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The Global Energy, CO_2 Emissions, and Economic Impact of Vehicle Fuel Economy Standards

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The Global Energy, CO_2 Emissions, and Economic Impact of Vehicle Fuel Economy Standards

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Abstract

Fuel economy standards for new light-duty passenger vehicles have recently been adopted or tightened in many nations. Using a global computable general equilibrium (CGE) model, we analyse the combined effect of existing and accelerated national and regional fuel economy standards on demand for petroleum-based fuels, CO_2 emissions, and economic cost, and compare the results to a carbon pricing scenario with identical emissions reductions. We find that fuel economy standards are less cost-effective than a carbon price, with year-on-year consumption loss rising to 10 per cent of global GDP in 2050 under fuel economy standards, compared with 6 per cent under carbon pricing.

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1.0 Introduction

Fuel economy standards have been adopted in many countries and regions as a strategy to reduce petroleum use, and, more recently, CO_2 emissions. 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, with little attention to how the combined effect of these policies will propagate through global fuel markets, and affect energy, environmental, and economic outcomes. Fuel economy (or emissions) standards target reductions in the fuel use or emissions per unit of distance travelled, and do not constrain the total quantity of fuel consumed. These standards typically apply only to new vehicles, potentially overlooking cost-effective opportunities to reduce fuel use in the existing fleet; for instance, through low-carbon fuel substitution or mileage conservation. This analysis investigates the global impact of fuel economy standards in a model that captures regional heterogeneity in passenger vehicle ownership and use, the technological and demand response to input price changes, and inter-market interactions. This framework allows us to analyse the magnitude and sensitivity of two important and potentially offsetting influences — the rebound and leakage effects.

Many nations have increased the stringency of vehicle 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. The latest US fuel economy standards would raise the combined city–highway test-cycle fuel economy from around 27.5 mpg in 2007 to around 54.5 mpg in 2025 (combined for cars and light trucks). China, Korea, Canada, India, Japan, and Australia also have fuel economy standards in place. These standards raise the overall fuel economy of the vehicle fleet gradually as new vehicles are introduced and old vehicles are retired. However, regulatory processes that assess the energy, emissions, and economic impacts of these fuel economy programmes typically rely on vehicle fleet and technology models that do not capture broader macroeconomic and global impacts. Regulatory impact assessments in the USA (EPA, 2012a, 2012b) focus on the new vehicle fleet, and do not assess impacts on fleet turnover, on non-transport sectors, or on global oil price and quantity demanded. In the European Union, EUCLIMIT, an economy-wide model for Europe, is used with broad sectoral coverage and fleet dynamics; however, international variables are still assumed to be exogenous (Eur-Lex, 2012). Given the scale of vehicle energy use and the stringency of announced fuel economy standards, the future impact of these policies on global energy markets and prices could be large.

Fuel economy standards have proven more politically feasible relative to other policy options, although the economics literature has found such approaches to be relatively costly.[1] New gasoline or diesel taxes, widely considered to be the most cost-effective option for displacing petroleum-based fuel use, have failed to gain political traction in the USA (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

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[1] There is wide variation in estimated costs of fuel economy standards. Studies that assume automakers actually realise improvements in fleet-wide fuel efficiency find high costs (Goldberg, 1998). In many cases, automakers exploit sources of compliance flexibility or pay non-compliance penalties. Anderson and Sallee (2010) find much lower costs of compliance when automakers exploit flex-fuel vehicle credits.

been opposition to increasing the gasoline tax, particularly given the recent economic slowdown (Sterner, 2012). Higher fuel prices have been shown to incentivise consumer purchases of more efficient vehicles, although consumer responses have been shown to vary across regions (Klier and Linn, 2011).

Despite ongoing debate over their cost and effectiveness, 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, as well as the ability for manufacturers to trade off across existing vehicle attributes, are important sources of sensitivity. Understanding potential outcomes under alternative policy and technology cost scenarios, and the implications of indirect responses to changes in underlying prices, is the objective of this study. In quantifying economic impacts, we focus on comparing the costs of policies designed to achieve a given outcome.

This paper is organised 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 characterises how the policy constraint leads to reductions in fuel demand, 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 in covered and uncovered regions by altering the effective fuel cost per mile. In Section 4 we implement a scenario analysis in a CGE model to study the effects of fuel economy standards adopted in subsets of countries or regions. Section 5 summarises the results and conclusions.

