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Abstract

In this paper, we explore automobile fuel efficiency policies in the presence of two externalities i) a global environmental problem and ii) international innovation spillovers. Using a simple model with two regions, we show that both a fuel tax and a tax on vehicles based on their fuel economy rating are needed to decentralize the first best. We also show that if policies are not coordinated between regions, the resulting gas taxes will be set too low and each region will use the tax on fuel rating, to reduce the damage caused by foreign drivers. If standards are used instead of taxes, we find that spillovers may alleviate free-riding. Under some conditions, a strict standard in one region may favour the adoption of a strict standard in the other one.

Keywords

Environmental policy, automobile, fuel efficiency standard, gasoline tax, innovation spillovers

JEL code: O38, Q48, Q54, Q58, R48

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I. Introduction

Climate change concerns and surging oil prices have renewed interest in energy efficiency in general and automobile fuel economy in particular. In many parts of the world, public policies have been adopted or revised in order to improve the performance of cars either in terms of fuel efficiency or GHG emission rates.[1] As recently as December 2007, the US has strengthened their Corporate Average Fuel Efficiency Standard (CAFE), requiring that new cars and light trucks meet a fleetwide average of 35 miles a gallon by year 2020. In 2006, Japan increased the stringency of its fuel economy standards, first adopted in 1999. Back in 2002, the State of California adopted a ground-breaking law requiring GHG emission limits from motor vehicles. The new limits were issued in 2004 and aimed at reducing emissions rate by about 30% in 2016, compared to model year 2004.[2] Several other US States and some Canadian provinces have since announced that they would also adopt them. Meanwhile, the European authorities are considering replacing voluntary limits on CO_2 emissions per km by mandatory targets. Limits of either 120 or 130 grams per km by 2012 are now being debated.[3] Beside standards, several jurisdictions have introduced incentive-based instruments to favour fuel efficient cars. For example, in Canada, the federal government introduced in 2006 a feebate program taxing the purchase of fuel inefficient vehicles, while providing a tax rebate on efficient cars. This program was however cancelled few months later because it was poorly designed and faced strong opposition by car manufacturers. In Belgium, the Walloon Region has also recently instituted a feebate program based on CO_2 emissions rates.

Economists have been critical of policies that directly target vehicle fuel or emission rates (for an overview of the arguments see Portney *et al.* 2003 and Fisher *et al.* 2007). Instead, they

[1] While reducing GHG emission rate may be achieved by developing alternative fuels (e.g. biofuels) or changes in air conditioners, improvements in fuel rating remain a key strategy for lowering emissions rate. We therefore focus our analysis on policies raising fuel efficiency.
[2] At this point, the Federal government disputes California's right to regulate GHG emissions.
[3] These different standards are not directly comparable. Besides using different measurement units, they are also based on fuel rating estimated by different methodologies. However, a comparative analysis by ICCT (2007) reveals that Japan and Europe have the most stringent targets while the US (including California) is lagging well behind.

recommend either increasing gasoline taxes or imposing a tax on CO_2 emissions.[4] The main advantage of this approach is that it leads not only to improvements in vehicle fuel rating, but it also affects other determinants of gasoline consumption such as driving behaviour or distance. For example, Austin and Dinan (2005) show that it is possible to achieve the same 10% reduction in the US gasoline consumption at a cost 58% to 71% lower by increasing the gasoline tax rather than by tightening the CAFE standards.[5] Furthermore, contrary to the gasoline tax, improving fuel efficiency lowers vehicles' operating cost and thereby stimulates driving. Empirical evidence suggests that this 'rebound effect' offsets 10% to 20% of the initial fuel reduction associated with improved fuel rating (see for example Small and Van Dender, 2007). Worst, the additional driving aggravates other traffic-related externalities such as local air pollution, noise and congestion (see Parry, 2007). Finally, tax revenues collected by a gasoline tax may be used to reduce labour income taxes, eventually increasing the labour supply, thereby bringing additional efficiency gains (for an evaluation see West and Williams III, 2005, 2007 and Parry, 2007).[6]

However, there are also arguments in favour of vehicle fuel efficiency policies. Some suggest that, because of bounded rationality, lack of information or uncertainty about future fuel prices, consumers are undervaluing fuel savings.[7] This would explain why some technologies that have negative net costs are not adopted. Market power among car manufacturers could also lead to distortions on the level of fuel efficiency.

In this paper, we consider another source of distortion that may justify fuel efficiency public policies, namely innovation spillovers. This has been mentioned before in the literature but never has it been analysed in a formal model for the car industry (for a general discussion on the

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[4] Note that taxing CO_2 emissions is equivalent to taxing gasoline. Indeed, there is no abatement technology for carbon dioxide. Obviously, an optimal tax should depend upon the carbon content of the fuel use. This is relevant when diesel, compressed natural gas or bio-fuels are being considered. For other pollutants such as NO_x, taxing gasoline is not equivalent to taxing emissions (see Fullerton and West 2002 on this issue).

[5] Imposing a uniform standard across car manufacturers is also inefficient if marginal costs of improving fuel efficiency vary across firms. According to Austin and Dinan, a tradable permit system among manufacturers would reduce compliance cost by 16%.

