The global energy, CO_2 emissions, and economic impact of vehicle fuel economy standards

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Abstract

Fuel economy standards have been recently tightened in the United States and Europe, and have been adopted in Japan, Korea, China, Australia, and Canada. This analysis uses a global computable general equilibrium model to analyze the combined effect of existing national or regional fuel economy standards on global demand for petroleum-based fuels, CO_2 emissions, and welfare. We also examine the impact of more aggressive targets for fuel economy through 2050 for all regions, and compare it to a market-based (cap-and-trade) instrument that achieves identical reductions. We find that while fuel economy standards reduce demand for petroleum-based refined fuels and lead to a net decrease in global CO_2 emissions, the standards are not cost effective in part because they indirectly subsidize the use of these fuels in unconstrained sectors and regions. Refined oil demand even increases in India, Indonesia (Rest of East Asia), and Africa due to lower refined oil prices, as fuel economy standards reduce demand in other parts of the world. Fuel economy standards are also a relatively expensive way of reducing global CO_2 emissions—year-on-year consumption loss reaches 10% in 2050 with fuel economy standards, as opposed to 6% by 2050 with a global cap-and-trade system that achieves comparable total CO_2 reductions. This study underscores how the effects of national and regional fuel economy standards can propagate through global fuels markets to offset petroleum or CO_2 reductions at the global level, as well as lead to surprising outcomes in unconstrained countries or regions.

1 Introduction

Many assume that fuel economy standards are synonymous with reductions in petroleum use and emissions, leading to associated environmental and energy security benefits. Yet fuel economy standards focus on one sector of the economy (motor fuel use in light-duty vehicles) and are implemented at the national or regional level, raising the question of how the combined effect of these policies will propagate through global fuels markets and affect global energy, environmental, and welfare outcomes. Furthermore, fuel economy (or emissions) standards focus on the efficiency (or emissions rate) of fuel use, and do not constrain the quantity of fuel use itself. They also target only new vehicles, potentially overlooking cost-effective opportunities to reduce fuel use in the existing fleet, for instance, through low carbon fuel substitution. Understanding the magnitude of these effects requires models that capture interactions across markets and macro-economic feedbacks to changes in prices. This knowledge is essential to inform cost-effective policy decisions at the national and regional levels aimed at reducing petroleum use and its associated security, health, and environmental externalities.

Many nations have increased the stringency of future fuel economy standards to unprecedented levels within the last decade. The European Union and the United States have enacted some of the toughest standards globally. China, Korea, Canada, India, Japan, and Australia also have fuel economy standards in place. Since fuel economy standards apply only to new vehicles, it can take decades for overall fleet fuel

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efficiency to approach regulated levels. For example, the latest U.S. fuel economy standards, which would raise the combined city-highway test-cycle fuel economy from around 27.5 mpg in 2007 to around 49 mpg in 2025 (combined for cars and light trucks), would be expected to have their largest impact in the period 2025 to 2050. Fuel economy standards have also proven more politically feasible relative to other policy options, although the economics literature finds such approaches to be less cost effective (Goldberg, 1998; Karplus, 2011). New gasoline or diesel taxes, widely considered to be the most cost-effective option, have failed to gain political traction in the United States (Knittel, 2012). Even in Europe, where taxes on refined oil (diesel and gasoline) used in vehicles have ranked among the world's highest since the late 1970s, there has been opposition to increasing the gasoline tax, particularly given the recent economic slowdown (Sterner, 2012). Higher fuel prices have been shown to incentivize consumer purchases of more efficient vehicles, although consumer responses have been shown to vary across regions (Klier and Linn, 2011).

Nevertheless, fuel economy standards are now entrenched in the policy landscape. It is therefore important to consider how both the coverage and stringency of these standards affects energy market and environmental outcomes on a global scale. The cost of advanced technologies in both the automotive and fuels sectors is another relevant source of sensitivity. Understanding the range of potential outcomes under alternative policy and technology cost scenarios, and the role of responses influenced (but not directly targeted) by fuel economy standards, is the objective of this study.

This paper is organized as follows. In Section 2 we review the fuel economy policies enacted in different parts of the world. In Section 3 we develop an illustrative model of a fuel economy standard that characterizes how the constraint leads to reductions in fuel demand (initially in new vehicles and then in the fleet over time), how falling demand feeds back to primary fuel prices, and how reduced fuel prices and higher vehicle fuel efficiency encourage changes in the level of driving by altering the effective fuel cost per mile. In Section 4 we conduct scenario analysis in a computable general equilibrium model to capture global macroeconomic feedbacks to the effects of fuel economy standards adopted in subsets of countries or regions, and identify key sensitivities. Section 5 summarizes the key results and draws conclusions for scholarship and practice.

2 Policy Status

Fuel economy standards have become a mainstay of energy policy in many parts of the world. In the wake of the first oil crisis, a fuel economy standard was implemented in the United States in 1978 after being established by the Energy Policy and Conservation Act of 1975 (United States, 1975; National Research Council, 1992). In Europe the response to oil crises largely involved taxation of petroleum-based fuels. More recently, voluntary or mandatory fuel economy standards have been implemented in several jurisdictions, including Canada, Japan, Korea, Australia, and China (ICCT, 2011). A summary of reductions required by these policies through 2025 is shown in **Figure 1**. So far, fuel economy standards have only been established through 2025 (at the latest). While tighter fuel economy standards may be enacted in the future, we show only announced standards and then extend the final level as a flat line (assuming no loosing or tightening of standard stringency) through 2050.

Countries and regions vary widely in terms of both the starting level of efficiency and reductions required under fuel economy standards (ICCT, 2011). Figure 1 shows a comparison of fleet fuel economy and the targets applied to new vehicles starting in 2010. While the United States for decades had among the highest fuel consumption of any fleet globally, it also has passed or proposed very stringent fuel economy standards that would bring its fleet within the range of Japan in terms of new vehicle fuel economy. In terms of final target fuel consumption, Europe's standards are the most aggressive, reaching 95 grams CO_2 per 100 km, equivalent to fuel consumption of 4.1 liters per 100 km. China has also suggested a relatively aggressive standard for 2020 equivalent to 5.0 liters per 100 km, a significant decrease given that passenger vehicle fuel economy averaged over 11 liters per 100 km in 2005.[1] Japan, Korea, and Canada have established fuel economy targets through 2015, while Australia has a voluntary target in place for 2010. Japan's target is the most stringent, while meeting Korea and Canada's targets will require large decreases in fuel economy from current levels. We report fuel requirements per unit distance traveled as fuel consumption in liters per 100 kilometers, and based on the New European Drive Cycle (NEDC) equivalent for all regions. When

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[1] China has only passed fuel economy standards through 2015. The target for 2020 is very aggressive and not yet finalized, so in this analysis we assume the standards extend through 2015 only.

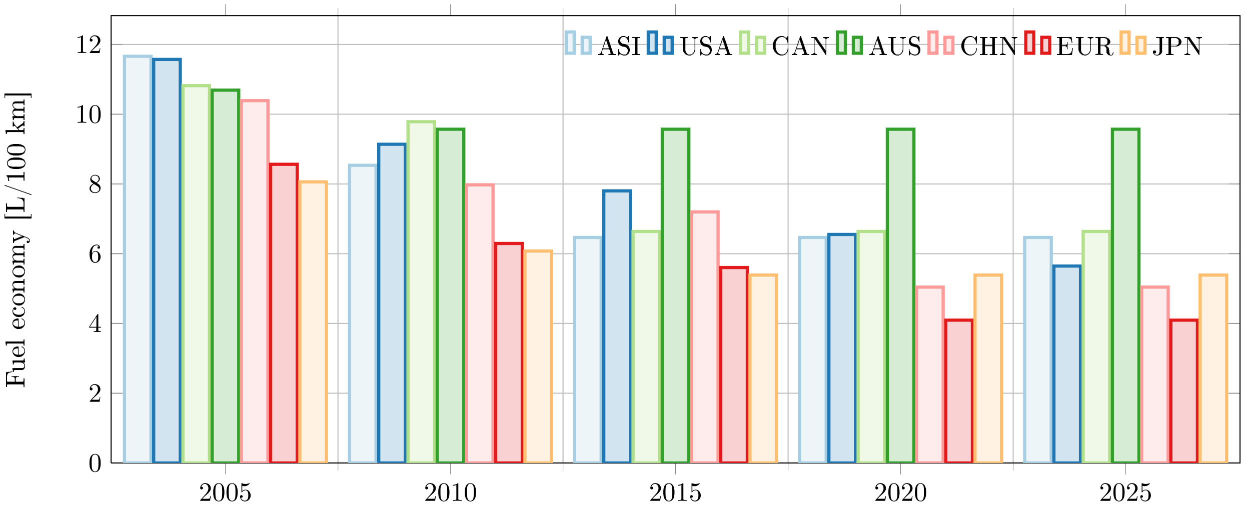

Figure 1: Fuel economy standards for regions with current policies, by year.

targets are stated in terms of grams CO_2 per kilometer, we report them in terms of liters of motor gasoline equivalent per 100 kilometers.