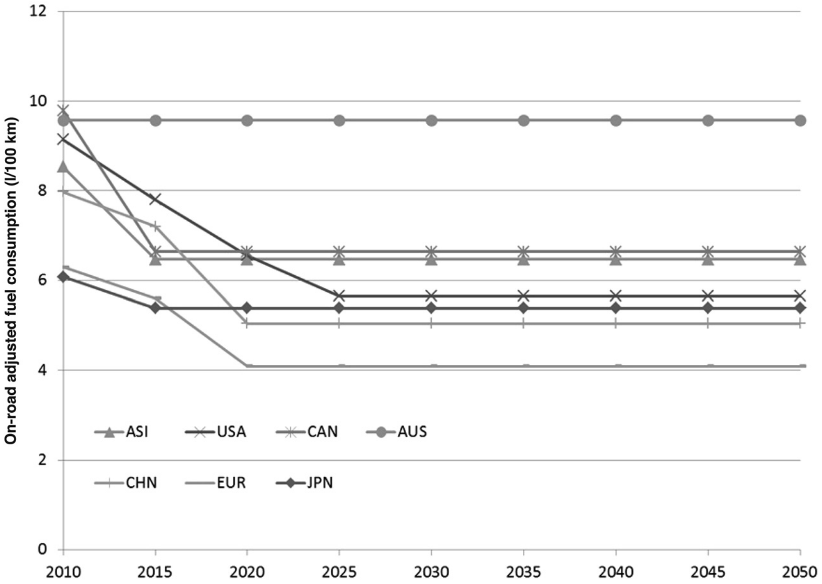
2.0 Policy Status

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 USA in 1978 after being established by the Energy Policy and Conservation Act of 1975 (EPCA, 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 to 2025 is shown in Figure 1. So far, fuel economy standards have only been established to 2025 (at the latest). While tighter fuel economy standards may be enacted in the future, Figure 1 shows only announced standards, extending the final level as a flat line (assuming no loosening or tightening of standard stringency) to 2050.

Countries and regions vary widely in terms of both their starting level of efficiency and reductions required under fuel economy standards (ICCT, 2011). While the USA for decades had among the highest fuel consumption of any fleet globally, recently passed (and proposed) fuel economy standards would bring its new vehicle fuel economy within the range of Japan's later in the century. In terms of the final target for fuel consumption, Europe's standards are the most aggressive, reaching 95 grams CO_2 per 100 km, equivalent to fuel consumption of 4.1 l per 100 km (57 mpg). China has also suggested a relatively aggressive standard for 2020, equivalent to 5 l per 100 km (47 mpg) — a significant decrease, given that passenger vehicle fuel economy averaged over 11 l per 100 km in

Figure 1

Fuel Economy Standards for Regions with Current Policies, by Year, Extended to 2050



2005 (21 mpg).[2] Japan, Korea, and Canada have established fuel economy targets to 2015, while Australia adopted a voluntary target starting from 2010. Japan's target is the most stringent, while meeting Korea (part of ASI in Figure 1) and Canada's targets will require large decreases in fuel economy from current levels. We report fuel requirements per unit distance travelled as fuel consumption in litres per 100 km, based on the New European Drive Cycle (NEDC) equivalent for all regions. When targets are stated in terms of grams CO_2 per kilometre, we convert them to litres of motor gasoline equivalent per 100 km using fuel carbon content.

National or regional government regulatory processes typically estimate the fuel use or emissions impacts at the regional or sector level, and do not consider the aggregate effects of adopting standards within and across adopting markets in response to changes in relative fuel prices. 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. The first response is often called the rebound effect, as it refers to the tendency for travel demand to increase in response to an efficiency-induced reduction in the marginal cost of driving (Small and Van Dender, 2007). The second response is the leakage effect, which occurs when a 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.

Previous studies of fuel economy standards have measured effectiveness of policy by summing the impact across multiple markets based on vehicle fleet and efficiency

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

technology assumptions (Cheah *et al.*, 2010). Other studies have been focused on the analysis of single markets (Goldberg, 1998; Bezdek and Wendling, 2005; Whitefoot *et al.*, 2010; Karplus and Paltser, 2013a), or on the design response of manufacturers at the vehicle level (Shiau *et al.*, 2009). Several recent studies have focused on the interaction between state and federal regulations in the USA, and quantify leakage across regions with standards of different stringency (Caron *et al.*, 2012; Goulder *et al.*, 2012). 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 behaviours — responses that are captured in our modelling framework. In this analysis, we do not model several policy design features 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. Many of these features are found in the current fuel economy policies implemented in the USA (EPA, 2012a), China (Oliver *et al.*, 2009), and elsewhere, but vary across regions in the details of their implementation.

3.0 Intuition and Illustrative Model

Since our focus in this work is on quantifying the global impact of a fuel economy standard when economic responses are endogenously represented, it is worthwhile to describe briefly the theory that underpins our representation of these responses. We focus on describing both the rebound effect (the tendency of consumers to increase usage when the marginal unit energy cost decreases) and the leakage effect (when energy- or carbon-intensive activities rise in sectors or regions 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 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 goods x and y, where x is passenger vehicle transportation services and y is a composite good representing non-transport consumption. Let us further assume that a fuel economy standard is imposed, requiring 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 parameterised using data on the cost and fuel use reduction potential of available technologies. The resulting consumer problem is structured as follows:

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

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

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 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. Achieving the mandated reduction in e requires resource inputs in the form of capital expenditures k to achieve. Depending on the relationship between cost of technology applied, and the savings resulting from the 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 increases non-linearly, as ever greater expenditures are required to achieve a fixed incremental energy efficiency improvement using a given technology platform (Karplus and Paltsev, 2012). In this simple structure, it is possible to see how efficiency improvements that lower the net cost per mile may incentivise increased driving, while the fact that efficiency improvements increase the cost of new vehicles place downward pressure on demand. Lower energy costs also lower the price of y in proportion to the share of energy $p_e e/p_y y$ in its production and provides an incentive to increase consumption (assuming all income is spent). The magnitude and dependency of these effects, and 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, such as fuel-efficient vehicles and energy-efficient appliances (Hausman, 1979; Small and Van Dender, 2007; Tierney, 2011; van den Bergh, 2011). In our simple model, the relationship between the mandated efficiency increase and distance driven is a function of the energy input expenditure share $\theta_e = p_e e/p_x x$, 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:[3]

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

Depending on the net effect on the price of the vehicle transportation service (cost per mile) p_x of a forced shift away from fuel, through the application of technology or reconfiguration of vehicle attributes, demand for vehicle-miles travelled (VMT) will rise or fall. As long as

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[3] All prices in equation (7) are unit prices.

the lower energy cost component trumps the higher vehicle capital cost component, the levelised cost of travel demand will fall; any corresponding change in fuel demand due to increased travel demand at the new efficiency level is defined as the rebound effect. 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.