[6] In fact, West and Williams (2005 and 2007) show that mileage and leisure are relative complements implying a negative (positive) effect on the labour supply of fuel efficiency improvements (gasoline tax).

[7] Empirical evidence on this issue is still limited and provides conflicting results. Some analysts suggest that car buyers only value three years of fuel saving or that they use very high implicit interest rates when trading off higher vehicle prices for lower gasoline expenditures (NRC, 2002 and Greene *et al.*, 2005). Others find implicit interest rates that are close to those available for car loans (see Dreyfus and Viscusi,1995 or see Verboven, 2002).

interactions between environmental and innovation externalities see Jaffe *et al.*, 2005). The idea is that improving car fuel economy may require R&D activities whose benefits may not be completely appropriated by the investing party. More specifically, we examine the impact of international spillovers that may exist between countries or regions. We develop a simple model with two regions where agents can choose how many cars to own, how often to drive them, their fuel economy and the level of consumption of other goods. Gasoline consumption is responsible for a global pollution problem that negatively affects all individuals. The existence of international innovation spillovers is modeled in a simple way by assuming that the average production cost of cars sold in one region depends upon the level of fuel efficiency in the other region. More precisely, we assume that better fuel rating in one region lowers the cost of improving fuel efficiency in the other. In this context, we show that a fuel tax is no longer sufficient to decentralize the "world" first best outcome. Indeed, the optimal policy calls for a tax on gasoline to internalize the environmental externality and a vehicle tax based on the fuel economy to internalize the spillovers. Furthermore, the tax revenues collected on fuel rating should be returned via a fixed subsidy on vehicle ownership. This combination of a tax and a subsidy is in fact reminiscent of the feebate programs adopted by some jurisdictions. Our analysis therefore provides a normative justification for having policies targeting fuel rating. We also offer a more positive justification by examining the policies followed when there is no coordination across regions. In such a setting, we show that each region adopts a gasoline tax that is too low compared to the coordinated outcome. Indeed, each region ignores the impact its drivers have on the other region. However, each region also sets a domestic tax on vehicles based on their fuel rating. This tax does not aim at internalizing the spillovers like in the coordinated policy, but rather it is using spillovers as a way to stimulate the fuel efficiency of foreign cars, thereby reducing the environmental damage caused by foreigners.

We also analyse more closely standard setting (as opposed to incentive based instruments) when there are international spillovers. Using a simplified version of our model where the only decision variable is fuel economy rating, we compare the outcome of simultaneous and sequential standard setting by governments. We show that standards are set to loose when governments act simultaneously because they ignore i) the environmental impact on the other region and ii) the positive spillovers. In a sequential game, the underprovision of fuel efficiency may become worse because the free-riding of the first mover may be exacerbated. However, interestingly, we show that if spillovers are sufficiently large, sequential-move may improve the final outcome. In fact, the follower may react to a stricter standard by the first mover by tightening, rather than loosening its own standard. This result may therefore contribute in explaining the wave of adoption by US States and Canadian provinces of the standards initially adopted in California.

The paper is organized as follows. In section II, we describe the model and analyse incentive-based fuel efficiency policies. We first derive the world first best outcome and examine how it can be decentralized using taxes and subsidies. We then explore the policies adopted by regions when there is no coordination. In section III, we analyse standard setting and illustrate our analysis using the California experience. We conclude in section IV.

II. Incentive-Based Fuel Efficiency Policies

The Model

Consider a world with two regions denoted by superscript *i*=1,2 and each populated by n^i agents. We assume that all agents are similar and have utility function:

$$U^i = u(x^i, D(v^i, m^i)) - E(F) \qquad (1)$$

x^i is the quantity consumed of a general consumption goods and D is the sub-utility from car travel, which is increasing in the number of vehicles v^i owned and miles travelled per car m^i. $E(F)$ represents the disutility associated with global pollution generated by cars, say climate change. It is increasing with worldwide fuel consumption $F = F^1 + F^2$ with $F^i = n^i v^i m^i g^i$, where g^i is gallons consumed per mile. U^i is assumed to be a well behaved utility function.

Following Innes (1996) and Fisher *et al.* (2007), we assume that cars are produced by a competitive industry with constant returns to scale.[8] Furthermore, we assume that there is no joint production meaning that car companies are different in the two regions. While these assumptions

[8] Each region is sufficiently large so that a large number of plants can produce at the minimum efficiency scale.

are not necessarily realistic, they focus the analysis on the interaction between cost spillovers and environmental externalities.[9] We discuss the impact their impacts on our results in the conclusion. The long term average production cost of a car sold in country *i* is given by $h^i(g^1, g^2)$. We assume that $h^i_{g^i} = \frac{\partial h^i}{\partial g^i} < 0$ and $h^i_{g^i g^i} = \frac{\partial^2 h^i}{\partial g^i \partial g^i} > 0$. In other words, fuel efficiency can only be improved (*i.e.* lowering g_i) by progressively installing more costly fuel saving technologies. This is a common hypothesis in the literature which is backed by factual evidence.[10] Note that this is a long term relationship implying that it takes into account that a stricter fuel efficiency target in region *i* is going to stimulate innovative activities, thereby limiting the production cost increase.[11] There is indeed mounting empirical evidence that environmental regulations induce R&D and patenting activities (see Landjouw and Mody, 1996, Jaffe and Palmer 1997, Brunnermeier and Cohen, 2003, Popp 2006) and give rise to lower abatement costs (see Fisher and Newell, 2007).