While the impacts of these standards have been evaluated in the course of national or regional government regulatory processes, the estimated reductions in petroleum or greenhouse gas emissions often focus on passenger vehicles only or on countries or regions in isolation, and therefore do not take into account how the broader system would react and the resulting impact on regional or global outcomes. These effects include both changes in passenger vehicle travel demand as well as demand for petroleum-based fuels in other sectors, such as electric power, petrochemicals, or heavy industry. This first response is often called the "rebound effect," as it refers to the tendency for travel demand to increase and erase part of the theoretical reduction in fuel use that would have occurred were it not for the increase in efficiency (Small and Van Dender, 2007; Wang and Zhou, 2012). The second response is sometimes called the "leakage effect," as the drop in fuel prices stimulates demand for the targeted fuel in sectors unconstrained by the policy. We discuss the relevance of each of these effects in Section 3.

In this study, we investigate how fuel economy standards implemented in individual countries or regions interact with economic incentives and affect inter-fuel competition across international borders in a technology-rich, energy-economic, computable general equilibrium (CGE) modeling framework. This framework allows us to capture both the rebound and leakage effects, given that consumer and producer responses to underlying price changes are explicitly modeled. Previous studies of fuel economy standards have measured effectiveness of policy by summing the impact across multiple markets based on vehicle fleet and efficiency technology assumptions (Cheah et al., 2010). Other studies have been focused on the analysis of single markets (Karplus, 2011; Whitefoot et al., 2010; Goldberg, 1998; Bezdek and Wendling, 2005), or on the design response of manufacturers at the vehicle level (Shiau et al., 2009). The focus in this study is on capturing how the economic responses interact with the incentives created by policy to deploy technology, substitute among fuels, or alter vehicle ownership and usage behaviors—responses that can all be captured in a CGE framework.

In this analysis, we do not model fine details of policy design that could loosen stringency in practice, for example, flex-fuel, vehicle electrification- or other advanced technology credits, or the application of standards based on vehicle characteristics, such as engine size, vehicle weight, or vehicle footprint. We also do not consider that manufacturers may have the ability in some regions to bank credits for future use, providing additional compliance flexibility. Many of these features are found in the current fuel economy policies implemented in the U.S. (USEPA, 2010, 2011), China (Oliver et al., 2009), and elsewhere. The variety of these policy features is too great relative to their modest impact to include in this analysis, which sets out to compare current policies on a consistent basis. We recognize that compliance flexibility would lead to lower costs but would also undermine energy and emissions reductions in countries and regions with fuel economy standards, and so we can take our impact estimates as an upper bound on both energy and emissions reductions achieved as well as economic cost by assuming no flexibility.

3 Intuition and Illustrative Model

Since our focus in this work is on quantifying the impact of a fuel economy standard when economic responses are endogenously represented, it is worthwhile to briefly describe the theory that underpins our representation of these responses. We focus on describing both the "rebound effect" i.e. the tendency of consumers to increase usage when the unit energy cost decreases, and the "leakage effect" (i.e. when energy- or carbon-intensive activities rise in sectors or jurisdictions unconstrained by policy in response to changes in relative prices). We illustrate how these effects operate in a simple two-sector model, and discuss its relevance for a multi-region, multi-sector analysis.

We begin with a model of two producing sectors, X and Y, that produce goods or services x and y at prices p_x and p_y, respectively, by employing inputs from suppliers of capital K and energy E at prices p_k and p_e. We further assume that a single representative household spends its income I on a combination of x and y. Let us further assume that a fuel economy standard is imposed on sector X, which requires producers of x to spend proportionally more on k in order to obtain reductions in the per-unit cost of input e. We now consider the implications for p_e when the required quantity of e decreases and the required quantity of k increases. It is straightforward to see how, *ceteris paribus*, a lower p_e would encourage increases in energy demand both within sector X itself (through increased vehicle useage) and in sector Y (as energy is now less expensive as an input). For this exercise we use an illustrative Cobb-Douglas utility function but in our numerical model introduced later on a more flexible functional form has been parameterized using data on the cost and fuel use reduction potential of available technologies. The resulting consumer problem is structued as follows:

$$\max\ U = x^a y^{1-a} \tag{1}$$

$$s.t.\ p_x x + p_y y = I = p_e e + p_k k \tag{2}$$

The production side of the economy can be further represented by the ability to combine k and energy e to produce x and y, as follows:

$$x = F(k_x, e_x) \tag{3}$$

$$y = G(k_y, e_y) \tag{4}$$

Total capital and energy required is simply the sum of that employed in the production of x and y:

$$k = k_x + k_y \tag{5}$$

$$e = e_x + e_y \tag{6}$$

We are interested in what happens to demand for energy when a forced reduction in the ratio of the input e to the output of vehicle services x occurs. A reduction in e, once mandated, requires resource inputs in the form of capital expenditures k to achieve. Depending on the relationship between cost of technology applied and the resulting improvement in energy efficiency, the net impact of these improvements will be to reduce or increase the cost of transport service consumption relative to other types of consumption. The shape of the efficiency technology cost curve is widely estimated to be non-linearly increasing, as ever greater expenditures are required to achieve a fixed incremental energy efficiency improvement using a given technology platform. Energy efficiency improvements are accompanied by a change in miles-traveled which is proportional to the change in cost per mile of driving. While we do not differentiate between fixed and reoccuring costs in our simplified example, we acknowledge that fixed capital plays an important role, which we investigate in our numerical model. Even in this simple structure, however, it is possible to see how efficiency reductions that lower the net cost per mile may lead to offsetting effects on energy use. Lower energy cost will also provide an incentive to increase consumption of y (assuming all income is spent), resulting in energy increases proportional to the energy input share $p_e e/p_y y$. It will also encourage an increase in the consumption of vehicle transport itself. The magnitude and dependency of these effects, the rebound and leakage effects, respectively, are discussed in the following sections.

3.1 The rebound effect

The rebound effect has been widely discussed in literature in the context of measuring the impact of improvements in energy efficiency across a wide range of economic sectors and with respect to particular technologies e.g. fuel efficient vehicles and energy efficient appliances (Small and Van Dender, 2007; Hausman, 1979; Tierney, 2011). In each of its manifestations, the rebound effect is the offsetting effect on energy or emissions reductions achieved due to increased usage that is incentivized by a lower cost of use, which is in turn a function of the mandated increase in efficiency. In our simple model, the relationship between the mandated efficiency increase and distance driven is a function of the energy input expenditure share $\theta_e = p_e e/p_x x$, and the capital expenditure share, $\theta_k = p_k k/p_x x$, and the extent to which k can be substituted for e, which is captured by an elasticity of substitution, σ. Efficiency improvements will then result in a change in the price per mile p_x according to the following relationship:[2]

$$p_x = (\theta_e [p_e]^{1-\sigma} + \theta_k [p_k]^{1-\sigma})^{\frac{1}{1-\sigma}} \tag{7}$$

Depending on the net effect on the price of the vehicle transportaiton service (cost per mile) p_x of the shift away from fuel and towards vehicle capital, demand for vehicle-miles traveled will rise or fall. This model is focused on the long-run response, which assumes consumers are able to update both their decision of which (and how many) vehicles to hold and how many miles to drive in response to the prices of both refined oil and vehicle capital.

