Optimum Tariffs and Exhaustible Resources: Theory and Evidence for Gasoline*

by

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Abstract

Domestic consumption taxes on oil products largely differ across countries, ranging from very high subsidies to very high taxes. The empirical literature on the issue has highlighted the role of revenue-raising (Ramsey commodity taxation) and externality-correction (Pigovian taxation) motives for national taxation. Isolatedly, the theoretical literature on non-renewable-resource taxation has emphasized the role of the optimum-tariff dimension of excise taxes which reflects countries' non-cooperative exercise of their market power. This paper reconciles these two strands by comprehensively addressing the issue. First, we propose a multi-country model of national taxation with oil – modeled as a polluting exhaustible resource – and some regular commodities. Domestic welfare is maximized with respect to domestic taxes under a revenue-collection constraint. The optimal domestic tax on oil consumption not only consists of a Ramsey inverse-elasticity term and of a Pigovian term, but also of an optimum-tariff component. In fact, resource exhaustibility implies a form of supply inelasticity that magnifies optimum-tariff arguments. Second, based on a multiple regression using a data set with a large number of countries, we test the power of the optimum-tariff tax component in explaining national gasoline taxes. We find strong evidence that this component plays a crucial role in countries' taxation of gasoline.

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1. INTRODUCTION

The statistical dispersion of taxes on oil products has attracted scholars' interest toward the factors driving governments' adoption of those taxes. Surprisingly, the empirical and theoretical literatures dealing with the issue of oil taxation have followed different trajectories.

A natural first hypothesis is that countries set their domestic taxes on oil products in order to raise revenues as well as to correct external effects of oil use. The underlying theories for such motives of taxation have been developed in the public economics literature and are well known as Ramsey taxation and Pigovian taxation.

On the one hand, Ramsey commodity taxation theory addresses the problem of a government concerned with social welfare but in the need of collecting a set amount of tax revenues; thus seeking to minimize the deadweight loss of taxation by evenly spreading distortions across sectors.[1] Its most famous result is the "inverse-elasticity rule": under simplifying conditions, commodities should be taxed at rates that are inversely proportional to the price elasticity of demand on each market. As oil demand is relatively price inelastic[2], the theory calls for relatively high taxes applied on the final consumption of oil products; all the higher as revenue needs are greater.

This simple and insightful rule assumes that distortions are only determined on the demand side: producer prices are given, either because countries are extremely small or because returns to scale are constant as they should be in the long run.[3] However, from a global perspective, long-run oil supply cannot be perfectly elastic since it results from an extraction decision. Therefore, when countries recognize their effect on prices, domestic demand and world supply combine to determine the tax distortion on the oil market;

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[1] The literature originated with Ramsey (1927) and Pigou (1928) and was further consolidated by Baumol and Bradford (1970), Diamond and Mirrlees (1971a), Dasgupta and Stiglitz (1974) and Atkinson and Stiglitz (1980), among others.

[2] Berndt and Wood, 1975; Pindyck, 1979; Hausman and Newey, 1995; Krichene, 2002.

[3] In Ramsey's original closed-economy setting, the general inverse-elasticity rule (1927, p. 56) reduces to its demand component only when supply is perfectly elastic.

Daubanes and Lasserre (2012) showed that account must be taken of the non-renewable character of oil to extend Ramsey's insight to the case of such a commodity.

On the other hand, Pigovian taxation consists of setting a tax in such a way as to correct a market failure due to an external effect generated by the production or the use of a commodity.[4] A Pigovian tax internalizes the external damages (benefits) and should be set equal to the marginal damage (benefit) evaluated at optimal quantities. The most often cited external effects of fuel use are pollution and congestion; both call for positive taxes whose magnitude should reflect how a country is contributing to, and subject to, such effects.

The recent availability of reliable, relatively-large-scale data has allowed empirical analyses of the determinants of oil taxes. This literature has focused on Ramsey and Pigovian taxation motives. Rietveld and van Woudenberg (2005) clearly and exhaustively addressed the question of how well factors thought to be characteristic of those motives explain actual international differences in final fuel prices. Their principal result is that countries mainly tax fuel with the view to raising revenues.[5] Neither Rietveld and van Woudenberg nor the other studies on the topic have addressed optimum-tariff arguments. As we will explain later in this introduction, their methods sometimes reveal the need to do so.

Parry and Small's (2005) contribution on gasoline's national taxation justifies the focus on the revenue-raising and corrective objectives of taxation. From a small-country model where producer prices are given, they derive a formula for the optimal national tax on gasoline.[6] The formula consists of a Ramsey inverse-elasticity term and of Pigovian terms (one corresponding to pollution and another to congestion). Since the exhaustible

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[4] The related literature originated with Pigou (1912 and 1920) and was further developed by Baumol (1972).

[5] Among other results, the analyses of Hammar, Löfgren and Sterner (2004) and Liddle and Lung (2010) deliver the same message. In Dunkerley, Glazer and Proost (2010), the median voter departure from the representative-agent standard aggregation should not hide that the underlying theories are Ramsey taxation and Pigovian taxation. Their empirical model, however, does not include a measure of government revenue needs.

[6] They compute it for the US and the UK. Ley and Boccardo (2010) reproduced Parry and Small's computations for other countries.

character of oil implies that the supply of oil products cannot be perfectly elastic, the insensitiveness of their international producer price must be interpreted as reflecting that countries are extremely small on the oil market. In fact, this assumption is at the root of their result; the common practice in the empirical literature to focus on revenue-raising and corrective objectives can be justified on this ground.