These induced innovations also explain our additional hypothesis that h^i depends upon g^j. More precisely, we assume that the innovative activities stimulated by a stricter fuel efficiency target in region *j* generate positive spillovers in region *i* , thereby leading to a reduction i) in the average production cost ($h^i_{g^j} = \frac{\partial h_i}{\partial g_j} > 0$) and ii) in the marginal average cost increase associated with a marginal improvement in fuel efficiency ($h^i_{g^i g^j} = \frac{\partial^2 h^i}{\partial g_i \partial g_j} < 0$).[12] Clearly, this specification should be viewed as a short cut aimed at capturing the main implications of international spillovers while keeping the analysis simple.[13] International spillovers occur when the prices of intermediate inputs do not fully incorporate the quality improvement resulting from

[9] We assume away market power to avoid adding an additional source of distortion that would blur the analysis. Combining joint production and perfect competition would also make the analysis much more cumbersome.

[10] NRC (2002) reviews several emerging technologies for improving fuel rating (e.g. use of advanced low friction lubricant, cylinder deactivation, continuously variable transmission) and evaluates their expected cost. Based on this review, incremental cost curves as a function of fuel rating are constructed for different vehicle types. These curves are decreasing and convex as we assume in our model.

[11] The automobile industry is the largest investor in R&D activities in the OECD. In 2003, it represented over 13% of all R&D expenditures (see Hashmi and Van Biesebroeck, 2007).

[12] Recall once again that improving fuel efficiency means lowering *g*.

[13] Also note that $h^i(g^1, g^2)$ could also represent a reduced form for other type of phenomenon such as economies of scale in the cost of adopting new technologies, learning by doing. We come back on this in the conclusion.

foreign innovations.[14] It is also the result of the public good aspects of knowledge. International trade, foreign direct investments, international alliances (licensing agreements, joint ventures), migration of scientists, international conferences or industrial spying may therefore all contribute to international spillovers. There is now a fairly large amount of empirical literature suggesting that foreign R&D is indeed a significant source of domestic productivity growth.[15] An interesting example is Bernstein and Mohnen (1998) who use data for 11 R&D intensive sectors, including transportation equipment (automobile production being part of this sector). They find significant spillovers from the US to Japan over the 1962-1986 period. In fact, their results suggest that a one percent increase in the US R&D capital would lead to a 0.4% reduction in Japanese average variable cost.[16]

The World First Best Outcome

A social planner interested in achieving the world first best outcome will try to maximize the sum of all the agents' utility under a world resource constraint. Formally,

$$Max \quad \sum_{i=1}^{2} n^i \left[u(x^i, D(m^i, v^i)) - E(n^1 m^1 v^1 g^1 + n^2 m^2 v^2 g^2) \right] + \lambda \left[\sum_{i=1}^{2} n^i \left(y - x^i - h^i(g^1, g^2) v^i - p m^i v^i g^i \right) \right]$$

$$wrt \; x^i, m^i, v^i, g^i, \lambda \qquad (2)$$

The price of x is normalized to one while p, the resource cost of gasoline, is assumed to be exogenous. y stands for the per capita quantity of resources available in each region. After dividing by n^i, the first order conditions become:[17]

$$u_{x_i} - \lambda = 0 \qquad (3)$$

$$u_D D_{m^i} - (n^1 + n^2) E_F v^i g^i - \lambda p v^i g^i = 0 \qquad (4)$$

[14] This will be the case unless the innovator is able to extract the entire surplus generated by its discovery.

[15] For example Coe and Helpman, 1995, Bernstein and Mohnen, 1998, Madsen, 2007. See also Brandstetter, 1998 and Cincera and Van Pottelsberghe de la Potterie, 2001 for surveys.

[16] More recently, Popp (2006) finds evidence of international knowledge spillovers in air pollution control technologies. Using patent citations, he finds that countries that are late to enact environmental regulation have domestic innovative activities that build upon foreign patents of countries that regulated early. For example, the US regulated NOx emissions from power plants later than Japan. This late regulation did stimulate US patenting activities that were based upon (citing) existing Japanese patents.

[17] A subscript indicates a partial derivate so that, for example, D_m^i represents the derivative of D with respect to m^i.

$$u_D D_{v^i} - (n^1 + n^2) E_F m^i g^i - \lambda[h^i(g^1, g^2) + pm^i g^i] = 0 \quad (5)$$

$$(n^1 + n^2) E_F m^i v^i + \lambda[v^i h^i_{g^i} + \frac{n^j}{n^i} v^j h^j_{g^i} + pm^i v^i] = 0 \quad (6)$$

with i=1,2.[18]

The interpretation of these conditions is standard and involves the balancing of marginal social benefits and costs. For example, conditions (6) state that the fuel consumption rate of a car owned by an agent in region i should be lowered so that the marginal cost increase for that agent ($-v^i h^i_{g^i}$) is equal to the resulting marginal social benefit of this reduction. The marginal benefit has three components. First, the increased fuel efficiency lowers the agent fuel consumption by $m^i v^i$, which reduces the environmental disutility of all agents ($(n^1 + n^2) E_F / \lambda$).[19] Second, the agent's fuel costs are reduced by $pm^i v^i$. Third, the decline in g^i leads to positive spillovers for region j's agents which are per capita $\frac{n^j}{n^i} v^j h^j_{g^i}$. Next, we examine how the first best can be decentralized through taxes and subsides.