In our two-sector model the rebound effect is equivalent to the offsetting increase in energy use in sector X that results from mandated efficiency improvements. To estimate the magnitude of the rebound effect we first consider the reduction in energy use and emissions that would occur in the absence of the rebound effect, e.g. for an initial level of output x how much would changes in the unit cost shares of K and E associated with efficiency improvements reduce the energy demand in sector X. We then consider the impact of these cost changes on the level of output demanded, which depends on the household's preferences across goods x and y. Assuming nonlinearly increasing costs of efficiency capital (consistent with cost estimates reported in USEPA 2010 for advanced vehicle technologies), for small changes in fuel efficiency, the per-mile unit cost of efficiency capital will be offset by the per-mile savings available to the household, while larger efficiency changes have the effect of discouraging vehicle ownership, eventually offsetting the upward pressure on travel demand. This dynamic is reflected in an estimated elasticity of substitution. As long as the lower energy cost component trumps the higher vehicle capital cost component, travel demand will rise; the corresponding change in fuel demand due to the change in travel demand at the new efficiency level is defined as the rebound effect.

Literature estimates of the rebound effect are relatively low, and often expressed as a percentage to indicate the fraction of the (energy) reduction that is offset by the rebound effect. Small and Van Dender (2007) estimate a short-run rebound effect of 4.5% and a long-run rebound effect of 22.2%. More recent work estimates low medium-run rebound effects within this range (Gillingham, 2012). Studies from developing countries are scarce, but a recent study on the rebound effect in urban China suggested that it may be as high as 96%, and the effect was found to decline with increases in per-capita income (Wang and Zhou, 2012).

3.2 The leakage effect

The leakage effect has been investigated in a wide range of contexts and for a vast array of policy designs and targets. In this context we are focused on leakage effects that act through displaced *consumption* rather than displaced *production*. A wide range of literature focuses on displaced production, as regulated industries respond by moving to locations with less stringent environmental controls (see for example Chan et al., 2010). However, leakage can also occur as producers and consumers in uncovered sectors or regions benefit from lower prices caused by policy-induced demand reductions in a covered sector or region. The magnitude of

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[2] All prices in 7 are unit prices.

the leakage effect depends on the relative size of the covered and uncovered sectors, the share of the energy input, and the responses of consumers and producers to changes in the energy component of costs, captured by the elasticity of substitution. The leakage effect ranges widely, depending on the sector or type of policy under consideration.

In our two-sector model, the leakage effect shows up as an increase in demand for fuel in sector Y, relative to the no policy case. Again consumer preferences across goods x and y will be an important determinant of the magnitude of the increase in y as relative input prices change. Depending on the structure of these preferences, it is plausible that a fuel economy standard could even lead to an increase in overall gasoline demand, or at the very least favor a situation in which uncovered sectors invest less in fuel efficiency than they otherwise would have in response to reduced price pressure.

3.3 Rationale for a computable general equilibrium framework

While our simple model illustrates the basic mechanisms that could erode the total reduction in petroleum use or emissions achieved by a fuel economy standard implemented in selective markets, estimating the magnitude of these effects requires a carefully parameterized gloabl energy-economic model. Here we use a CGE framework that can capture both the rebound effects and the leakage effects, based on careful parameterization of the passenger vehicle sector in each region. In our model the richness of the leakage effect is far greater than in our two-sector model, as we are able to capture leakage that occurs across sectors within economies, across regions, and even between new and used passenger vehicles (as lower fuel prices may increase travel in used vehicles, consistent with previous empirical studies). The rebound effect is also captured and based on careful parameterization of the costs associated with vehicle efficiency improvements as well as the contribution of resulting fuel savings given diverse taxation regimes for motor vehicle fuel, as well as heterogeneity in vehicle ownership and travel demand patterns. The model further captures how these two effects interact with each other, and may trade off against each other.

4 Model Developments and Scenarios

4.1 Numerical Model Description

The model used in this analysis is a specialized version of the MIT Emissions Prediction and Policy Analysis (EPPA) model that includes a technology-rich representation of the passenger vehicle transport sector and its substitution with purchased modes, which include aviation, rail, and marine transport. The EPPA model is a recursive-dynamic general equilibrium model of the world economy developed by the Joint Program on the Science and Policy of Global Change at the Massachusetts Institute of Technology (Paltsev et al., 2005). The EPPA model is built using the Global Trade Analysis Project (GTAP) dataset (Hertel, 1997; Dimaranan and McDougall, 2002). For use in the EPPA model, the GTAP dataset is aggregated into 16 regions (**Table 1**) and 24 sectors with several advanced technology sectors that are not explicitly represented in the GTAP data. Additional data for greenhouse gases (carbon dioxide, CO_2; methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF_6) are based on United States Environmental Protection Agency inventory data and projects.

Several features were incorporated into the EPPA model to explicitly represent passenger vehicle transport sector detail. These features include an empirically-based parameterization of the relationship between income growth and demand for vehicle-miles traveled, a representation of fleet turnover, and opportunities for fuel use and emissions abatement. These model developments, which constitute the EPPA5-HTRN version of the model, are described in detail in Karplus (2011).

USA	United States
CAN	Canada
MEX	Mexico
JPN	Japan
ANZ	Australia & New Zealand
EUR	Europe
ROE	Eastern Europe
RUS	Russia Plus
ASI	East Asia
CHN	China
IND	India
BRA	Brazil
AFR	Africa
MES	Middle East
LAM	Latin America
REA	Rest of East Asia

Table 1: Regions in the MIT EPPA model.

4.2 Implementation of the Fuel Economy Standard

We implement a fuel economy standard as a constraint on the fuel allowed per mile of household travel based on *ex ante* usage assumptions (i.e. before any change in miles traveled due to the higher efficiency). This constraint forces the model to simulate adoption of vehicle technologies that achieve the target fuel economy consumption level at the least cost. Opportunities to improve fuel economy in each region are described by a response function that relates cost of technology and abatement potential, which is used to parameterize the elasticity of substitution between fuel and powertrain capital as an input to household vehicle transport. This parameter is estimated separately by region and by technology.

The model then captures how total vehicle-miles traveled (VMT) will then respond when fuel economy has been forced to high levels by the constraint. The form of the utility function, the input shares, and the substitution elasticity between vehicle and powertrain capital determines how much the cost of a mile of travel changes in response to changes in the underlying fuel requirement and vehicle characteristics, which in turn determines the magnitude of the rebound effect. The vehicle fuel economy consumption constraint equation is shown in (8).

$$FES_{t_0} \leq A_t(Q_{f,t_0}/Q_{VMT,t_0}) \tag{8}$$

All future reductions are defined relative to the ratio of fuel, Q_{f,t_0}, to miles-traveled,Q_{VMT,t_0}, in the model benchmark year. Vehicle fuel economy as described in EPPA is based on the actual quantity of energy used and is expressed here as on-road (adjusted) fuel consumption in liters per 100 kilometers (L/100 km). Targets set by policymakers are typically reported in the literature and popular press using unadjusted fuel consumption (or fuel economy) figures. Unadjusted fuel consumption refers to the fuel requirement per unit distance determined in the course of laboratory tests, while adjusted figures reflect actual energy consumption on the road. To obtain adjusted fuel consumption, we divide the unadjusted numbers by 0.8, which is an approximation of the combined effect on-road adjustment factors for city and highway test cycle estimates (USEPA, 2006).

The trajectory A_t is a fraction that defines allowable per-mile fuel consumption relative to its value in the model benchmark year in each future model period. The constraint requires that the on-road fuel consumption realized in each period for new (zero to five-year-old) vehicles remain below the target for that year by requiring investment in energy saving technology, which is a substitute for fuel. For instance a value of $A_t = 0.5$ in 2030 means that fuel consumption relative to the model benchmark year must decline by half. To translate from the model year standard into a constraint consistent with the model's five-year time step, we average the fuel economy requirement across the five most recent model years, weighted by the age-specific contribution of each vintage to vehicle-miles traveled. For example, age-specific miles-traveled per vehicle are reported in Davis et al. (2009) for the United States.