As earlier anticipated by Bizer and Stuart (1987), the international oil price is endogenously determined so that domestic taxes affect it.[7] Thus the determination of optimal taxation policies "requires modeling equilibria in a game of trade policy played by different countries." (p. 1019). When account is taken of this remark, we will see that the optimal domestic tax on oil products consists of an additional, optimum-tariff component.

The resource economics literature has emphasized the ability of domestic taxes on non-renewable-resource consumption to improve countries' national surpluses, even when revenue constraints and pollution are assumed away. This is clearly the case in Bergstrom's (1982)[8] multi-country model of oil trade where countries selfishly set their excise taxes on oil in order to maximize national welfare. In Nash equilibrium, their constant-rate optimal taxes on the costlessly-extracted resource are given by a "rule relating the equilibrium excise tax rates to demand elasticities and market shares" (p. 194). Bergstrom's rule implies that oil-importing countries should impose positive taxes on oil domestic consumption while oil-exporting countries should set them negative.[9] As

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[7] According to Karp and Newbery (1991) "the evidence for potential market power on the side of importers is arguably as strong as for oil exporters" (p. 305); see also Liski and Montero (2011). For an empirical validation of the effect of US states' gasoline taxes on the producer price, see Chouinard and Perloff (2004): the lower consumer incidence of federal or big states taxes must rely on some producer incidence.

[8] Following his contribution, Amundsen and Schöb (1999), Rubio and Escriche (2001), Liski and Tahvonen (2004), Strand (2008) and Daubanes and Grimaud (2010) have integrated pollution externalities arising from the use of the resource; their results show how the rent-extracting effect of domestic taxes highlighted by Bergstrom and the willingness to regulate pollution combine to determine countries' optimal taxes on the resource. Long's (2011) recent survey paper emphasizes the fundamental strategic aspect of this literature as well as Bergstrom's (1982) connection with contributions on tariffs. The literature has not attempted to empirically validate its findings on the factors of oil taxation. An exception is Bretschger and Valente (2010) to the extent that they show oil-importing countries' relative income to positively depend on the level of their domestic oil taxes.

[9] Bergstrom focused on oil-importing countries and omitted to comment on the second part of the proposition. However, this is immediate from Bergstrom's analysis and consistent with the optimum-

a result, the final price of oil in importing countries is above the international price of oil while it is below this level in oil-exporting countries. Introducing revenue constraints and pollution damages in Bergstrom's canonical trade model, we will show that Bergstrom's rule combines with Parry and Small's (2005) Ramsey and Pigovian tax components.

Bergstrom's excise tax is not a trade tariff, but is only formally equivalent to it when importing countries have no reserves at all like in Karp and Newbery (1991).[10] Much of his insights survive when countries set proper tariffs instead of domestic consumption taxes (Brander and Djajic, 1983). In fact, forces at work in Bergstrom (1982) are the same as in the old optimum-tariff literature – originating with Bickerdike (1906) and consolidated by Graaff (1949-1950) and Johnson (1951), among others – which investigated how a country benefits from trade taxation. The resemblance with results on domestic taxation supposes that domestic taxes are not unlike tariffs. This is the point of Friedlander and Vanderdorpe (1968) and Dornbusch (1971), showing that a tariff dimension of domestic consumption taxes arises when countries are constrained on their tariffs.[11] Thus, optimum-tariff arguments are relevant to the issue of optimal taxation of domestic consumption: in essence, one country's optimal domestic tax on a traded commodity reflects its effect on the international price of the commodity, manipulating the country's terms of trade in the country's favor. Such exercise of one country's market power through its taxation policy requires that the commodity's supply is non-perfectly elastic and culminates in the case of an inelastically-supplied commodity. The exhaustible character of oil implies that cumulative oil supply is inelastic in the long run. This peculiar form of long-term inelasticity must be the reason why the tax competition problem received so much attention in resource economics. Perfect inelasticity of the resource stock generates pure economic scarcity rents accruing to producers. The tax

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tariff theory. More on this further below.

[10] When consuming countries and producing countries are disjoint, as in many treatments of non-renewable resource taxation, domestic consumption and domestic production respectively coincide with imports and exports, implying that domestic taxes are perfectly equivalent to tariffs.

[11] The results heavily relies on the property that a tariff can be reproduced by the combined use of a domestic consumption tax and of a domestic production subsidy; see Mundell (1960, p. 96). A justification for such tariff constraints may be the existence of international tariff agreements. On this, see, e.g., Friedlander and Vanderdorpe (1968) and Keen (2002).

competition problem can then be interpreted as a ”fight for the rent” and has found a particular echo as such in the resource literature, also referring to the ”rent-capturing” dimension of oil taxes.

Neither is this paper about tariffs per se; the analysis is rather about all domestic taxes that are added (deducted) to (from) the international producer price to determine the final price domestic consumers face in each country. Nevertheless, to the extent that, following the above rent-capture literature, a full account should be taken of how the international price of oil depends on them, domestic taxes will acquire the dimension of optimum tariffs.

There might be another consideration. Governments may also be concerned with the intra-country distributional impacts of taxes. Domestic taxes differently affect heterogeneous individuals within countries. Hence, as is well-known from the public economics literature, distributional objectives, when they cannot be reached by other means of transfer, may bias countries' optimal taxes, whether they are applied to raise revenue (Diamond and Mirrlees, 1971b) or to correct externalities (e.g. Cremer, Gahvari and Ladoux, 2003). The same remark must apply to tariffs or to domestic taxes pursuing the same objective as tariffs. Distributional effects imply that political economy theories may combine with optimal taxation theories addressed here. Such complications are out of the scope of our theoretical analysis; as in many conventional treatments, we will assume a representative agent per country.