Decentralizing the world first best outcome

We assume that the social planner can impose taxes on gasoline (e^i), which may potentially differ across regions. We also allow for the possibility of a two part tax on vehicles: the first part being fixed per vehicle (s^i) and the second part depending upon the chosen fuel consumption rate ($t^i g^i$). Note that these taxes may be negative (*i.e.* a subsidy). As usual, net tax revenues are returned to agents as a lump sum rebate which, for simplicity, we assume is included in the agent's income y. Based on these taxes, agents and car manufacturers in each region act simultaneously. Region i's agent solves the following problem:

$$\begin{array}{l} Max\, u(x^i, D(m^i, v^i)) - E(F) + \delta^i [y - x^i - k^i v^i - (p + e^i) m^i v^i g^i] \\ wrt\ x^i, m^i, v^i, \delta^i \end{array} \quad (7)$$

where k^i is the price of a vehicle (including any tax or subsidy). The first order conditions are:

[18] To be concise, we do not repeat the resource constraint which is obviously also part of the first order conditions.

[19] Note that dividing by the marginal utility of income (λ) translates the utility change in monetary terms.

$$u_{x^i} - \delta^i = 0 \qquad (8)$$

$$u_D D_{m^i} - \delta^i[(p+e^i)v^i g^i] = 0 \qquad (9)$$

$$u_D D_{v^i} - \delta^i[k^i + (p+e^i)m^i g^i] = 0 \qquad (10)$$

Contrary to the social planner, the individual does not take into account the impact of his car travel decision on the global environment.[20] Competition in the car manufacturing industry leads to $k^i = h^i(g^1, g^2) + s^i + t^i g^i$ with g^i minimizing the total costs for a consumer of owning and operating a vehicle:

$$\underset{wrt\ g^i}{Min} \quad h^i(g^i, g^j) + s^i + t^i g^i + (p+e^i)m^i g^i \qquad (11)$$

In other words, competition leads to cars with a consumption rate that drivers desire. The first order condition of this problem is:

$$h^i_{g^i} + t^i + (p+e^i)m^i = 0 \qquad (12)$$

Comparing (3)-(6) with (8)-(10) and (12), we immediately find that, besides $\delta^i = \lambda$, the first best conditions match those in the decentralized setting if: [21]

$$e^i = \frac{E_F(n^1+n^2)}{\lambda} \qquad (13)$$

$$t^i = \frac{n^j v^j}{n^i v^i} h^j_{g^i} \qquad (14)$$

$$s^i = -t^i g^i \qquad (15)$$

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[20] We assume that the number of agents is so large that it is a good approximation to assume that the agent ignores the impact of its travel decision on F.

[21] As always, we assume that the social planner can, without any cost, transfer income across individuals and regions to insure $\delta^i = \lambda$.

Matching conditions (4) and (9) leads to the usual Pigovian tax (see for example Fullerton and West, 2002). This gas tax, which is here equivalent to an emission tax, fully internalizes the external environmental cost associated with driving. However, this instrument alone is not sufficient in our setting to achieve the first best. Indeed, the spillovers - another source of externality – also require taxing cars based on their fuel consumption rate in order to take into account the knowledge externality. By matching conditions (6) and (12), we find the appropriate tax rate t^i, which depends upon the importance of spillovers $h^j_{g^i}$. It also depends upon the size of the fleet benefiting from the knowledge spillovers ($n^j v^j$) relative to the size of the fleet being taxed ($n^i v^i$). Finally by matching (5) and (10), we also find that the revenues collected through t^i should be returned as a subsidy to car ownership. Interestingly, this two part tax structure (a subsidy on car ownership plus a tax based on the fuel consumption rate) is reminiscent of the feebate programs adopted or discussed in several countries.

The first best can in principle be achieved when regions or countries cooperate. One way to build the grand coalition is by designing a system of transfers that makes all countries better off (Chander and Tulkens, 1994). In most discussions on international environmental agreements only international transfers (in order to have full participation) and an emission reduction target by country is needed. Here, we need to force countries to use an extra tax instrument to address the R&D externality.