4.3 Scenarios

In this analysis we consider four scenarios to understand the global consequences of national or regional fuel economy policies to reduce petroleum-based fuel use and CO_2 emissions. No fuel economy policy is implemented in our reference scenario, which provides the basis for comparing outcomes of the other three scenarios. We then include a "current policies" scenario in which we consider all regions in which fuel economy mandates have been either proposed or implemented. We then consider a "stringent policies" scenario in which aggressive fuel economy mandates are implemented through 2050, continuing the trajectories established by the current policies scenario. We also include lagged policies in the unconstrained countries that are relatively less stringent as shown in **Table 2**. For the stringent policies scenario, we consider two cost assumptions for the plug-in hybrid electric vehicle (PHEV), a potential low carbon alternative to the internal combustion engine vehicle that runs on both liquid fuel as well as electricity. Finally, we consider a "market-based" instrument that imposes a cap-and-trade regime to constrain CO_2 emissions in each country or region at a level identical to the "stringent policies" case, and allows trading across countries. In all scenarios current biofuels mandates in the United States and Europe are included as well.

Year	USA	CAN	MEX	JPN	ANZ	EUR	ROE	RUS	ASI	CHN	IND	BRA	AFR	MES	LAM
2010	10.5	10.9	14.2	7.4	10.9	7.8	9.8	10.1	9.5	9.8	8.3	9.2	10.0	15.6	13.0
2015	8.9	10.0	14.2	6.8	10.9	7.1	9.8	10.1	8.9	9.1	8.3	9.2	10.0	15.6	13.0
2020	8.0	8.4	14.2	6.2	9.2	5.4	9.8	10.1	7.8	6.7	7.4	9.2	10.0	15.6	13.0
2025	6.8	7.2	11.2	5.7	7.9	4.9	9.8	10.1	6.9	6.0	6.8	9.2	10.0	15.6	12.1
2030	5.9	6.3	9.0	5.2	6.9	4.5	8.1	9.5	6.2	5.5	6.2	9.2	9.0	12.3	9.9
2035	5.1	5.6	7.5	4.9	6.2	4.2	6.8	8.0	5.6	5.0	5.5	7.8	7.5	10.0	8.3
2040	4.5	5.1	6.4	4.5	5.6	3.9	5.9	7.0	5.2	4.6	5.0	6.7	6.5	8.5	7.2
2045	4.0	4.6	5.6	4.2	5.1	3.7	5.2	6.1	4.8	4.3	4.5	5.9	5.7	7.3	6.4
2050	3.7	4.2	5.0	4.0	4.6	3.5	4.7	5.5	4.4	4.0	4.2	5.2	5.0	6.5	5.7

Table 2: Regional constraints under stringent fuel economy standard, in liters per 100 kilometers. REA is not subject to a constraint.

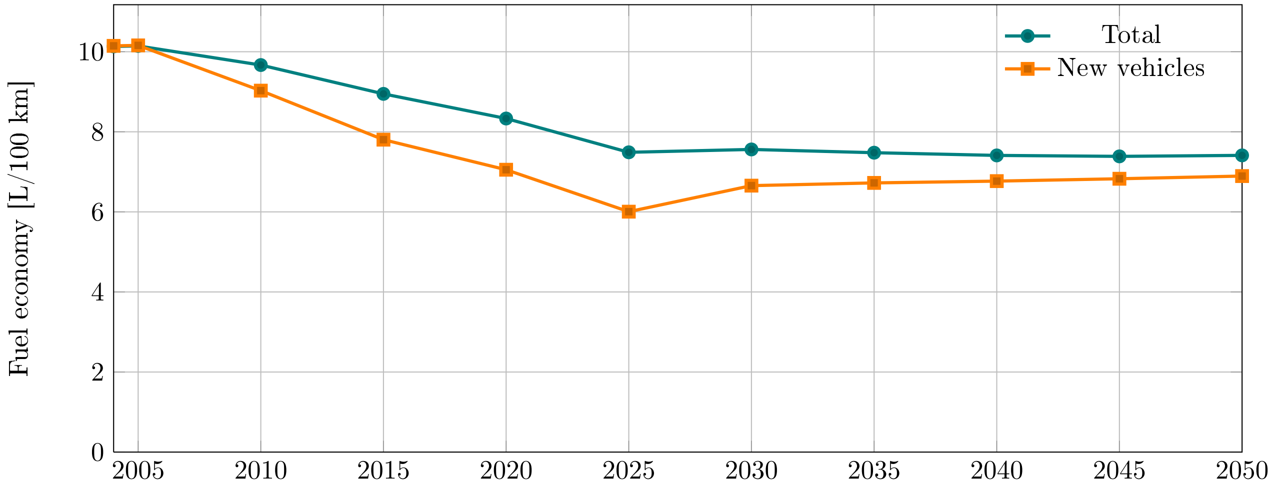

Figure 2: On-road adjusted vehicle fuel economy, by year.

5 Results

We now turn to the results of the scenarios, and focus on several questions. First, we are interested in quantifying the combined impact of the currently-announced fuel economy policies to be implemented at the national or regional level. Second, we are interested in the effects of a stringent fuel economy path applied globally through 2050, and in understanding how this stringent path compares to a cap-and-trade system that achieves the same CO_2 reduction as the fuel economy standards in each nation and region. Finally, we consider sensitivity of our results to the cost of a representative low-carbon vehicle, the PHEV.

5.1 Impact of current policies: Cost-effectiveness and distribution of impacts globally

To illustrate how the fuel economy standard acts upon fuel use in each region, we first show the model forecast for the change in imputed fuel consumption (fuel used divided by distance traveled, in liters per 100 km) of an average on-road vehicle by country or region, focusing on how it changes relative to the reference case. As anticipated, we observe a declining trend in imputed global fuel consumption through 2025 before observing stabilization through 2050, as shown in **Figure 2**. The trajectories shown are the VMT-weighted (on-road) fuel consumption realized across the entire fleet (both newly sold and pre-existing vehicles considered together), as well as for the new vehicles sold in the most recent five years, and includes any associated increases or decreases in distance traveled associated with changes in the fuel- and vehicle-related cost of driving. Since we only model currently announced standards, all standards are assumed to remain constant after 2025 (some level off sooner). As a result, total fleet fuel consumption and new vehicle fleet fuel consumption approach each other as the new vehicles sold gradually enter the on-road vehicle fleet, although as this figure illustrates, the time scales involved are lengthy, up to several decades.[3] These trajectories underscore the long time scales needed for new, more efficient vehicles to enter the vehicle fleet and contribute to changes in fleet-wide fuel use.

5.1.1 Energy and environmental impacts of current policies

We now consider the net effect of current fuel economy policies on energy and environmental outcomes, both globally and by region. We first focus on the change in global refined oil consumption shown in **Figure 3**(a). Under the model assumptions, currently announced fuel economy policy is predicted to reduce total global year-on-year passenger vehicle fuel use by 14% in 2030 and 16% by 2050, shown in gallons of gasoline equivalent. Constrained regions see higher reductions of 21% in 2030 and 25% in 2050, while unconstrained regions experience net reductions as well of 1% in 2030 and 3% in 2050. Unconstrained regions overall experience reductions because the net effect of imposing standards is to raise the vehicle capital cost by requiring the application of more efficient technology. These costs place upward pressure on the price of capital worldwide, which across the unconstrained regions as a whole is not offset by reductions in the cost per mile of travel. The total global reduction in motor vehicle fuel demand does not change very much between 2030 and 2050, and the change is mainly due to an unchanging policy targets against the backdrop of continually rising baseline demand.[4] Most of the demand reduction occurs in the OECD (accounting for 55% of total global petroleum-based fuel reduction) as a result of policies in the United States, Europe, Japan, and Canada, while most of the remainder comes from China, which is expected to see growth in demand for vehicles and vehicle travel through 2030 (though trends in China are a major source of uncertainty). In almost every region there is a net negative effect on vehicle travel as households reduce investment in new vehicles (in response to the increased cost of purchasing a more efficient vehicle), despite an incentive to drive more, *ceteris paribus*, due to increased efficiency.