Would optimum-tariff arguments have any relevance for oil domestic taxation in the real world? Could this theory help explain the international distribution of oil taxes? Two elements suggest the answers to these questions should be positive. First, the optimum-tariff theory has recently received renewed attention by Broda, Limão and Weinstein (2008) who empirically showed the importance of countries' market power exercise in taxation decisions by finding strong evidence that countries' relative market power and world supply elasticity have been crucial factors of domestic tariffs. Second, this theory seems to have a crucial explanatory advantage. Basic observations on the international distribution of oil taxes suggest that importers tax oil consumption while most of exporters subsidize it. In other words the latter set a domestic price lower than the international price at which they export. This feature is very consistent with Bergstrom's theoretical predictions and with the optimum-tariff theory while neither revenue-collection nor negative-externality-correction motives can account for negative taxes on oil.[12] This has not handicapped most of the empirical studies on oil taxation, which restricted their attention to OECD countries, mostly oil importers. A notable exception is Rietveld and van Woudenberg's (2005) paper where OPEC and non-OPEC countries were given a different treatment in the regression analysis, making their public-finance-inspired empirical model consistent with very low prices in the former subgroup.[13]

Rietveld and van Woudenberg also consider border tax competition between neighboring countries (Kanbur and Keen, 1993) by integrating the prices in neighboring countries to explanatory variables. While border tax competition interestingly captures part of the intra-regional homogeneity in taxes, it cannot account for their observed inter-regional heterogeneity (e.g. between Europe, Middle East, Africa...). In contrast, the optimum-tariff theory suggests that domestic taxes reflect the respective situations of countries vis-à-vis the oil market as a whole (in terms of consumption and production), yet relative to other countries, but irrespective of their proximity or distance. As a matter of facts, countries' consumption and production patterns are often similar within the same region while they widely vary from one region to another. Therefore, the optimum-tariff dimension of domestic taxes should be expected to complementarily account for the intra-regional homogeneity of taxation patterns while also contributing to explain their inter-regional heterogeneity.

This paper aims at reconciling the empirical and the theoretical literatures on the factors of domestic oil taxation. Our contribution is twofold. In a first theoretical

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[12] As noted earlier, distributional effects are not addressed here. However, such considerations are at the root of the very popular belief that some countries subsidize oil in order to operate transfers to some groups of consumers; see e.g. Gupta et al. (2002). As they argue, such subsidies do not reach their supposed equity objectives.

[13] This distinction was meant to control for the "presence of alternative tax base". It can also be interpreted as the recognition that public-finance variables alone cannot account for oil subsidies.

part, we show how Ramsey and Pigou taxation motives combine with the optimum-tariff dimension of domestic oil taxation to determine the optimum domestic tax on oil consumption in each country. We propose a highly stylized multi-country model of national taxation with oil – explicitly modeled as an exhaustible resource – and some conventional commodities. Equilibrium national taxes on oil consumption consist of three separable terms, each weighted according to the cost of raising tax revenues: a Ramsey, open-economy inverse-elasticity component, a Pigovian component and a Bergstrom's optimum-tariff component.

In a second part, we revisit the empirical literature on the factors of domestic gasoline taxation by introducing an optimum-tariff variable. Theory suggests the optimum-tariff dimension of oil taxes to depend on the long-term cumulative net imports, i.e. the long-term difference between domestic consumption and production. We compute the optimum-tariff variable by approximating the long-term relative difference between consumption and production. Based on a multiple regression model and using a data set consisting of a large number of countries, we show that this variable powerfully explain national gasoline taxes. The evidence provided by this paper consolidates and extends the recent empirical findings on the relevance of the optimum-tariff theory (Broda et al., 2008).

2. A MODEL OF NATIONAL OIL TAXATION UNDER A REVENUE CONSTRAINT

Optimum taxation à la Ramsey easily extends to an international framework as long as supply elasticity is infinite. However, the supply of a non-renewable resource cannot be so as it is a flow extracted from a limited stock; in fact, a standard Hotelling representation implies that long-run total reserves are perfectly inelastic. It is thus interesting to see how Ramsey's problem carries over to a multi-country setting in the presence of a non-renewable resource.

This requires modifying the traditional treatment of optimum commodity taxation in at least two respects. First, the extraction of a non-renewable resource has an intertemporal dimension; the problem should thus be addressed in a dynamic setting.

In the absence of revenue constraint and under simplifying conditions, we know from Bergstrom (1982) that the intertemporal dimension vanishes to deliver clear and insightful messages on the optimal taxation problem. The same simplification should be expected with revenue constraints. Second, the Ramsey problem should be interpreted as a game-theoretic problem. The strategy of each government is its set of domestic commodity taxes, chosen with the view to maximizing national welfare while raising a specific amount of fiscal revenue. From Bergstrom's (1982) paper, we know that the strategic aspect of the problem is crucial and that it should modify the optimal domestic tax on oil consumption in a way that depends on each country's aggregate position and power over the oil market. Finally, there is the consideration of negative externalities arising because pollution/congestion.

Our problem essentially consists in extending Bergstrom's framework by imposing country-specific revenue constraints and by assuming external damages from domestic oil consumption. In the sequel, we do so in a highly stylized fashion; in particular, we borrow standard assumptions from the optimum-commodity-taxation literature and adapt them to a dynamic setting as in Daubanes and Lasserre (2012).