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 per cent and a long-run rebound effect of 22.2 per cent. More recent work estimates low- to 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 per cent, and the effect was found to decline with increases in per-capita income (Wang *et al.*, 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 to higher compliance costs by moving to locations with less stringent policy controls (see, for example, Chan *et al.*, 2010).

However, leakage can also occur as intermediate or final consumers of energy in uncovered sectors or regions benefit from lower prices caused by policy-induced demand reductions in a covered sector or region. The magnitude of 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. Leakage can be positive or negative, as discussed in Baylis *et al.* (2014), with implications for the cost of climate policy (Baylis *et al.*, 2013). Winchester and Rausch (2013) point out that because elasticities of energy demand are typically less than unity in empirically based calibrations, negative leakage is rarely observed. Caron *et al.* (2012) investigated the magnitude of leakage due to state-based climate policy in California, and estimated net domestic leakage rates of 2 per cent under an economy-wide climate policy with a CO_2 price of \$65/ton.

In our two-sector model, the leakage effect shows up as an increase in demand for fuel in sector Y as the energy input price falls, 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, a fuel economy standard could favour a situation in which uncovered sectors invest less in fuel efficiency than they otherwise would have as a result of reduced energy price pressure.

3.3 Rationale for a general equilibrium framework

While our simple model illustrates the basic mechanisms that affect the total reduction in petroleum use or emissions achieved by a fuel economy standard, estimating the magnitude of these effects requires a carefully parameterised global energy-economic model. Here we use a CGE framework that can capture both the rebound effect and the leakage effect in its many manifestations, based on careful parameterisation 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. The model further captures how these two effects interact with each other.

4.0 Model Developments and Scenarios

4.1 Numerical model description

The model used in this analysis is a specialised version of the MIT Emissions Prediction and Policy Analysis (EPPA) model (Version 5) 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) data set Version 7, which records national energy and economic (input–output) flows in 113 regions for the year 2004 (Hertel, 1997; Dimaranan and McDougall, 2002). For use in the EPPA model, the GTAP data set is aggregated into sixteen regions (Table 1) and twenty-four 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; hydrouorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexauoride, SF_6) are based on US 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 parameterisation of the relationship between income growth and demand for VMT, a representation of fleet turnover, and opportunities for fuel use and emissions abatement, including representation of the plug-in hybrid electric vehicle. These model developments, which constitute the EPPA5-HTRN version of the model, are described in detail in Karplus *et al.* (2012). Here we briefly summarise the model features that capture heterogeneity in the transportation system across regions.

First, the EPPA model captures how each region has a unique share of household spending devoted to transport activities, part of which is spent on travel in household-owned vehicles. The value share of household vehicle transport varies from 6 per cent in Latin America and the rest of East Asia to 13.4 per cent in Europe (which is higher than the USA at 10.4 per cent, due to the high taxes on motor vehicle fuel).[4] This share is then adjusted over time using exogenous estimates of income elasticity to obtain baseline

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[4] The EPPA model represents the range of taxes on labour, capital, energy, and intermediates as described in Paltsev *et al.* (2005). The EPPA model captures variation in motor vehicle fuel taxes at the pump by region.

Table 1
Sectors and Regions in the EPPA Model

Sectors	*Regions*
Non-Energy	**Developed**
Agriculture	United States (USA)
Forestry	Canada (CAN)
Energy-intensive products	Japan (JPN)
Other industries products	Europe (EUR)
Industrial Transportation	Australia and Oceania (ANZ)
Household Transportation	Russia (RUS)
Food	Eastern Europe (EUR)
Services	
	Developing
Energy	India (IND)
Coal	China (CHN)
Crude Oil	Indonesia (IND)
Refined Oil	Rest of East Asia (REA)
Natural Gas	Mexico (MEX)
Electricity generation technologies	Central and South America (LAM)
Fossil	Middle East (MES)
Hydro	Africa (AFR)
Nuclear	Rest of Europe and Central Asia (ROE)
Solar and wind	Dynamic Asia (ASI)
Biomass	
Natural Gas Combined Cycle (NGCC)	
NGCC with CO_2 Capture and Storage (CCS)	
Advanced Coal with CCS	
Synthetic Gas from Coal	
Hydrogen from Coal	
Hydrogen from Gas	
Oil from Shale	
Liquid Fuel from Biomass	

Note: Detail on aggregation of sectors from the GTAP sectors and the addition of advanced technologies are provided in Paltsev *et al.* (2005). Details on the disaggregation of industrial and household transportation sectors are documented in Paltsev *et al.* (2004).

scenario vehicle fleet growth; in policy scenarios, these income elasticity values remain unchanged. Such adjustment is essential to capture income-driven changes in demand for vehicle ownership and driving, and the elasticity values used in each of the regions are discussed in Karplus *et al.* (2013a). Second, the model also captures the starting level of fuel efficiency in each region implicit in the base year data, which varies widely across regions, from 18 mpg in Latin America to 29 mpg in Japan and 27 mpg in Europe in 2004. Third, the model further differentiates regions based on the total number of miles driven and represents an implicit cost-per-mile in each region, which affects the relative economic attractiveness of introducing more efficient vehicle technologies. Finally, total mileage and fuel economy is differentiated in every region between the newly purchased and pre-existing vehicle fleets.