Uncoordinated policies in the two regions

Next, we examine the situation where there is no coordination in the policies followed by the two regions. We assume a two-stage game with both governments simultaneously setting their policy instruments at the first stage. At the second stage, consumers and car manufacturers in both regions simultaneously take their consumption and production decisions based on the first stage policy parameters. This game can be resolved by backward induction by first deriving stage two optimal decisions as functions of the policy instruments. In each region, consumers and car manufacturers' optimisation problems are identical to (7) and (11), leading to first order conditions similar to (8)-(10) and (12). For each region, the solution to this system provides a link between a region's policy choice and its agents' optimal decisions. But because of the spillovers, the decisions of agents in one region also depend upon the fuel consumption rate in the other region. Formally, for region j we have:[22]

$$x^j(e^j, t^j, s^j, p, y, g^i) \qquad (16)$$

$$m^j(e^j, t^j, s^j, p, y, g^i) \qquad (17)$$

$$v^j(e^j, t^j, s^j, p, y, g^i) \qquad (18)$$

$$g^j(e^j, t^j, s^j, p, y, g^i) \qquad (19)$$

(16) to (19) define a system of 8 equations with 8 unknowns whose solution gives stage two optimal choices as a function of stage one policy decisions of both governments.[23] Stage two optimal decisions may then be plugged into the governmental objective functions to solve the game. Rather than proceeding in this way, it is more revealing to start by analysing government i decision problem, assuming that it directly controls x^i, m^i, v^i, g^i while decisions are decentralized in region j. Government i objective function is then given by:

$$\begin{aligned} Max \quad & u(x^i, D(m^i, v^i)) - E(n^i m^i v^i g^i + F^j(e^j, t^j, s^j, p, y, g^i)) + \\ & \qquad \lambda^i [y - x^i - h^i(g^i, g^j(e^j, t^j, s^j, p, y, g^i))v^i - pm^i v^i g^i] \\ wrt \quad & x^i, m^i, v^i, g^i, \lambda^i \end{aligned} \qquad (20)$$

with $F^j(e^j, t^j, s^j, p, y, g^i) = n^j v^j(.) m^j(.) g^j(.)$ (21)

and where $v^j(.), m^j(.), g^j(.)$ are abbreviations for the functions (16) to (19). Government i realizes that its fuel efficiency target (g^i) is going to affect foreigners' decisions, which in turn have an impact on its citizens. First, g^i has an impact on the fuel consumed by foreign drivers and thereby on the level of domestic environmental disutility. Second, g^i is also affecting g^j which in turn has an impact on the cost of domestic cars via the spillovers. The first order conditions for this problem are:

$$u_{x^i} - \lambda^i = 0 \qquad (22)$$

[22] As the environmental externality is separable in the utility function (1), it will not affect the consumption of private commodities.

[23] For example, $g^i(e^i, t^i, s^i, e^j, t^j, s^j, y, p)$.

$$u_D D_{m^i} - E_F n^i v^i g^i - \lambda^i p v^i g^i = 0 \quad (23)$$

$$u_D D_{v^i} - E_F n^i m^i g^i - \lambda^i [h^i + p m^i g^i] = 0 \quad (24)$$

$$E_F (n^i m^i v^i + \frac{\partial F^j}{\partial g^i}) + \lambda^i [(h^i_{g^i} + h^i_{g^j} \frac{\partial g^j}{\partial g^i}) v^i + p m^i v^i] = 0 \quad (25)$$

To decentralize this outcome, government i should set its policy instruments so that conditions (8)-(10) and (12) match (22)-(25). This leads to:

$$e^i = \frac{E_F n^i}{\lambda^i} \quad (26)$$

$$t^i = \left(\frac{E_F}{\lambda^i v^i} \frac{\partial F^j}{\partial g^i} + h^i_{g^j} \frac{\partial g^j}{\partial g^i} \right) \quad (27)$$

$$s^i = -t^i g^i \quad (28)$$

Without coordination, both governments set fuel tax rates that are too low when compared to the world first best (compare (26) with (13)). It is easy to understand why: each government only cares about the environmental damage to its citizens. In other words, it ignores the environmental impact of its citizens' driving on foreigners. From (27), we observe that government i may want to stimulate its citizens' demand for fuel efficiency by imposing $t^i > 0$ if this reduces fuel consumed by foreign drivers (*i.e.* if $\frac{\partial F^j}{\partial g^i} > 0$). Note that the second term of (27) is an 'echo effect': if reducing g^i lowers g^j, this will bring back positive spillovers to region i ($h^i_{g^j}$). Once again the tax collected on vehicle performance should be returned as a lump-sum subsidy on car ownership (equation (28)). In the uncoordinated case, the motivation for taxing vehicle fuel rating is therefore quite different than in the world first best situation. Indeed, the tax does not aim at internalizing the spillovers but rather it is using the innovation spillovers in order to mitigate the environmental externality. Based on (21), we have that:

$$\frac{\partial F^j}{\partial g^i} = n^j \left(m^j(.) v^j(.) \frac{\partial g^j}{\partial g^i} + v^j(.) g^j(.) \frac{\partial m^j}{\partial g^i} + m^j(.) g^j(.) \frac{\partial v^j}{\partial g^i} \right) \quad (29)$$

The impact of g^i on foreign gasoline consumption depends upon how it is going to affect foreign vehicle fuel rating and the vehicle and mileage demand. The sign and magnitude of these effects depends upon the structure of the preferences and the cost function. However, since reducing g^i lower the marginal cost of providing fuel efficiency improvement in region *j*, we may expect a lowering of g^j in equilibrium. The impact on mileage and vehicle number is difficult to predict as both operating and ownership cost are affected in equilibrium by g^i.[24]