2.1 The model

The economy consists of $n \geq 2$ countries indexed by $i = 1, 2, ..., n$, each represented by one consumer. There are $m \geq 1$ conventional, producible commodities indexed by $j = 1, ..., m$ and oil, that will be indexed by $j = 0$.

Arbitrage possibilities will establish a single producer price $p_j(t)$, for each good $j = 0, ..., m$, at each date $t \geq 0$, that suppliers receive regardless of the country in which they sell. At each date t, each country i imposes an ad valorem consumption tax $\theta_j^i(t) > -1$ on good j so that the consumer price for this good is

$$q_j^i(t) = p_j(t)\big(1 + \theta_j^i(t)\big). \tag{1}$$

The quantities of goods $j = 0, ..., m$ consumed and supplied by country $i = 1, ..., n$ at date $t \geq 0$ are respectively denoted by $x_j^i(t)$ and $s_j^i(t)$. Storage is not possible so that goods must be consumed as they are produced. Since the resource is non-renewable, all countries' exhaustibility constraints

$$\int_0^{+\infty} s_0^i(t)\,dt \leq S_0^i \tag{2}$$

must be satisfied, where S_0^i is the initial size of country i's stock of oil.

For given taxes $\Theta \equiv \left(\left\{\theta_j^i(t)\right\}_{t\geq 0}\right)_{j=0,\ldots,m}^{i=1,\ldots,n}$, world competitive markets lead to the equilibrium allocation $\left(\left\{\widetilde{x}_j^i(t)\right\}_{t\geq 0}, \left\{\widetilde{s}_j^i(t)\right\}_{t\geq 0}\right)_{j=0,\ldots,m}^{i=1,\ldots,n}$; in the sequel, a tilda on the top of a variable or function will mean that this variable or function is evaluated at the competitive equilibrium for given taxes Θ.

Defining country i's welfare as the discounted sum of instantaneous national surplus $W^i(t)$, the national optimum-commodity-taxation problem of this country in a multi-country economy consists in choosing a set of taxes $\Theta^i \equiv \left(\left\{\theta_j^i(t)\right\}_{t\geq 0}\right)_{j=0,\ldots,m}$ in such a way as to maximize national welfare in competitive equilibrium while raising a set amount of discounted revenue $R^i(0)$, taking as given the taxes of other countries $\Theta^{-i} \equiv \left(\left\{\theta_j^k(t)\right\}_{t\geq 0}\right)_{j=0,\ldots,m}^{k\neq i}$:

$$\max_{\Theta^i} \int_0^{+\infty} \widetilde{W}^i(t) e^{-rt}\,dt \tag{3}$$

$$\text{subject to} \int_0^{+\infty} \sum_{j=0}^{m} \theta_j^i(t)\widetilde{p}_j(t)\widetilde{x}_j^i(t) e^{-rt}\,dt \geq R^i(0), \tag{4}$$

where r is the international discount rate. It is assumed that the set of taxes capable of levying $R^i(0)$ is not empty.

Financial markets allow expenditures to be disconnected from revenues so that the tax revenue constraint (4) does not bind the government at any particular date. Hence, the government accumulates an asset $a^i(t)$ over time by saving tax revenues:

$$\dot{a}^i(t) = ra^i(t) + T^i(t), \tag{5}$$

where $T^i(t) \equiv \sum_{j=0}^{m} \theta_j^i(t)\widetilde{p}_j(t)\widetilde{x}_j^i(t)$ denotes the current tax revenue. Normalizing the initial amount of asset to zero, the problem of maximizing (3) subject to (4) is equivalent to the maximization of (3) subject to (5) if

$$\lim_{t\to+\infty} a_j^i(t) e^{-rt} = R^i(0) \tag{6}$$

is satisfied.

As in Ramsey (1927), Baumol and Brandford (1970), Atkinson and Stiglitz (1980) and traditional contributions deriving the inverse-elasticity rule of optimum commodity taxation, we assume that the demand $D_j^i\big(q_j^i(t)\big)$ of country $i = 1, ..., n$ for any commodity $j = 0, ..., m$ depends only on its price, with $D_j^{i\prime}(.) < 0$. Moreover, following Baumol and Bradford (1970), Atkinson and Stiglitz (1980) and many other treatments of optimal commodity taxation, we assume, as it should be in a long-run perspective, that the supply of conventional, producible commodities $j = 1, ..., m$ by any country i is perfectly elastic, i.e. that marginal costs of production are constant. Let c_j denotes the marginal cost of producing good $j = 1, ..., m$ regardless of the country in which the good is produced[14]. In competitive equilibrium, we must have $\widetilde{p}_j = c_j$ for all $j = 1, ..., m$.