In an economy-wide analysis of fuel economy standards, it is essential to differentiate between the new and used vehicle fleets, given that the standard constrains only new model year vehicles sold, but energy and emissions depend on characteristics of the total fleet and turnover dynamics. The importance of capturing the fleet-wide effects of fuel economy standards has been previously documented in Johansson and Schipper (1997), Goldberg (1998), and Bento *et al.* (2009), among others. The EPPA model includes a parameterisation of the total miles travelled in both new (zero to five-year-old) and used (six years and older) vehicles, and tracks changes in travel demand in response to changes in income as well as price-per-mile. The EPPA framework allows explicit specification of substitution between new and used vehicles — for instance, to capture the intuition that households could respond to a fuel economy standard that raises up-front vehicle cost by holding on to their existing vehicles longer or selling it for a higher price. This specification captures how consumers respond to changes in relative prices, including those changes that result from the introduction of a fuel economy policy or an increase in the price of fuel given a carbon price.

In particular, the representation of technology and its endogenous response to underlying cost conditions is particularly important to our results, and thus we elaborate here on its representation in the model. We represent opportunities to reduce petroleum-based fuel use and emissions by improving the efficiency of the internal combustion engine (ICE-only) vehicle, by substituting compatible fuels, and by reducing travel demand. We also represent similar opportunities for a plug-in hybrid electric vehicle (PHEV), which is modelled as a substitute for the ICE-only vehicle that can run on gasoline in a downsized internal combustion engine (ICE) or on grid-supplied, battery-stored electricity. The PHEV itself is assumed to be 30 per cent more expensive relative to a new internal combustion engine ICE-only vehicle, an assumption at the low end of the range of estimates from a recent literature review (Cheah and Heywood, 2010).[5] Vehicle characteristics and technology requirements for the PHEV are defined based on a mid-sized sedan, which relies on grid-supplied electricity for 60 per cent of miles travelled and liquid fuels for the remaining 40 per cent.[6] The ICE fuel economy of the PHEV assumes operation in hybrid (charge-sustaining) mode, while the battery is sized for an all-electric range of forty miles. As the levelised price per mile of ICE vehicle ownership increases over time (with increasing fuel cost and the introduction of efficiency technology), the cost gap is allowed to narrow and may eventually favour adoption of the PHEV. When initially adopted, the PHEV faces increasing returns to scale as parameterised in earlier work, to capture the intuition that development and early deployment are more costly per unit produced until large-scale production volumes have been reached, which also affects its cost relative to the ICE vehicle (Karplus *et al.*, 2010). The results of this analysis are sensitive to the parameterisation of these responses, and therefore we have calibrated these responses based on available empirical data on the cost and CO_2 emissions reductions available from introducing particular technologies at the vehicle level (Karplus *et al.*, 2013a).

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[5] Specifically, we choose as a relatively optimistic scenario the estimate from Plotkin and Singh (2009) for a PHEV40 in 2015, which gives a markup over a conventional ICE car of US $6,000.

[6] This mileage split is a function of travel patterns in the USA and battery all-electric range, as discussed in Karplus *et al.* (2010). The mileage share driven on electricity is referred to as the PHEV utility factor.

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 (in other words, before any change in miles travelled 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 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 parameterise 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 VMT responds 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 consumption per mile constraint is shown in equation (8):

$$\mathrm{FES}_{t_0} \leqslant A_t(Q_{f,t_0}, Q_{\mathrm{VMT},t_0}). \tag{8}$$

All future reductions are defined relative to the ratio of fuel, Q_{f,t_0}, to miles travelled, 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 litres per 100 km (l/100 km). The trajectory A_t defines allowable per-mile fuel consumption in each future model period relative to its value in the model benchmark year. The constraint requires that the on-road fuel consumption realised in each period for new (zero to five-year-old) vehicles remains 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 total VMT. For example, age-specific miles travelled per vehicle are reported in Davis *et al.* (2009) for the USA.

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 policy is implemented in our reference scenario, which provides the basis against which we compare the outcomes of the other three scenarios. We include a 'current' policy scenario that imposes fuel economy mandates that match regulations that have either been proposed or implemented as previously described. We then consider a 'stringent' policy scenario in which fuel economy mandates are implemented in all regions to 2050, including and extending the trajectories established by the current policy 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.

Table 2
Regional Constraints Under Stringent Fuel Economy Standard, in Litres per 100 Kilometres. REA is Not Subject to a Constraint

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

Finally, we consider a ‘cap-and-trade’ policy that constrains CO_2 emissions in each country or region at a level identical to that achieved in the stringent policy scenario, resulting in a price on emissions of CO_2. In this scenario, permit trading is only allowed across sectors within countries and not across regional borders. In all scenarios, current biofuels mandates in the USA and Europe are included as well.