We also find that the leakage effect is important in two ways: both in terms of leakage to other sectors that use refined oil, as demand reduction places downward pressure on prices, and in terms of leakage to unconstrained regions. **Figure 3**(b) shows how constrained regions reduce demand while the response in unconstrained regions is mixed. Some unconstrained regions, such as in India, Africa, and the Rest of East Asia (which includes populous Indonesia), see increases in fuel use as downward pressure on fuel prices encourages greater vehicle use and lessens the burden on private households.[5] The benefits are concentrated in countries where private vehicle ownership is still a limited part of overall household consumption. The implications of these concentrated increases in fuel use are interesting given that a fuel economy standard is not sold as a fuel subsidy to developing nations.

Turning to CO_2 emissions, we observe that emissions reductions are relatively modest and are not proportional to reductions in refined oil. Total global CO_2 emissions are shown in **Table 3**, and represent reductions of 7.8% relative to global levels in the reference case. Potential reductions due to the displacement of petroleum-based fuels are offset by increases in other carbon-rich primary energy sources in unconstrained sectors and regions, any increases in vehicle travel due to the reduced cost per mile (a result of both higher vehicle efficiency and reduced fuel cost), and the adoption of plug-in hybrid electric vehicles (which run on electricity and raise its associated carbon footprint). In short, total CO_2 emissions suggest that when viewed in global perspective, the net effect on global CO_2 emissions is fairly modest and is much less effective at reducing carbon emissions (which act globally) than it is at reducing national or regional fuel demand. We consider the cost effectiveness of achieving these reductions in the next section.

To gather a more complete picture of how fuel economy standards affect on-road vehicle efficiency and the motor fuel market, we also report the realized new vehicle fuel consumption (in L/100 km) by country and region in **Table 3**. In the case of passenger vehicle fuel use, we find that in some regions actually increase their use of refined oil, including Africa, Rest of East Asia (including Indonesia), and India. While small in

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[3] The on-road fuel efficiency realized by the new and used vehicle fleets, which is imputed by dividing miles traveled into quantity of fuel consumed, is unlikely to fully converge in the long run because wear on used vehicles will slightly erode efficiencies and new (relatively more efficient) vehicles are used more relative to used vehicles, keeping the realized efficiency (measured as fuel consumption) for new vehicles below that of used vehicles.

[4] Motor vehicle fuel demand in this case includes a small percentage of biofuels representing the effects of current biofuels mandates in the United States and Europe.

[5] The aggregate impact on the unconstrained regions is still negative, with an approximately 3% decrease in passenger vehicle fuel use relative to the reference case.

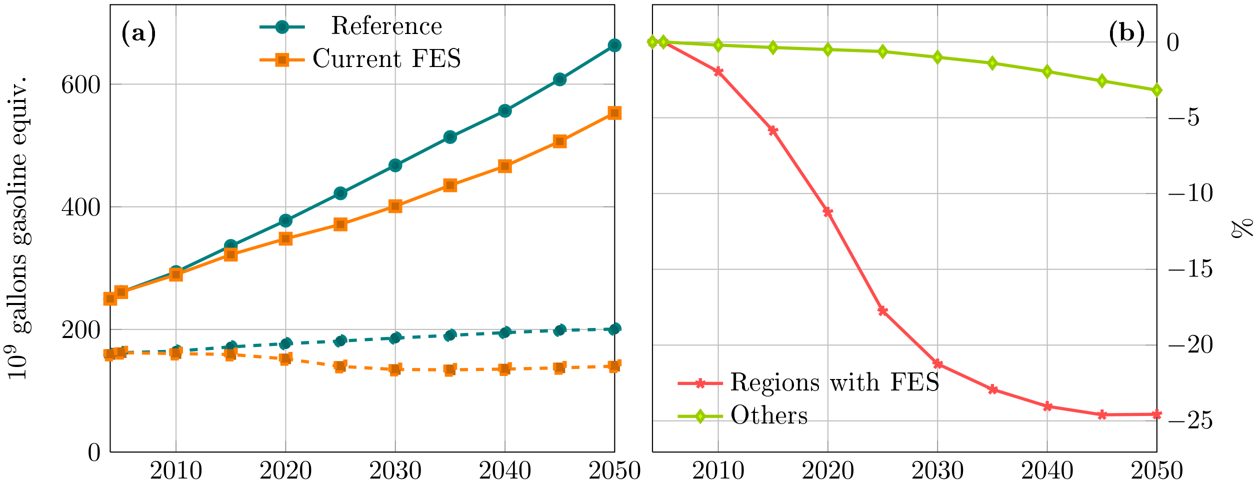

Figure 3: Refined oil use by household vehicles under reference scenario and current FES: OECD (dotted) and global total (a); and percentage change due to policy (b).

Year	LAM	EUR	USA	JPN	ROE	CHN	ANZ	AFR	MES	IND	RUS	ASI	REA	MEX	BRA	CAN	Global
Refined oil use [EJ]																	
2010	87.5	6.8	7.8	12.8	4.3	49.2	2.7	8.1	18.5	28.7	18.5	8.6	13.0	8.7	11.9	2.3	289.4
2030	72.0	7.6	12.7	12.8	5.3	37.0	3.6	11.1	22.8	83.3	58.3	14.3	19.7	15.4	19.9	5.2	401.0
2050	74.4	8.5	20.1	12.6	6.2	38.4	4.2	12.2	25.7	148.7	92.4	18.7	31.5	21.5	29.0	8.9	553.0
Decrease in refined oil use, relative to reference [%]																	
2010	2.4	0.3	0.4	0.9	0.5	3.1	1.1	0.5	0.9	0.2	−0.1	0.3	−0.1	0.3	0.4	−0.4	1.5
2030	30.7	4.9	1.2	7.0	1.7	32.7	5.0	2.7	17.2	9.7	0.3	2.0	−0.6	1.3	2.4	−1.2	14.2
2050	36.3	5.5	1.5	4.6	2.4	30.5	6.9	5.3	29.0	17.5	4.6	3.8	−1.2	2.1	4.5	−1.6	16.6
On-road adjusted fuel economy, private vehicles [L/100 km]																	
2010	11.0	10.7	14.2	7.6	10.6	8.1	9.7	10.0	10.8	9.9	8.3	9.2	10.0	15.4	13.0	10.8	9.7
2030	6.9	8.3	14.1	6.5	10.1	4.9	8.8	9.6	8.0	8.7	8.3	9.0	9.6	14.0	12.7	10.2	7.6
2050	6.3	7.9	14.0	6.4	9.8	4.8	8.2	9.2	7.2	8.1	8.0	8.7	9.3	13.0	12.4	9.7	7.4
On-road adjusted fuel economy, private vehicles [miles/gallon]																	
2010	21.3	22.0	16.6	30.8	22.2	29.2	24.2	23.5	21.9	23.8	28.2	25.5	23.5	15.3	18.1	21.8	24.3
2030	33.9	28.5	16.7	36.4	23.3	48.0	26.7	24.6	29.3	27.2	28.3	26.1	24.5	16.8	18.5	23.1	31.1
2050	37.3	29.8	16.8	36.5	24.1	49.2	28.6	25.5	32.7	29.2	29.5	26.9	25.3	18.1	18.9	24.4	31.7
CO_2 emissions due to fossil fuel use [Pg]																	
2010	5.6	0.6	0.4	1.3	0.4	3.9	1.1	1.5	2.4	7.8	1.8	1.2	1.1	1.7	0.9	0.6	32.3
2030	6.0	0.7	0.5	1.3	0.5	4.0	1.7	1.4	2.8	13.7	4.7	1.1	1.4	2.3	1.1	1.1	44.3
2050	7.8	0.9	0.8	1.4	0.6	5.0	2.0	1.5	2.6	15.4	6.7	1.2	1.9	2.7	1.4	1.7	53.5
Decrease in consumption, relative to reference [%]																	
2010	0.4	0.7	0.4	0.8	0.7	1.5	1.1	0.9	0.4	0.1	0.2	0.6	0.1	0.4	0.6	−0.1	0.8
2030	2.8	3.8	1.9	4.2	3.9	8.3	6.4	5.0	2.7	0.6	1.2	3.4	0.4	2.3	3.6	−0.2	3.7
2050	4.8	6.7	2.6	7.5	6.8	13.3	12.0	9.7	5.4	1.6	3.0	6.8	0.4	3.9	7.1	−0.1	5.9

Table 3: Summary of projections under current policies establishing fuel economy standards.

percentage terms, these increases could be significant for households in these developing regions, as fuel for everyday uses more affordable.