As far as oil is concerned, the exhaustibility constraint (2) implies that supply cannot be infinitely elastic even with a constant or zero marginal extraction cost. Following Bergstrom (1982), we assume that marginal costs of extraction are zero. However, Hotelling's analysis shows that, in competitive intertemporal equilibrium, the producer price must satisfy

$$\widetilde{p}_0(t) = \widetilde{\eta}(t), \tag{7}$$

where $\widetilde{\eta}(t)$ is the current-value unit Hotelling rent and must grow at the rate of interest over time (e.g. Dasgupta and Heal, 1979):

$$\widetilde{\eta}(t) = \widetilde{\eta}e^{rt}. \tag{8}$$

At any date, the net consumer surplus, the net producer surplus and the oil rent of country i are respectively

$$\widetilde{CS}^i(t) \equiv \sum_{j=0}^{m} \int_0^{\widetilde{x}_j^i(t)} D_j^{i-1}(x)\, dx - \widetilde{q}_j^i(t)\widetilde{x}_j^i(t), \tag{9}$$

$$\widetilde{PS}^i(t) \equiv \sum_{j=1}^{m} \big(\widetilde{p}_j(t) - c_j\big)\widetilde{s}_j^i(t) + \big(\widetilde{p}_0(t) - \widetilde{\eta}(t)\big)\widetilde{s}_0^i(t), \tag{10}$$

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[14] Assuming that each country had a different constant marginal cost of production would imply that, in equilibrium, only the countries with the lowest cost produce. As no profits are derived from constant-returns-to-scale production schedules, our results would immediately survive the restriction that only a subset of countries produce.

$$\widetilde{\Phi}^i(t) \equiv \widetilde{\eta}(t)\widetilde{s}_0^i(t). \tag{11}$$

All damages internalized by country i from its use of oil are given by the money-metricized function[15]

$$\widetilde{\Omega}^i(t) \equiv \Omega^i\big(\widetilde{x}_0^i(t)\big), \tag{12}$$

with $\Omega^{i\prime}(.) > 0$.

Then, $\widetilde{W}^i(t)$ in problem (3) is the sum of the consumer surplus, the producer surplus and the oil rent, net of the damages[16] of country i. This formulation aims at making the scarcity value of oil explicit, whether producers are interpreted as owners of the resource aware of this value or as buying the resource at its scarcity price $\widetilde{\eta}(t)$. The present-value Hamiltonian associated with problem (3) of maximizing discounted national welfare subject to the intertemporal revenue constraint (5) with (6) is

$$\mathcal{H}^i\big(a^i(t), (\theta_j^i(t))_{j=0,...,m}, \lambda^i(t)\big) = \big(\widetilde{CS}^i(t) + \widetilde{PS}^i(t) + \widetilde{\Phi}^i(t) - \widetilde{\Omega}^i(t)\big)e^{-rt} + \lambda^i(t)\big(ra^i(t) + \widetilde{T}^i(t)\big),$$

where $\lambda^i(t)$ is the co-state variable associated with the state $a^i(t)$ and where $\big(\{\theta_j^i(t)\}_{t\geq 0}\big)_{j=0,...,m}$ is the vector of control variables. $\lambda^i(t)$ can be interpreted as the date-t current unit shadow cost of levying one dollar of present-value revenues through commodity taxes in country i. From the maximum principle, $\dot{\lambda}^i(t) = -r\lambda^i(t)$ so that $\lambda^i(t) = \lambda^i e^{-rt}$, where λ^i denotes the present-value shadow cost of levying tax revenues: tax revenues should be discounted according to the date when they are collected. Because of the deadweight loss of commodity taxation, λ^i is always greater than or equal to unity.

Since in equilibrium $\widetilde{p}_j(t) = c_j$ and $\widetilde{q}_j^i(t) = D_j^{i-1}(.)$, the first-order condition for the choice of the tax $\theta_j^i(t)$ on conventional commodity $j = 1, ..., n$ reduces to $-\frac{d\widetilde{q}_j^i(t)}{d\theta_j^i(t)}\widetilde{x}_j^i(t) + \lambda^i\big(c_j\widetilde{x}_j^i(t) + \theta_j^i(t)c_j\frac{d\widetilde{x}_j^i(t)}{d\theta_j^i(t)}\big) = 0$, where $\widetilde{q}_j^i(t) = c_j\big(1 + \theta_j^i(t)\big)$ implies $\frac{d\widetilde{q}_j^i(t)}{d\theta_j^i(t)} = c_j$ and $\widetilde{x}_j^i(t) = D_j^i(\widetilde{q}_j^i(t))$ implies $\frac{d\widetilde{x}_j^i(t)}{d\theta_j^i(t)} = D_j^{i\prime}(.)c_j$. Hence, the optimal tax on good $j = 1, ..., m$ for country i is $\theta_j^{i*} = \frac{\lambda^i - 1}{\lambda^i}\frac{\widetilde{x}_j^i}{-D_j^{i\prime}(.)c_j}$, or equivalently,

$$\theta_j^{i*} = \frac{\lambda^i - 1}{\lambda^i}\frac{(1 + \theta_j^{i*})}{-\widetilde{\varepsilon}_j^i}, \tag{13}$$

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[15] Only internalized damages are relevant to optimal taxation; restricting attention to such damages simplifies the exposition.

[16] Since tax revenues of country i are given over the horizon, they can be treated as a constant that does not need to enter the objective.

where $\varepsilon_j^i \equiv \frac{q_j^i D_j^{i\prime}(.)}{x_j^i}$ is the price-elasticity of demand for good j in country i, which is constant under stationary market conditions.

Ad valorem consumption taxes applied on conventional, producible commodities are thus satisfying the standard inverse-elasticity rule of optimum commodity taxation. They vanish when the optimal covering of revenue needs does not imply the introduction of distortions ($\lambda^i = 1$) and are strictly positive otherwise.