5.0 Results

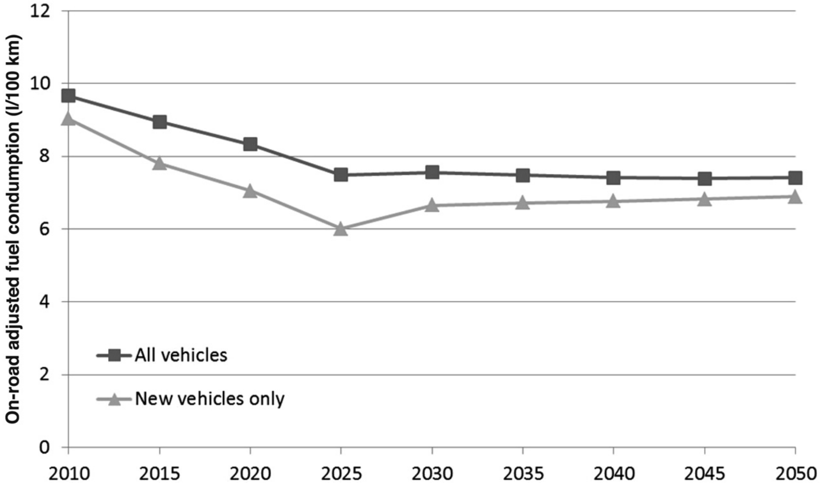
In interpreting the results of the scenarios, we focus on several outcomes. First, we are interested in quantifying the aggregate impact of current fuel economy policies on energy, CO_2 emissions, and the economy. Second, we are interested in the effects of a stringent fuel economy path applied globally to 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.

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 show the resulting imputed on-road fuel consumption (fuel used divided by distance travelled, in litres per 100 km) of an average on-road vehicle in the new and total vehicle fleet, by region. As anticipated, we observe a declining trend in imputed global fuel consumption to 2025 before observing stabilisation to 2050, as shown in Figure 2. The trajectories shown are the VMT-weighted (on-road) fuel consumption realised for the new vehicles sold in the most recent five years as well as for the entire fleet (both newly sold and pre-existing vehicles considered together), and includes any associated increases or decreases in distance travelled associated with changes in the fuel- and vehicle-related costs of driving. Since we only model currently announced standards, all standards are assumed to remain constant after 2025 (some level off sooner). The fact that the standards stay constant, while a disproportionate number of new vehicles are being added rapidly in unconstrained markets, translates into falling average fuel economy of new vehicles over time.

Figure 2

Weighted Average Global On-road Adjusted Vehicle Fuel Consumption for New and All Vehicles in the Current Policy Scenario



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 globally and by region. We first focus on the change in global refined oil consumption shown in Figure 3. In our model simulations, currently announced fuel economy policy is predicted to reduce total global year-on-year passenger vehicle fuel use by 14 per cent in 2030 and 16 per cent by 2050, shown in gallons of gasoline equivalent. Constrained regions see higher reductions of 21 per cent in 2030 and 25 per cent in 2050, while unconstrained regions experience net reductions as well of 1 per cent in 2030 and 3 per cent in 2050. Unconstrained regions experience reductions because the net effect of imposing standards in constrained regions is to require additional deployment of fuel-saving capital and thus raise the global price of capital as a factor of production.[7] These costs place upward pressure on the price of vehicle capital worldwide, which across the unconstrained regions is not offset by reductions in the cost per mile of travel through mandated increases in vehicle efficiency. The magnitude of the reduction in global motor vehicle fuel demand does not change very much between 2030 and 2050, given unchanging policy targets against the backdrop of continually rising baseline demand.[8] Most of the demand reduction occurs in the OECD (accounting for 55 per cent of total global petroleum-based fuel reduction), as a result of policies in the USA, 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 to 2030 (though trends in China are a major source of uncertainty). In

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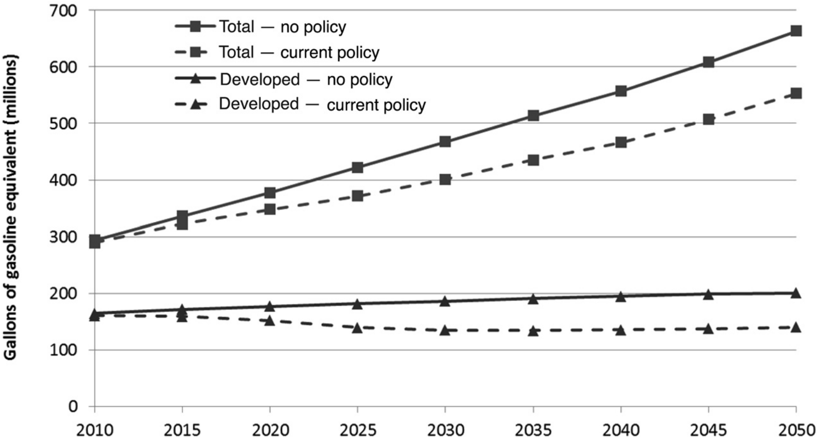
[7] The EPPA model represents a global market for capital as a factor of production. Increased capital demand for vehicle efficiency improvements puts upward pressure on global capital prices, and thus the cost of vehicles in unconstrained regions also increases.