To gain more insight, suppose that government *i* only considers the impact of its decision on foreign car manufacturers, wrongly ignoring the reaction of foreign drivers.[25] In such a setting, government *i* only considers the reaction of region *j* car manufacturers. For these manufacturers, g^j is such that:

$$h^i_{g^j} + t^j + (p + e^j)m^j = 0$$

By totally differentiating this condition, we obtain:

$$\frac{\partial g^j}{\partial g^i} = -\frac{h^j_{g^j g^i}}{h^j_{g^j g^j}} > 0$$

which justifies taxing vehicle in region *i*. Note that if spillovers have no impact on the other region's marginal average cost ($h^j_{g^j g^i} = 0$), region *i* has no control over foreign emissions. In this case, a gasoline tax is sufficient to achieve the outcome that the regional government can reach without coordination. If at the other extreme, spillovers from region *i* fully compensate region *j*'s marginal average cost increase when g^j is reduced (*i.e.* $\left|h^j_{g^j g^i}\right| = h^j_{g^j g^j}$), government *i* has the same control over foreign car performance than on its domestic fleet.[26] Note that, even if the

[24] How these variables change in equilibrium also depends on their relationship in the utility function. Empirical evidence suggests that mileages per car are declining with the number of cars owned, suggesting these goods are substitutes.
[25] Specifically, government *i* assumes that m^j and v^j remain constant.
[26] Note that this situation could also occur if cars in the two regions are produced by the same companies (joint production) and that adjustment costs and relative market size lead manufacturers to produce only one type of car for the two markets. For example, Canadian models are usually either very close or identical to their US counterparts. It may therefore be that US policy makers have control over the performance of Canadian cars. Another example is the

choice of g^i has a limited impact on g^j, the overall benefit of a small reduction in reducing g^j for region i may still be significant if the total vehicle-miles in region j , $n^j v^j m^j$, is large (see (29)).

To summarize, we find that a fuel tax (or emission tax) may not be sufficient to insure the first best outcome when there are international knowledge spillovers. Taxing cars on their fuel rating is required to internalize the spillover effects between regions. If governments are unable to coordinate their policies, we find that a tax based on fuel rating may be a way to have an indirect impact on foreign emissions.

As mentioned in the introduction, several countries are adopting standards rather than taxes and subsidies to stimulate automobile fuel efficiency. It is therefore interesting to analyse standard setting when there are international knowledge spillovers. To that end, we use in the next section a simplified version of our model.

III. Fuel Efficiency Standards

We now consider a partial equilibrium model where the only control variables of governments are the car fuel consumption rates (g^i). To simplify further, assume that i) both regions have an identical number of agents ($n^1 = n^2 = n$), ii) each agent has one car ($v^i = n^i$) and iii) the distance driven is fixed and identical for all ($m^1 = m^2 = m$). As a benchmark, we start by characterizing the world first best solution. In this simplified world, the social planner objective is to minimize the sum of the environmental damage, the cost of producing cars and their fuel costs. Formally,

$$\begin{array}{ll} Min & 2nE\big((g^1 + g^2)nm\big) + nh^1(g^1, g^2) + nh^2(g^1, g^2) + pnm(g^1 + g^2) \\ wrt & g^1, g^2 \end{array} \quad (22)$$

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export of used cars from Europe to Africa. Improvements in fuel efficiency in Europe increase therefore in the long run the performance of cars in Africa.

$E(.)$ represents the per capita environmental damage expressed in monetary value as a function of total fuel consumption.[27] The optimal policy calls for setting a standard in each region so that the marginal social benefit equals the marginal cost:

$$2E_F nm + h^j_{g^i} + pm = -h^i_{g^i} \qquad (23)$$

Positive knowledge spillovers ($h^j_{g^i} > 0$) favour the adoption of stricter standards. For the case of uncoordinated standards in the two regions, we consider two scenarios, depending on whether governments move simultaneously or sequentially.

Simultaneous standard setting

Each region's authority sets its standard by solving:

$$\begin{array}{ll} Min & E\left((g^1 + g^2)nm\right) + h^i(g^1, g^2) + pmg^i \\ wrt & g^i \end{array} \qquad (24)$$

The first order condition is

$$E_F nm + pm = -h^i_{g^i} \qquad (25)$$

which implicitly defines a reaction function ($g^i(g^j)$). The intersection of both regions reactions function gives the equilibrium standards. Comparing (25) with (23), it is immediate that standards are set too loose when comparing to the first best. Without coordination, cars have fuel consumption rates that are too high for two reasons: i) each government ignores the impact its drivers have on the other region and ii) knowledge spillovers are not fully used. Both aspects lead to an under-valuation of the marginal benefit of fuel efficiency.

Sequential standard setting

The simultaneous game results are not particularly surprising. More interesting is the case of sequential decision making. Suppose government 1 decides first on fuel efficiency. Government 2 follows suit after having observed region 1's decision. Using backward induction, government

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[27] It is different from *E()* in Section II, which represented the agent's disutility linked to pollution.