Following Bergstrom (1982), we restrict the ad valorem tax on oil $\theta_0^i(t)$ to be constant over time in every country.[17]

Unlike the world producer price for conventional, producible commodities, the world producer price of oil, which is, in the absence of cost, the unit Hotelling rent, is affected by taxation. Hence, the first-order condition for the choice of θ_0^i by country i is $-\frac{d\widetilde{\eta}}{d\theta_0^i}\widetilde{x}_0^i(t) - \theta_0^i \frac{d\widetilde{\eta}}{d\theta_0^i}\widetilde{x}_0^i(t) - \widetilde{\eta}\widetilde{x}_0^i(t) + \frac{d\widetilde{\eta}}{d\theta_0^i}\widetilde{s}_0^i(t) + \widetilde{\eta}\frac{d\widetilde{s}_0^i(t)}{d\theta_0^i} - \Omega^{i\prime}(.)\frac{d\widetilde{x}_0^i(t)}{d\theta_0^i} + \lambda^i\left(\widetilde{\eta}\widetilde{x}_0^i(t) + \theta_0^i\frac{d\widetilde{\eta}}{d\theta_0^i}\widetilde{x}_0^i(t) + \theta_0^i\widetilde{\eta}\frac{d\widetilde{x}_0^i(t)}{d\theta_0^i}\right) = 0$, where we have used that, in equilibrium, $\widetilde{p}_0(t) = \widetilde{\eta}e^{rt}$ and $\widetilde{q}_0^i(t) = \widetilde{\eta}(1+\theta_0^i)e^{rt}$, which implies that $\frac{d\widetilde{q}_0^i(t)}{d\theta_0^i} = \frac{d\widetilde{\eta}}{d\theta_0^i}(1+\theta_0^i)e^{rt} + \widetilde{\eta}e^{rt}$.

Integrating over the horizon with $\int_0^{+\infty}\widetilde{s}_0^i(t)\,dt = S_0^i$, where S_0^i is given so that $\int_0^{+\infty}\frac{\widetilde{s}_0^i(t)}{d\theta_0^i}\,dt = 0$, and denoting by $\widetilde{X}_0^i \equiv \int_0^{+\infty}\widetilde{x}_0^i(t)\,dt$ the equilibrium cumulative oil consumption of country i, which implies $\int_0^{+\infty}\frac{d\widetilde{x}_0^i(t)}{d\theta_0^i}\,dt = \frac{d\widetilde{X}_0^i}{d\theta_0^i}$, the condition yields $\theta_0^{i*}\lambda^i\widetilde{\eta}\frac{d\widetilde{X}_0^i}{d\theta_0^i} = (1-\lambda^i)\left(\widetilde{\eta}\widetilde{X}_0^i + \theta_0^{i*}\frac{d\widetilde{\eta}}{d\theta_0^i}\widetilde{X}_0^i\right) + \Omega^{i\prime}(.)\frac{d\widetilde{X}_0^i}{d\theta_0^i} + \frac{d\widetilde{\eta}}{d\theta_0^i}\left(\widetilde{X}_0^i - S_0^i\right)$; rearranging gives the following necessary condition for the optimal tax on oil:

$$\theta_0^{i*} = \frac{\lambda^i - 1}{\lambda^i}\frac{\left(1 + \theta_0^{i*}\frac{d\widetilde{\eta}}{d\theta_0^i}\frac{1}{\widetilde{\eta}}\right)}{\frac{d\widetilde{X}_0^i}{d\theta_0^i}\frac{1}{\widetilde{X}_0^i}} + \frac{1}{\lambda^i}\frac{\Omega^{i\prime}(.)}{\widetilde{\eta}} + \frac{1}{\lambda^i}\frac{\frac{d\widetilde{\eta}}{d\theta_0^i}\frac{1}{\widetilde{\eta}}}{\frac{d\widetilde{X}_0^i}{d\theta_0^i}\frac{1}{\widetilde{X}_0^i}}\frac{\left(\widetilde{X}_0^i - S_0^i\right)}{\widetilde{X}_0^i}. \tag{14}$$

This expression of the optimal tax on oil for country i involves the effects of θ_0^i on the present-value equilibrium producer price $\widetilde{\eta}$ and on the equilibrium cumulative oil consumption in country i $\widetilde{X}_0^i$. These effects will be derived shortly.

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[17] As Bergstrom (1982) noted (p. 198), "The analysis of a Nash equilibrium in varying strategies is, in general, much more complicated, both conceptually and as a matter of computation." In fact, this is not so in the case of conventional goods. It must be remarked that the property of Bergstrom's model in the isoelastic-demand case, that there is a Nash equilibrium in which all countries choose a constant tax rate even if variable tax rates are possible carries over to our setting.

The world oil market clearing condition

$$\int_0^{+\infty} \sum_{k=1}^{n} D_0^k\big(\widetilde{\eta}(1+\theta_0^k)e^{rt}\big)\, dt = \sum_{k=1}^{n} S_0^k \tag{15}$$

implicitly determines the equilibrium present-value producer price of oil $\widetilde{\eta}$ as a function of oil taxes.

The right-hand side of this equality being given, it implies, by differentiation with respect to θ_0^i, the effect of country i's tax on the world present-value producer price of oil, given by the elasticity $\frac{d\widetilde{\eta}}{d\theta_0^i}\frac{1}{\widetilde{\eta}} = \frac{-\int_0^{+\infty} D_0^{i\prime}(.)e^{rt}\, dt}{\sum\limits_{k=1}^{n}\int_0^{+\infty}(1+\theta_0^k)D_0^{k\prime}(.)e^{rt}\, dt}$. This elasticity also writes

$$\frac{d\widetilde{\eta}}{d\theta_0^i}\frac{1}{\widetilde{\eta}} = \frac{-1}{(1+\theta_0^i)}\frac{\widetilde{X}_0^i\widetilde{\xi}_0^i}{\sum\limits_{k=1}^{n}\widetilde{X}_0^k\widetilde{\xi}_0^k} \leq 0, \tag{16}$$