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

Figure 3

Refined Oil Use by Household Vehicles Under Reference and Current Policy Scenarios (Squares = Total, Triangles = Developed Regions Only Including EUR, JPN, CAN, ANZ, EUR, RUS, and ASI)



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 vehicle). Consistent with the intuition that household vehicle ownership in developed countries is relatively saturated, we find that vehicle travel falls less in developed regions relative to developing ones, where consumers are highly cost-sensitive. 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 inadvertently subsidise mobility demand by private households.[9] 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 commensurate with global reductions in refined oil demand. Under the current policy scenario, global emissions fall by around 4 per cent relative to global levels in the reference case in 2050. Potential reductions due to the displacement of petroleum-based fuels are partially offset by increases in other carbon-rich primary energy sources in unconstrained sectors and regions, 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 therefore displace refined oil, but not necessarily

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

CO_2). In short, total CO_2 emissions suggest that when viewed in a global perspective, the net effect of current fuel economy policy on global CO_2 emissions is fairly modest. We consider the cost-effectiveness of achieving these reductions relative to an efficient instrument targeting CO_2 in the next section.

5.1.2 Economic impacts

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 per cent. Europe is hardest hit by the new standards (a 13 per cent consumption loss by 2050), as vehicles in many European Union countries are already starting from a very efficient level, and the cost of incremental improvements increases non-linearly with standard aggressiveness (a parameterisation based on engineering-cost estimates). The USA experiences a decrease in consumption of 4.8 per cent in 2050, while other constrained regions also experience consumption loss in the range of 5–7 per cent. Total global consumption loss reaches 6 per cent assuming current policies. The reason for the slight increase in consumption in the rest of East Asia 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.

We investigate the extent of leakage under the current policy scenario by comparison to the counterfactual in which global oil price is fixed at the levels observed in the no policy case. We find that leakage is modest — in a ‘no leakage’ case, global refined oil demand is 1.4 billion barrels lower in 2030 (0.78 per cent of refined oil demand in all uncovered regions). In 2050 the magnitude of leakage rises to 6.4 billion barrels (2.6 per cent of refined oil demand in all uncovered regions). Domestic oil prices are lower by 5–15 per cent by 2050 in all regions, not just regions constrained by the fuel economy standard. Exceptions to this trend include the regions in which fuel use increased — India, rest of East Asia, and Africa. In percentage terms, consumption 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. Indeed, it is through this channel that a fuel economy standard can result in substantial negative leakage, as unconstrained regions also feel the effect on higher capital prices in the constrained regions.

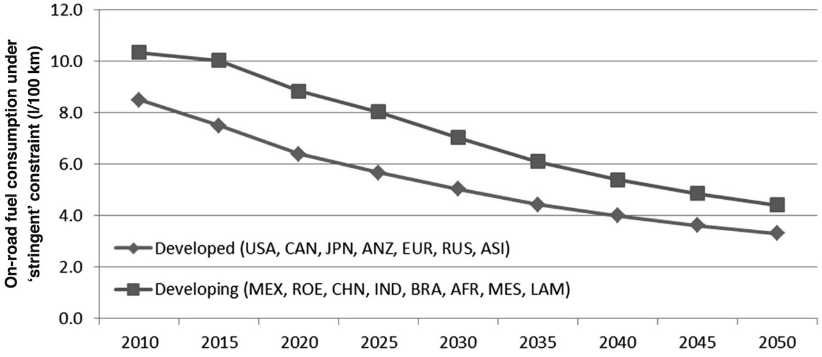
5.2 Comparing a stringent FES policy to a cap-and-trade system on CO_2 emissions

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.

The effect of the stringent fuel economy constraint (shown for all regions in Table 2) translates into significant reductions in mileage-weighted fuel consumption in both developed and developing regions, as shown in Figure 4. Developing regions face less

Figure 4

The VMT-weighted Fuel Economy Constraint in Developed and Developing Regions in the 'Stringent' Policies Scenario



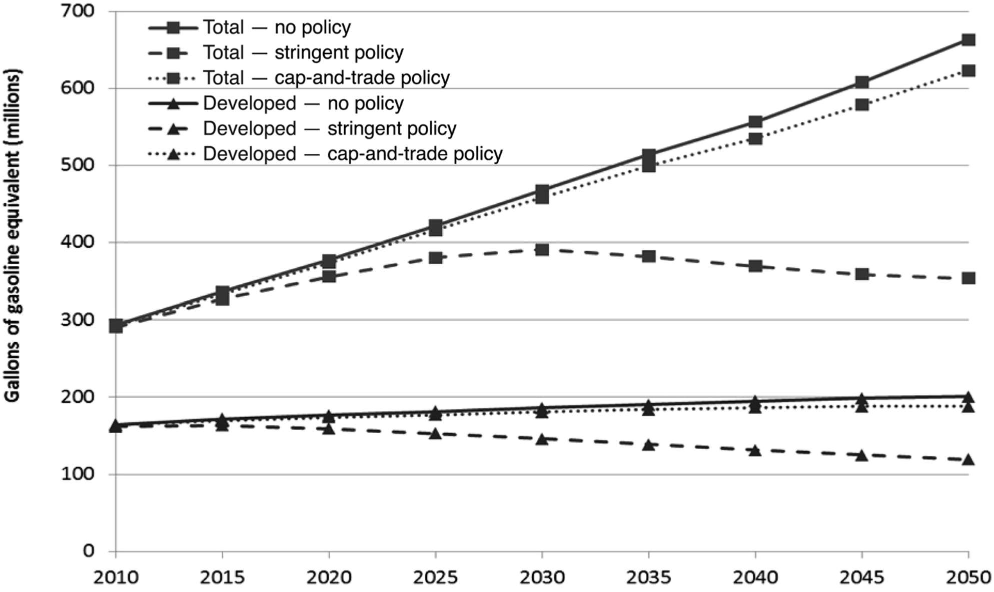
stringent targets, but vehicles in these countries will make an ever larger contribution to total global VMT. For our market-based policy, we design a cap-and-trade system for CO_2 emissions that targets a reduction equivalent to that achieved under the stringent fuel economy standard in each region (with no inter-regional trading). The cap-and-trade policy 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 refined oil use in passenger vehicles falls far more under fuel economy standards than under a cap-and-trade system, as shown in Figure 5. Under a cap-and-trade system, passenger vehicle fuel use falls by only 6 per cent in 2050, relative to the stringent fuel economy policy which reduces fuel demand by 47 per cent 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 per euro, dollar, or yen spent.