5.1.2 Economic impacts

We also report the forecast consumption loss due to current fuel economy policies in all countries and regions in **Table 3**. We find that on balance that consumption is reduced in every region except for the Rest of East Asia, where consumption actually increases by 0.1 to 0.2%. Europe is hardest hit by the new standards (a 13% consumption loss by 2050), as vehicles in many European Union countries are already starting from a very efficient level, and incremental improvements increase non-linearly with standard aggressiveness (a parameterization based on engineering-cost estimates). The United States experiences a decrease in consumption of 4.8% in 2050, while other constrained regions also experience consumption loss in the range of 5 to 7%. Total global consumption loss reaches 6% assuming current policies. The reason for the slight increase in consumption in the Rest of East Asia region is that consumers in this region benefit from reduced refined oil prices. These benefits are not swamped by the effects of increasing capital prices, as they are in Africa, India, and other unconstrained regions, because Rest of East Asia is relatively less capital intensive. Domestic oil prices are lower by 5 to 15% by 2050 in all regions, not just regions constrained by the fuel economy standard.

The fact that regions that increased fuel use did not experience commensurate consumption gains suggests that they may have been negatively affected at the same time due to changes in the prices of other fuels that are embodied in major household consumption items, for instance, heating and cooking fuel. Exceptions to this trend include the regions in which fuel use increased—India, Rest of East Asia, and Africa. In fact, in percentage terms, these losses are also high in unconstrained countries and regions, driven primarily by the burden of higher vehicle capital costs and the terms-of-trade effects caused by reductions in consumption in covered regions.

5.2 Achieving a stringent FES policy through a cap-and-trade system on CO_2 emissions

Today, many countries have implemented fuel economy standards, while market-based instruments for addressing energy and climate challenges have gained far less political traction. Only the European Union has a full-fledged emissions trading system, and market-based policy proposals (for taxes or cap-and-trade systems) have faced intense opposition in many other countries. An important question is how fuel economy standards compare to market-based instruments in terms of their ability to address energy- and climate-related goals, and at what cost they do so. We now consider how achieving fuel use and CO_2 emissions reductions through a stringent fuel economy standard compares to an alternative market-based policy instrument.

For our market-based policy, we design a cap-and-trade system for CO_2 that targets an emissions reduction equivalent to that achieved under the stringent fuel economy standard and allows global permit trading across regions. It does not explicitly constrain motor vehicle fuel use, but instead requires that reductions be met with the least cost solutions available, which are deployed over time in order of increasing cost to comply with the emissions cap. The sectoral contribution to total reductions will differ across regions because of differences in resource costs, household consumption patterns, and production technology.

We first consider the impact that each of the two policies has on global refined oil use in constrained and unconstrained regions. We find that passenger vehicle fuel use falls far more under a fuel economy standards than under a cap-and-trade system, as shown in **Figure 4**. Under a cap-and-trade system, passenger vehicle fuel use falls by only 6% in 2050, relative to the stringent fuel economy policy which reduces fuel demand by 47% in 2050. These different response patterns indicate that improving passenger vehicle fuel economy is not the most cost-effective way to reduce CO_2 emissions relative to opportunities in other sectors. This is not surprising, given that changing vehicle technology is often cited as one of the most expensive opportunities to reduce energy use and CO_2 emissions in both developed and developing economies. Investments in improving the efficiency of electricity generation and industrial processes yield significantly more emissions reduction bang for (inflation-adjusted taxpayer) buck.

It is further interesting to consider the contribution of different countries and regions to the total reduction under a stringent fuel economy policy, in which all regions face fuel economy constraints of varying stringency.

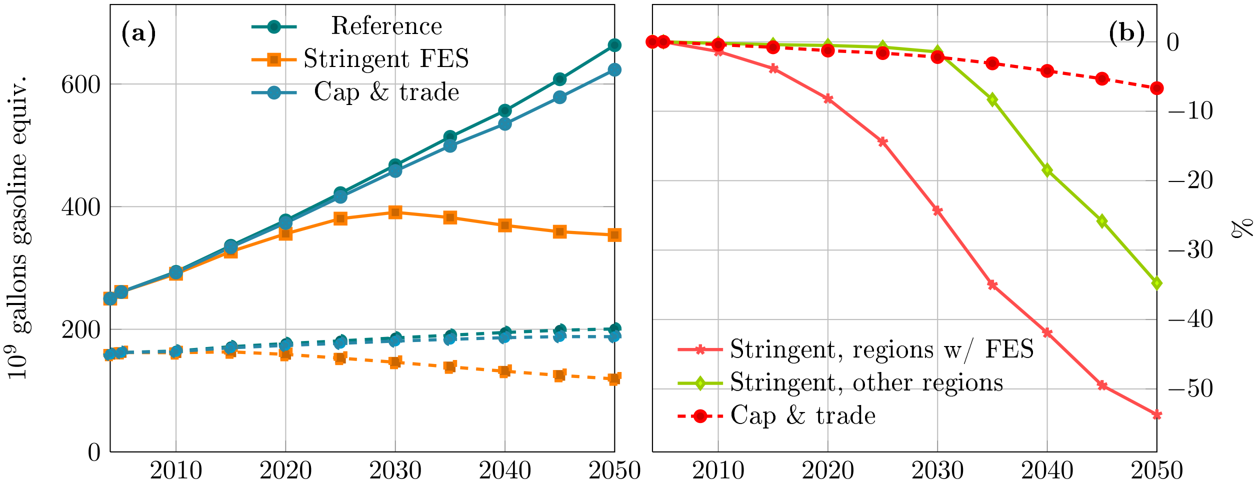

Figure 4: Refined oil use by household vehicles under reference scenario, stringent FES and equivalent cap & trade: OECD (dotted) and global total (a); and percentage change due to policy (b).

Under the stringent fuel economy policy, the OECD experiences a reduction of around 60% of passenger vehicle fuel demand relative to the reference case in 2050, but this accounts for only 26% of the 2050 reduction, while other regions, particularly developing regions which are also constrained, account for the largest share of the reduction.

The change in the primary energy mix (relative to reference, not shown) underscores the divergence in the types of actions each of these policies incentivize. A cap-and-trade system incentivizes changes that lead to greater utilization of low carbon fuel sources, displacing primarily coal and gas with a more modest contribution from oil, while a fuel economy standard relies primarily on a sharp reduction in oil. As shown in **Figure 5**, a fuel economy standard provides no incentive otherwise to switch to low carbon primary fuels (particularly away from coal, which has a higher carbon content than oil). On the other hand, the cap-and-trade system penalizes (or encourages) all primary energy sources according to their embodied CO_2 (or lack thereof). Interestingly, natural gas continues to play an important role under a fuel economy standard, while an cap-and-trade system would penalize natural gas alongside coal because of its carbon content. Total primary energy use is reduced by 6.4% under the under the cap-and-trade policy, which is lower than the -9.6% change under a fuel economy standard. This reduction follows in both cases as a result of costs of complying with the policy, which increase the underlying costs of production, resulting in reductions in consumption and associated energy demand.

How much does achieving an identical energy and emissions target through these two policies alternatives cost? Under global fuel economy policy, we find that global consumption loss is about 75% higher by 2050 than loss under an equivalent cap-and-trade policy (measured as equivalent variation relative to the reference case in 2004 USD). Global consumption loss for both cases is shown in **Figure 6**. In 2050, global consumption loss accounts for just under 6% in the cap-and-trade case, while for the fuel economy standard it exceeds 10%.[6]

5.3 The role of advanced technologies

Finally, we consider how sensitive our results are to the assumption about the cost of an advanced low carbon vehicle alternative, the plug-in hybrid electric vehicle (PHEV), which is capable of running on both gasoline and electricity. All cases considered above include a PHEV with a markup of 40% ("high cost")

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[6] The consumption loss under a cap-and-trade system is sensitive to assumptions about the existence of a global market for emissions trading (allowing the equalization of marginal cost across national borders), as well as assumptions about which sectors and greenhouse gases are covered under the cap. In this case, we allow global trading, but in a sensitivity case that prevents trading we find only slight increases in global consumption loss (not shown), and so we do not focus on it here. By contrast, a policy that includes more sectors or gases than the policy we have modeled would result in equal or reduced consumption loss, making it even more attractive relative to a fuel economy policy as an emissions reduction strategy.