2's decision problem is identical to (24). However, at the first stage of the game, government 1 can take into account the impact of its decision on government 2's decision. Formally, it sets its standard by solving:

$$Min \quad E\Big((g^1 + g^2(g^1))nm\Big) + h^1(g^1, g^2(g^1)) + pmg^1 \qquad (26)$$

The first order condition is:

$$E_F mn(1 + \frac{\partial g^2}{\partial g^1}) + h^1_{g^1} + h^1_{g^2} \frac{\partial g^2}{\partial g^1} + pm = 0 \qquad (27)$$

where $\frac{\partial g^2}{\partial g^1}$ is the slope of government 2's reaction function. Differentiating (25) with respect to g^1, g^2, we find that:

$$\frac{\partial g^2}{\partial g^1} = -\frac{E_{FF}(nm)^2 + h^2_{g^2 g^1}}{E_{FF}(nm)^2 + h^2_{g^2 g^2}} \qquad (28)$$

which may be positive or negative. Indeed, if there are no knowledge spillovers ($h^2_{g^2 g^1} = 0$), an effort by country 1 to reduce emissions by lowering g^1 is partially compensated by a higher g^2. This is the traditional free-riding curse. However, if positive spillovers are sufficiently important, a higher fuel standard in country 1 leads to the adoption of a stricter standard in country 2. In turn, this reaction pushes region 1 to adopt a stricter standard, thereby partially countervailing the free-riding incentive. When the marginal environmental damage function is constant ($E_{FF} = 0$), a higher fuel efficiency policy in one country will generate a larger emission reduction in the other region via the innovation spillovers. Once again, even if the spillovers are limited, the potential benefits may be important if the other region is large. To illustrate the relevance of these effects, we develop in the next section a simple numerical example, which is based on the Californian standards and their potential impacts on the rest of the US and Canada.

Illustration

The purpose of this example is not to provide a comprehensive and detailed numerical simulation but rather to provide a 'back of the envelop' computation of how and to what extend the effects described above may be of relevance. In 2004, California imposed a 30% reduction in GHG emission rates by 2016. While the standards vary by type of vehicles and allow reducing GHG emission rates via improvements in air conditioning systems, the *California Air Resources Board* (2008) estimates that they would raise the average fuel efficiency of the fleet from about 25.1 to 35.7 MPG or equivalently reduce the fuel consumption rate from 3.98 to 2.8 gallons per 100 miles. To simplify the illustration, assume that i) these standards have no impact on driving distance or on the number of vehicles and ii) California ignores the 'eco effect' (*i.e.* it assumes that $h_{g}^{Cal}{}_{RUSC} = 0$). Based on our simplified model, the standard should be set so that the marginal fuel cost saving (*MFCS*) plus the marginal environmental benefit (*MEB*) equal the marginal cost (*MC*) imposed by the standard via higher vehicle prices. We evaluate *MFCS*, *MEB* and *MC* in annual and per capita terms.

Based on Fisher *et al.* (2007), the price increase of a vehicle as the fuel consumption rate is reduced may be approximated by:

$$213 + 1941(\bar{g} - g)$$

with $\bar{g}$ being the initial level of the fuel consumption rate (in our case $\bar{g}$ =3.98). Assuming that vehicles last for 14 years, government uses a social discount rate (r) of 5% and given that in the US the number of cars per capita is about 0.8 (Harrington, 2008), the per capita marginal cost of reducing g is approximately:[28]

$$MC = 16 + 150(\bar{g} - g).$$

For *MFCS*, we use a per Californian annual driving distance of 8,015 miles (FWH Statistics, 2005) and a 2004 average price of gasoline net of taxes in California of 1.59$ per

[28] We multiply the vehicle price increase by 0.8 x (1-d)/(1-d^{14}) with d=1/(1+r).

gallon.[29] The total reduction in fuel expenditure is thus given by $1.59\,x\,80.15\,(\bar{g}-g)$, implying a *MFCS* constant at 127$.

For *MEB*, we only consider climate changes as it is the driving motivation behind the Californian initiative and we assume that environmental damage is linear in the quantity of fuel consumed. The *MEB* associated with a reduction in *g* is therefore given by:

$$MEB = w\left(n^{Cal}m^{Cal} + \frac{\partial g^{RUSC}}{\partial g^{Cal}} n^{RUSC} m^{RUSC}\right)$$

with *w* the constant per capita environmental damage generated by one gallon of gasoline. *Cal* stands for California and *RUSC* for rest of the US and Canada. For the population figures, we use n^{Cal}=36 millions, n^{RUSC}=300 millions and for the mileage per capita (expressed in 100 miles) m^{Cal}=80.15 and m^{RUSA}=100. Following Fisher *et al.* (2007), we assume a value of 50$ per ton of CO_2 implying a worldwide damage of 12 cents per gallon of gasoline. If damages are equally distributed across the world, the damage per capita is then a meagre 0.12$/6.6 billions! In fact, if we use this figure, *MEB* is negligible even in the best case scenario, where the rest of the US and Canada also adopt the Californian standards (*i.e.* $\frac{\partial g^{RUSC}}{\partial g^{Cal}} = 1$). Indeed, *MEB* is less than 0.6$ and represents about 0.5% of *MFCS*. From these simple computations, we derive a first observation: *California should somehow take into account the world damage for climate change to be a significant factor affecting the stringency of the standards*.