Under the stringent fuel economy policy, the OECD experiences a reduction of around 60 per cent of passenger vehicle fuel demand relative to the reference case in 2050, but this accounts for only 26 per cent of the 2050 reduction, while other regions, particularly developing regions which are also constrained, account for the largest share of the reduction. The fuel economy standard has the effect of limiting rapid fleet growth somewhat, as the cost of installing efficiency technology raises vehicle prices, and also because such a large fraction of the total (rapidly growing) fleet in these countries is comprised of new vehicles subject to fuel efficiency improvements.

Figure 5

Refined Oil Use by Household Vehicles Under Reference, Stringent, and Cap-and-trade Policy Scenarios (Squares = Total, Triangles = Developed Regions Only Including EUR, JPN, CAN, ANZ, EUR, RUS, and ASI)



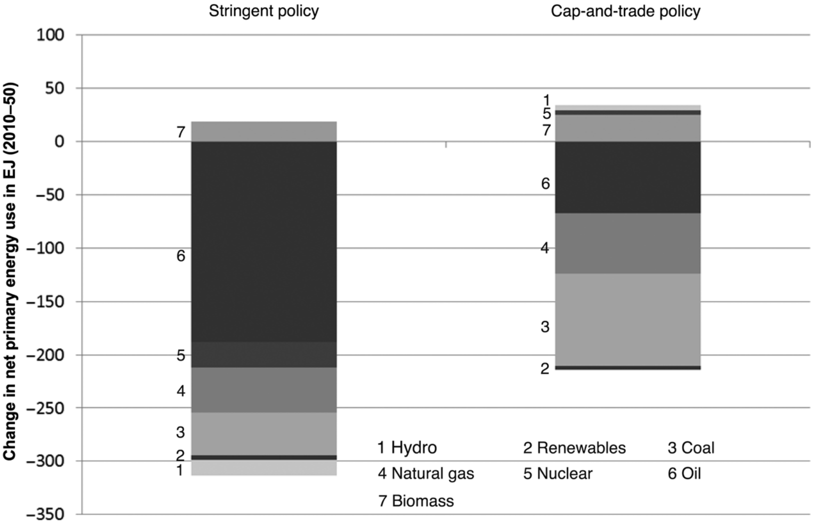
The change in the composition of the primary energy mix underscores the divergence in the types of actions each of these policies incentivise. A cap-and-trade system incentivises changes that lead to greater utilisation of low-carbon fuel sources, displacing primarily coal and gas with a more modest contribution from oil, while a fuel economy standard relies primarily on a sharp reduction in oil. As shown in Figure 6, a fuel economy standard provides no incentive to switch to low-carbon primary fuels (particularly away from coal, which has higher carbon content than oil). On the other hand, the cap-and-trade system penalises (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 a cap-and-trade system would penalise natural gas alongside coal because of its carbon content. The total net change in energy required under a fuel economy standard is higher because refined oil has lower carbon content relative to coal, and thus more must be displaced to achieve an equivalent reduction.

When it comes to reducing CO_2 emissions, the impact of light-duty vehicle fuel economy standards — simulated in a model that captures global rebound and leakage effects — is relatively modest. As shown in Figure 7, total reduction of CO_2 in 2050 relative to the no policy reference reaches just over 4 per cent in the current policy case, and falls just shy of 10 per cent in the stringent policies case.

We consider the cost of achieving a CO_2 emissions reduction equivalent to that achieved by the stringent fuel economy policy using a market-based instrument (with no inter-regional trading). In 2050 global consumption loss accounts for just below 6 per cent in

Figure 6

Change in Cumulative Primary Energy Use Relative to the No Policy Reference for the Stringent Policy and the Cap-and-trade Policy Scenarios



the cap-and-trade case, while for the stringent fuel economy standard it exceeds 10 per cent. In other words, we find that global consumption loss is about 67 per cent higher by 2050 under a global fuel economy policy, compared with the consumption 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 over time is shown in Figure 8.