where $\widetilde{\xi}_0^i \equiv \frac{\widetilde{q}_0^i(0)\frac{d\widetilde{X}_0^i}{dq_0^i(0)}}{\widetilde{X}_0^i} = \frac{\widetilde{\eta}(1+\theta_0^i)\int_0^{+\infty} D_0^{i\prime}(.)e^{rt}\, dt}{\widetilde{X}_0^i}$ is the elasticity of total cumulative demand for oil in country i, that we define as the long-run elasticity of the cumulative oil demand to the present-value consumer price, evaluated at the equilibrium allocation. Note that, in the isoelastic case, it is exactly equal to the flow demand elasticity $\varepsilon_0^i \equiv \frac{D_0^{i\prime}(.)q_0^i}{x_0^i}$ previously defined.

Since the present-value equilibrium consumer price of oil in country i is $\widetilde{q}_0^i(0) = \widetilde{\eta}(1+\theta_0^i)$, it follows by differentiation with respect to θ_0^i and by use of (16) that

$$\frac{d\widetilde{q}_0^i(0)}{d\theta_{0^i}}\frac{1}{\widetilde{q}_0^i(0)} = \frac{1}{(1+\theta_0^i)}\frac{\sum\limits_{k=1,k\neq i}^{n}\widetilde{X}_0^k\widetilde{\xi}_0^k}{\sum\limits_{k=1}^{n}\widetilde{X}_0^k\widetilde{\xi}_0^k} \geq 0. \tag{17}$$

In turn, $\widetilde{X}_0^i = \int_0^{+\infty} D_0^i\big(\widetilde{q}_0^i(0)e^{rt}\big)\, dt$ implies

$$\frac{d\widetilde{X}_0^i}{d\theta_0^i}\frac{1}{\widetilde{X}_0^i} = \widetilde{\xi}_0^i\frac{d\widetilde{q}_0^i(0)}{d\theta_{0^i}}\frac{1}{\widetilde{q}_0^i(0)} \leq 0. \tag{18}$$

Substituting these elasticities into (14) and simplifying yield the following expression for the optimal tax on oil in country i:

$$\theta_0^{i*} = \frac{\lambda^i - 1}{\lambda^i}\left(\frac{\sum\limits_{k=1}^{n}\widetilde{X}_0^k\widetilde{\xi}_0^k}{\sum\limits_{k=1,k\neq i}^{n}\widetilde{X}_0^k\widetilde{\xi}_0^k} + \theta_0^{i*}\right)\left(\frac{1}{-\widetilde{\xi}_0^i}\right) + \frac{1}{\lambda^i}\left(\frac{\Omega^{i\prime}(.)}{\widetilde{\eta}}\right) + \frac{1}{\lambda^i}\left(\frac{\widetilde{X}_0^i - S_0^i}{\sum\limits_{k=1,k\neq i}^{n} -\widetilde{X}_0^k\widetilde{\xi}_0^k}\right). \tag{19}$$

This complex formula brings up simple insights.

Unlike for conventional goods, the optimal tax rate on domestic oil consumption consists of three terms. The first one in equation (19) is the generalization of the Ramsey inverse-elasticity term for a traded commodity whose world producer price is affected by taxation. It features an inverse-elasticity rule but depends as well on the rest of the world's demand elasticities and market share. The second term is the standard Pigovian tax. Like in Sandmo's (1975) famous contribution on optimum commodity taxation with externality-generating goods, it is weighted according to the need of raising revenues. The third term corresponds to an optimum-tariff component. As in Bergstrom (1982), this component of the optimal tax depends on the country's position on the oil market – it is positive for an oil importer and negative for an oil exporter – and on the rest of the world's market share weighted by demand elasticities. Recalling that the elasticity of Hotelling reserves is nil, it appears that the denominator of this term is also the elasticity of the residual supply – i.e. net of the rest of the world's consumption – that country i faces. The difference between this term and the original tax rate in Bergstrom (1982) is the intervention of the cost of levying revenues λ^i. Like the Pigovian term in Sandmo (1975), the optimum-tariff dimension of the optimal tax on oil should be weighted according to the need of raising tax revenues.

When the revenue constraint (5) is not binding, the cost of levying revenues reduces to unity, $\lambda^i = 1$, and it is not necessary for the government to impose distortions to its economy. However, unlike the Ramsey tax (13) for regular commodities, the oil tax given by (19) does not vanish in this case. When $\lambda^i = 1$, the first, Ramsey distortionary term is equal to zero and the tax reduces to the sum of its second and third terms, which are respectively the Pigovian component and the tariff component of the tax. The Pigovian term is corrective and should be set equal to marginal damages to maximize welfare even in the absence of any revenue-collection constraint. The third term can also be interpreted as being corrective as it participates to country i's welfare maximization even in the absence of revenue constraint. In Boadway et al.'s (1973) words, "domestic commodity taxes *introduce* a distortion while optimum tariffs *eliminate* a distortion" (p.

397, their italics). Once the mechanism by which a domestic tax takes the dimension of a tariff (Friedlander and Vanderdorpe, 1968) is understood, the same remark applies to the third term in (19). Hence, as long as these two terms, computed for $\lambda^i = 1$, raise a fiscal amount equal to or greater than $R^i(0)$, a unitary value for λ^i is indeed compatible with the problem of country i's government; neither regular sectors, nor the oil sector are imposed Ramsey distortions in that context.

