model years 2003 and 2019. All regressions are weighted by the average annual sales. Standard errors are clustered at the model level. Panel A includes vehicles sold by Japanese automakers (Honda, Isuzu, Lexus, Mazda, Mitsubishi, Nissan, Subaru, Suzuki, and Toyota). Panel B includes vehicles sold by American automakers (Buick, Cadillac, Chevrolet, Chrysler, Dodge, Fisker, Ford, GMC, Hummer, Jeep, Lincoln, Mercury, Oldsmobile, Pontiac, Saturn, Tesla, and Wheego). Year by Car or Truck FE, Model FE, and Year by Make FE

Table A.3: Difference-in-differences Estimation on Entry, Exit, Net Entry

	(1) Entry Ratio	(2) Exit Ratio	(3) Net Entry Ratio
Treated \times Post	0.063 (0.054)	0.038 (0.056)	0.010 (0.064)
N	32	32	30
Year FE	Yes	Yes	Yes
T-C group FE	Yes	Yes	Yes

Note: For each model-year, we identify product entries and exits to calculate net entry counts. We then compute the entry, exit, and net entry ratios for each group by dividing the respective counts of entry, exit, and net entry by the total number of models in that group for the given year.

Table A.4: Additional Evidence from Other Countries: Global Spillover Effects on Fuel Economy

Panel A: Germany				
	(1)	(2)	(3)	(4)
Treated \times Post	0.083 (0.035)	0.076 (0.031)	0.078 (0.024)	0.076 (0.020)
Treated	-0.263 (0.114)	-0.263 (0.115)		
Post		0.061 (0.022)	0.047 (0.014)	
N	547	547	543	543
Year FE	No	Yes	No	Yes
Model FE	No	No	Yes	Yes

Panel B: India				
	(1)	(2)	(3)	(4)
Treated \times Post	0.173 (0.135)	0.144 (0.142)	0.285 (0.056)	0.272 (0.060)
Treated	-0.016 (0.139)	-0.016 (0.143)		
Post		0.115 (0.123)	-0.006 (0.009)	
N	147	147	145	145
Year FE	No	Yes	No	Yes
Model FE	No	No	Yes	Yes

Note: These tables shows our DID estimation in Equation (1) using data from Germany and India.