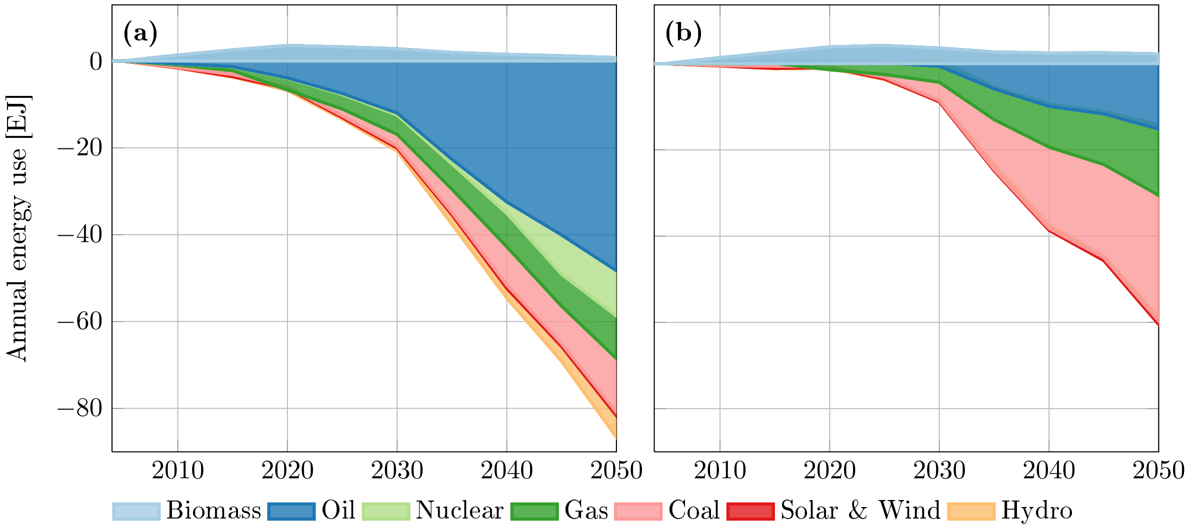

Figure 5: Change in primary energy use relative to reference, for stringent FES (a) and equivalent cap & trade (b), by year.

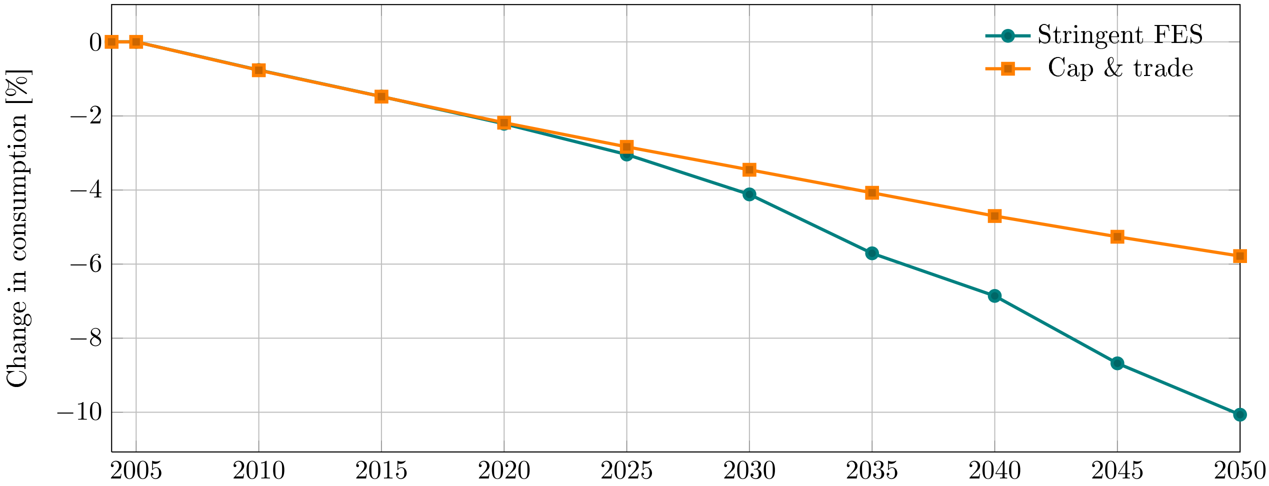

Figure 6: Percentage change in consumption relative to reference case, for stringent FES and equivalent cap & trade, by year.

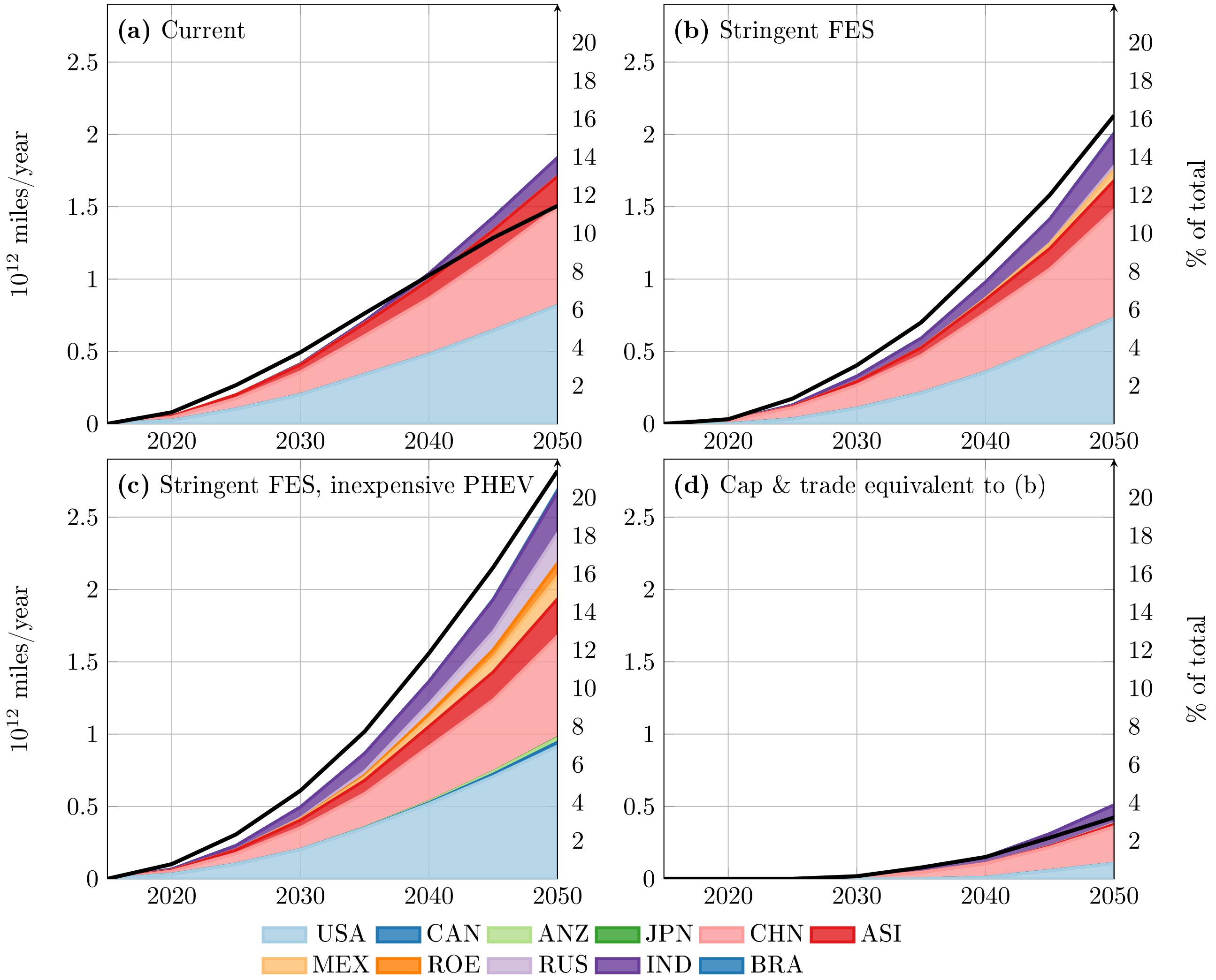

Figure 7: VMT for PHEVs under four policies by region and year; and total PHEV VMT as percentage of global total VMT (solid line). Only regions with PHEV adoption are shown; others are omitted—see 5.3 on the next page.