Therefore let us assume that California evaluates *MEB* using the worldwide climate change damage of 12 cents, which per Californian translates into 0.12$/$n^{Cal}$. *MEB* becomes:[30]

$$MEB = 0.12\left(m^{Cal} + \frac{\partial g^{RUSC}}{\partial g^{Cal}} \frac{n^{RUSC}}{n^{Cal}} m^{RUSC}\right)$$

If $\frac{\partial g^{RUSC}}{\partial g^{Cal}} = 0$ (absence of spillovers), *MEB* is 9.6$ which combines with *MFCS* and takes into account *MC,* justifies a standard of 3.16 gallon per 100 miles. This leads to our second observation: *if Californian standards have no impact on fuel efficiency elsewhere, climate change*

[29] Based on the *California Energy Commission*, the 2004 yearly average price of gasoline was 2.12$ per gallon so that the price net of taxes was about: 2.12/1.08 (sale taxes of 8%) minus the federal and state excise taxes of 0.364$.
[30] Obviously if every region takes into account the world damage, we could end-up with an over-production of the public good in the sequential setting.

concerns only marginally affect the standard. Indeed, compared to a fuel rating based on *MFCS* exclusively, *MEB* increases the stringency of the standard by less than 3%.[31]

At the other extreme, suppose that innovation spillovers are such that the rest of the US and Canada follow the Californian lead ($\frac{\partial g^{RUSC}}{\partial g^{Cal}} = 1$), *MEB* is then 109.6$ and calls for a standard at 2.51 gallons per 100 miles. To justify the 2016 standard of 2.8 requires having $\frac{\partial g^{RUSC}}{\partial g^{Cal}} = 0.56$ or equivalently that 56% of the rest of the US and Canada adopt the Californian standards. Recall that, as of May 2008, 16 US States and Canadian Provinces, representing about half of the population, have announced that they would adopt the California norms. Consequently, a third observation we can make is the following: *having an impact on the out of State fuel efficiency may be a key in understanding the Californian policy*. In fact, this consideration is made explicit in some of the State official report. For example, the *California Global Warming Solution Act of 2006* assumes that stricter domestic regulations will favour stricter standard abroad: *"…actions taken by California to reduce emissions…will have far-reaching effects by encouraging other states, the federal government, and other countries to act"* (Chapter 2, section (d), page 89). Obviously, several factors could explain this bandwagon effect. It therefore remains to evaluate, in future research, to what extent spillovers are involved in explaining policies interdependence.[32]

IV. Conclusions

In this paper we constructed a simple model to understand the widespread use of unilateral fuel efficiency policies for cars. The model contains environmental spillovers generated by car use, but also innovation spillovers associated to making more fuel efficient cars. The cooperative solution requires the use of extra incentives to increase the fuel efficiency selected by each region. In the non-cooperative solution, each region uses the innovation spillovers as a way to

[31] *MFCS* justifies a fuel rating of 3.24.
[32] Note that the role of innovation is clearly a central aspect of Californian strategy as expressed in the State Global Warming Solution Act of 2006: *'More importantly, investing in the development of innovative and pioneering technologies…will provide an opportunity for the state to take a global economic and technological leadership role in reducing emissions of greenhouse gases'*

counter the under-taxation of the environmental externality resulting from the lack of cooperation. This means that each region imposes a domestic car tax on fuel rating with the objective of improving the fuel rating abroad, thereby reducing pollution caused by foreigners. If standards are used to improve fuel efficiency, we find that spillovers may somewhat alleviate free-riding. Indeed, we show that, in a sequential game, a more ambitious fuel efficiency standard by the leader may stimulate the following region to also adopt more ambitious standards.

In our model, we have assumed perfect competition in the car markets. Adding market power would certainly be interesting but it is unlikely to affect the main conclusions of our analysis. Indeed, even with market power, it is very likely that the equilibrium fuel economy of cars will depend upon the marginal cost of offering more efficient cars. Policy in one region should therefore still have an impact on the other region's car performance when there are spillovers. For simplicity, we have also assumed that manufacturers are only producing cars in one region. With multi-product and multi-market firms, some spillovers are probably going to be internalized. However, it is likely that spillovers continue to plague the innovation process. Moreover, even if the world car market was dominated by a monopolist internalizing all innovation spillovers, each region government may still have an incentive to affect the fuel efficiency of car sold abroad.[33]

More generally, all what is needed to justify fuel efficiency policy in an international setting is some cost dependence between the vehicles sold in the two regions. Here, we have assumed that innovation spillovers create such a link but other factors may be at play, such as economies of scale in the production of fuel saving technologies or learning by doing. For example, if the cost of a new fuel saving technology is declining with the number of equipped vehicles, a standard that forces adoption in one region may reduce the adoption cost in other regions. Also, with multi-market firms, adjustment costs associated with offering market specific models could lead to policy interdependence.

[33] Obviously in the coordinated case, a gasoline tax should be sufficient to decentralize the first best outcome.

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