Figure 7

Total CO_2 Emissions in the Current and Stringent Fuel Economy Policy Scenarios, and Percentage Change Relative to Reference

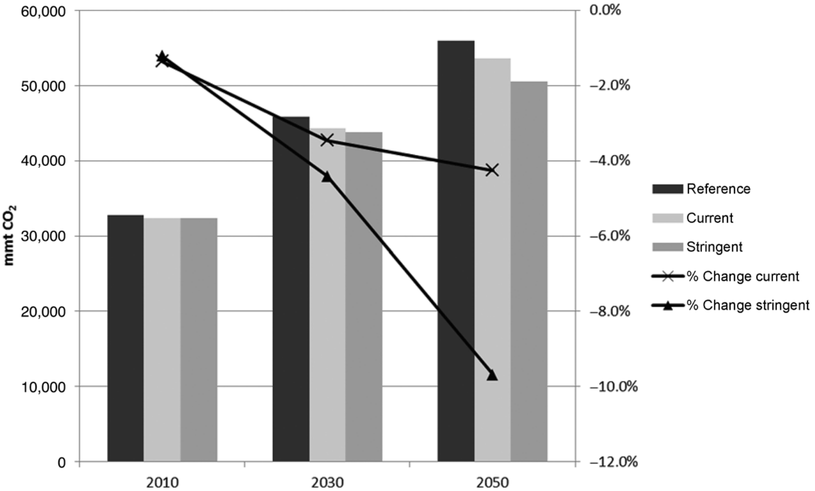
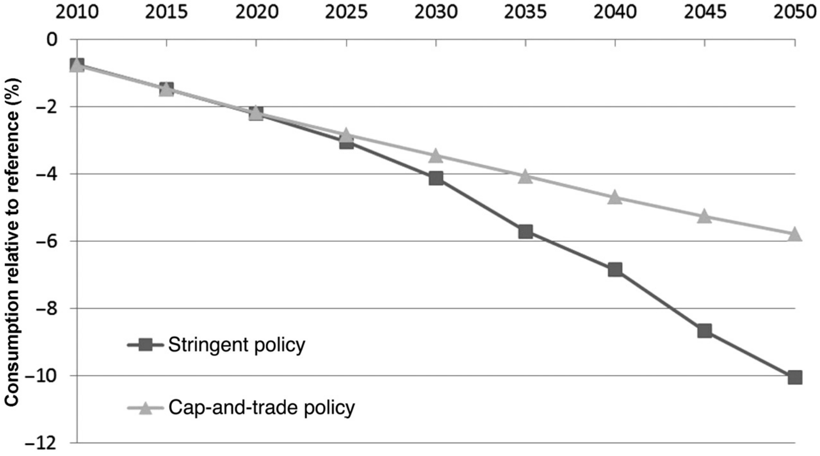


Figure 8

Percentage Change in Consumption Relative to the Reference Case, for Stringent FES and Equivalent Cap and Trade Policy, by Year



6.0 Conclusions

Although fuel economy standards are typically implemented at the national or regional level, this analysis illustrates the importance of understanding how they will interact to affect energy, CO_2 emissions, and economic outcomes on a global scale. Our modelling framework enables us explicitly to consider how fuel economy standards interact with 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 how these effects operate simultaneously in 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 (that is, 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 costs that a fuel economy standard places on the economy, as capital costs rise to achieve vehicle efficiency improvements or accommodate the production of alternative fuel vehicles. Under current policies, we find that, in 2050, global passenger vehicle refined oil use is reduced by 16 per cent, while global CO_2 emissions fall by 4 per cent, and global economic consumption falls by around 6 per cent. A more stringent fuel economy standard reduces global passenger vehicle refined oil use by 46 per cent and CO_2 emissions by 10 per cent in 2050 at a cost equal to 10 per cent of reference consumption in the same year. By contrast, 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 per cent. However, the cap-and-trade policy is less effective at addressing energy security objectives, as it only reduces passenger vehicle refined oil use by 6 per cent relative to the reference case. The cap-and-trade system incentivises the most cost-effective CO_2 emissions reductions across the economy as a whole, which involve only very modest reductions in refined oil use in passenger vehicle transportation, suggesting a significant trade-off between climate and national security policy objectives. However, if displacing (imported) petroleum use is the goal, it is worth considering alternative policy designs (such as fuel taxes), which have been shown to be more cost-effective in previous econometric and modelling analyses (Goldberg, 1998; Karplus *et al.*, 2013b).[10]

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 the 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. It is important to note that we focus on comparing the costs of policy, rather than analysing any benefits (such as avoided global climate change damages) or co-benefits (for example, health effects associated with reductions of non-target pollutants) associated with policy-induced changes in the energy system.

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 emissions than projections at the national or regional level anticipate, and could impose significant costs on the economies of both implementing and non-participating nations and regions. Nevertheless, fuel economy standards continue to be sold as a 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 realise a price reduction of 5–15 per cent 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 be very high in economies that have enacted tough standards through political consensus. However, indirect effects of these standards may incur costs and affect energy markets far beyond national borders.

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[10] Karplus *et al.* (2012b) has also considered how an FES policy compares to a fuel tax as a strategy for reducing petroleum reduction. The paper shows how a tax reduces fuel demand by all vehicles, while a fuel economy standard leads to more efficient new vehicles that are driven slightly more. Comparing an FES policy to a cap on passenger vehicle fuel use provides a similar comparison, and the cost of reducing a similar level of emissions through an FES policy would be expected to be higher than a cap-and-trade policy in the absence of other economic distortions.

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