relative to a comparable internal combustion engine-only (ICE-only) vehicle, with an additional constraint on early adoption to reflect constraints on manufacturing capacity and market acceptance in the first years that it becomes available. Here we compare the stringent case with a high cost PHEV to a scenario where the incremental PHEV markup is only 20% ("low cost"). We assume the PHEV is available in all regions affected by the fuel economy constraint. Fleet turnover further limits PHEV uptake to newly sold vehicles added to the fleet in each model period. Today, PHEVs are still in the early stages of development, and to date only very few PHEVs have been sold to private households. We consider the effect of PHEV cost on the contribution of PHEVs to global VMT, as shown in **Figure 7**. We also report PHEV VMT as a percentage of the global total in all policy scenarios.

- In **Figure 7** the left-hand axis in each graph shows total miles-traveled in PHEVs by region, while the right-hand axis shows the percentage of total global passenger vehicle miles-traveled. The results indicate that under a fuel economy standard, the level of PHEV adoption is not very sensitive to the cost of a PHEV. In both scenarios, China and the U.S. are the major PHEV adopting nations (accounting for 31% and 22% of miles-traveled in passenger vehicles in each country, respectively, for the high-cost case; 30% and 29% for the low-cost case), while Industrializing East Asia, Rest of Europe, Russia, and India account for smaller slices of miles-traveled in PHEVs globally.

Of note is the fact that PHEVs do not enter the passenger vehicle market in Europe, even in the low cost scenario, despite the relatively high tax-inclusive price of petroleum-based transportation fuel. A likely reason is that these vehicles are not cost-competitive given Europe's highly efficient diesel vehicles and potential to realize additional reductions through further engine downsizing and turbo-charging in gasoline powered ICE-only vehicles. This results is sensitive to assumptions about future reductions in the cost of advanced technologies for both the PHEV and ICE-only vehicle platforms.

For comparison, we also show the "current policy" scenario considered earlier, which indicates that like the "stringent policy" scenario, it too incentivizes substantial PHEV adoption in the U.S. and China but differs in that adoption starts earlier (as the current policies case is slightly more stringent in the early years). Earlier adoption helps to overcome initial adoption barriers sooner, but a constant fuel consumption constraint in the periods after 2025 reduces the pressure to adopt PHEVs slightly relative to the stringent standard case. We further compare the three fuel economy standard scenarios to the cap-and-trade policy (which achieves reductions equivalent to the stringent fuel economy case with an expensive PHEV), and find that PHEV adoption is significantly lower (accounting for only 4% of miles-traveled globally by 2050), suggesting that the PHEV represents a relatively expensive strategy for reducing CO_2 emissions.

6 Conclusions

Although fuel economy standards are implemented at the national or regional level, this analysis illustrates the importance of understanding how they will interact to affect energy, CO2 emissions, and economic outcomes on a global scale. Our modeling framework allows us to explicitly consider the role of global capital and fuels markets, trade linkages, and the preferences of diverse populations. As a result our analysis captures the combined effect of the "rebound effect" (within the market for new private vehicles) and the "leakage effect" (in the pre-existing vehicle fleet, across sectors within a single nation or region, and across national borders). The results we report demonstrate the how these effects operate in tandem through an illustrative set of policy scenarios that consider the impact of today's policies and explore the prudence of pursing fuel economy standards as a carbon reduction policy over the longer term.

Our model results suggest that at the global level, a fuel economy standard serves energy policy goals far better than long-term global climate change mitigation objectives. A fuel economy standard is effective at reducing petroleum demand (e.g. it is not swamped by the rebound or leakage effects). Reductions in demand for petroleum as well as other fuels are further facilitated by the drag that a fuel economy standard places on the economy, as capital costs rise in the wake of increased demand to achieve vehicle efficiency improvements even as new, more efficient vehicles realize lower costs of travel per unit distance. Assuming current policies, we find that in 2050 global passenger vehicle refined oil use is reduced by 16%, global CO_2 emissions fall by just under 8%, and global consumption falls by around 6%. A more stringent fuel economy standard reduces global passenger vehicle refined oil use by 46% and at a cost equal to 10% of reference consumption. A cap-and-trade system that achieves an equivalent reduction in CO_2 emissions in each country or region incurs a consumption loss of around 6%, although it only reduces passenger vehicle refined oil use by 6% relative to the reference case. The reason is that a cap-and-trade system incentivizes the most cost effective reductions across the economy as a whole, which involve only very modest reductions in refined oil use in passenger vehicle transportation. Since reductions in passenger vehicle petroleum demand may be sought for energy security reasons, a cap-and-trade system may not be sufficient to achieve national objectives. However, it is worth considering alternative policy designs (such as fuel taxes) targeted at this energy policy goal, which have been shown to be more cost effective in previous econometric and modeling analyses (Karplus, 2011; Goldberg, 1998).

Also noteworthy are the regional impacts of fuel economy policies, which are uneven. In terms of refined oil demand, currently-announced fuel economy standards result in significant reductions in China as well as other constrained regions. China will be an interesting case to consider further because of the continued (albeit uncertain) growth expected to take place in its vehicle fleet over same period, as personal mobility demand rises with income and economic opportunity. On balance, unconstrained regions experience a decline in refined oil demand but a few countries and regions (India, Rest of East Asia, and Africa) see increases. Interestingly, the effects on unconstrained regions may be of importance to the policy debate, as they could introduce the angle of whether fuel economy standards will drag down or boost development prospects in localities far from markets directly constrained by the standards. Consumption loss is likewise highly variable across regions, but is highest in Europe, where the vehicle fleet has already reached very efficient levels, requiring broad adoption of costly advanced technology.

Our results further suggest that under a fuel economy standard, cost may not matter as much when it comes to determining PHEV adoption. Previous studies that have looked at how cost affects PHEV uptake under a cap-and-trade system have observed that PHEV cost is one of the most sensitive parameters (Karplus et al., 2010). However, a fuel economy standard operates differently. It incentivizes the lowest cost solutions from a much smaller solution pool—those that are capable of reducing passenger vehicle use per distance traveled. Defining the policy target in this way forecloses many technological and behavioral strategies that would otherwise reduce petroleum consumption and CO_2 emissions. Many of these unavailable strategies may be more cost effective in terms of one or both goals. Since a PHEV is one among fewer available strategies, changing its assumed cost may not substantially affect its adoption, as long as it is not partially or wholly displaced by an alternative, more cost-effective strategy for reducing vehicle fuel consumption. A fuel economy standard is perhaps a good way to create favorable market conditions for PHEVs. Beyond that, it falls short as a cost-effective strategy for mitigating global climate change.

Taken together, our results suggest that currently planned fuel economy standards may be quite costly on a global scale, will have much more limited impact on CO_2, and could drag down the economies of both implementing and non-participating nations and regions. Nevertheless, fuel economy standards continue to be successfully sold as way to tackle the energy and environmental externalities of road transport. One selling point is the claim that reducing fuel consumption will ensure a future of lower gasoline prices. Indeed this claim seems to bear out in our analysis, in which all nations realize a price reduction of 5 to 15% by 2050. The fact that lower fuel prices are masking the true high costs of the fuel economy standards, relative to alternative policy measures, may be easily overlooked. The costs of fuel economy standards may in fact be very high in economies that have enacted tough standards through political consensus. However, these policies will also have costs and other ramifications far beyond national borders that deserve greater consideration in the policy process.

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