Keeping in mind from Boadway et al.'s remark that the Pareto-improving tariff dimension of the commodity tax is corrective in a similar way to a Pigovian tax, the following observation by Sandmo (1976, p. 38) applies to our problem: "taxation need not be distortionary by the standard of Pareto optimality. But it seems definitely sensible to admit the unrealism of the assumption that the public sector can raise all its revenue from neutral or Pigovian taxes, and once we admit this we face the second-best problem of making the best of a necessarily distortionary tax system. This is the problem with which the optimal tax literature is mainly concerned." On this ground, attention should be restricted to the most relevant case where $\lambda^i > 1$, for all $i = 1, ..., n$. The following proposition summarizes our findings.

Proposition. *When the revenue-collection constraint (5) binds the government of country* $i = 1, ..., n$, *so that* $\lambda^i > 1$, *its optimal tax rate on oil (19) not only consists of an open-economy Ramsey term and of a Pigovian term, but also of an optimum-tariff component.*

Recalling that the optimal tax on regular commodities $j = 1, ..., m$ (13) solely consists of a Ramsey tax rate, an immediate consequence of Proposition 1 is the following. Optimum tariffs, while irrelevant in the optimum taxation of conventional, producible goods, are crucial for the optimum taxation of an exhaustible resource.

This should not come as a complete surprise. It is standard in the optimum-taxation literature to assume supply of commodities to be perfectly elastic. The non-renewable nature of oil implies a long-run perfect inelasticity such that short-run supply cannot be infinitely elastic. In other words, while the producer price for conventional commodities is given in competitive equilibrium by the marginal cost of production, the producer price of oil, which is also the unit oil scarcity rent, directly depends on taxes.

In fact, had we assumed supply of non-oil commodities not to be perfectly elastic, the optimal commodity tax on those goods would have taken an optimum-tariff dimension as well. However, this shows that the long-run supply inelasticity on the oil market, which is very peculiar to oil, implies trade-related motives for taxation to be especially important for this commodity.

Hence, to conclude, not only revenue-raising and externality-correction motives for taxation determine countries' optimal taxation of domestic oil consumption, but also optimum-tariff motives; the latter being especially important in the oil sector.

The following section will measure the ability of an optimum-tariff variable, derived and computed from above expressions, to explain actual national taxes on a major oil product, gasoline. This variable will be shown to play a critical role in explaining gasoline taxation.

3. An empirical analysis of the determinants of national taxes on gasoline

Gasoline is the most important oil product and is mostly consumed by individuals; this is why gasoline taxes have been considered to provide the ideal measure of oil products' final-consumption taxation level. There is another practical consideration. The availability of data on gasoline retail prices at a relatively large scale allows the computation of national taxes/subsidies on gasoline consumption.

To explain the international distribution of gasoline taxes, the existing empirical literature has mainly focused on revenue-raising and externality-correction motives for taxation. In the light of the theoretical Section 2, this means giving a particular attention to the key factors traditionally thought of as determining the first two terms of Formula (19) – in our words, the Ramsey and Pigovian tax components.

This section aims at measuring the explanatory power of the optimum-tariff dimension, as we termed it, of domestic taxation. In the light of the existing empirical literature, this would mean measuring the role of factors thought of as determining the third term of Formula (19), that is the optimum-tariff component of the theoretical domestic oil tax.

A more direct and efficient approach consists in isolating the meaningful part of this theoretical term and to compute it for each country, so as to treat it as an explanatory variable. It is particularly adapted to our purpose. First, the quantity components of the optimum-tariff term (essentially domestic consumption and production) may individually affect other tax components. Second, this method permits the isolation of one single variable as the one representing the optimum-tariff dimension of domestic taxation.

The analysis will consist of two steps. We will first consider gasoline taxes and the computed optimum-tariff variable in isolation. Then, their relationship will also be examined in a regression analysis where other factors identified as being of importance by the related literature are controlled for.

3.1 Computing gasoline taxes

Transportation and distribution costs represent relatively small parts of gasoline before-tax retail prices. Moreover, a substantial part of those costs are retailing costs and margins from the distribution activity, whose contribution to gasoline prices is very homogeneous across countries. Finally, the cost of transporting oil products, at any stage and at the final stage in particular, includes some fixed parts which make it "practically independent from the distance of transport"; its homogeneous contribution to gasoline retail prices is considered to be of "minor influence" (GTZ, 2005, p. 68).

For these reasons, the distribution of oil products' final prices is generally thought of as reflecting almost exclusively the distribution of domestic taxes on those products. The difference between final prices and taxes is the international producer price that is, in first approximation, common to all countries. Therefore, any arbitrary estimation of the producer price is suitable to compute domestic taxes, while only implying a negligible loss of information. Following GTZ (2009), the US gasoline retail price (average cost-covering price including industry margin, VAT and US-$ 0.10 for road funds) "may be considered as the minimum international benchmark for a non-subsidized road transport policy". Let us thus compute the 2008 gasoline domestic taxes by taking the differences between final gasoline prices and this international benchmark price.[18]

What matters is that the procedure captures all taxes which are added to the international producer price to determine final consumption prices; that is regardless of whether they are specific (per unit) or proportional (ad valorem) and whatever the stage at which they are applied.[19]

This procedure does not give an exact measure of the actual level of taxes applied on gasoline. In this respect, the IEA's direct measurement of exclusive-of-VAT national taxes on gasoline in OECD-member countries is more reliable (IEA, 2008). The comparison of taxes computed as above from the final gasoline prices given by GTZ (2009) with the IEA's directly-measured gasoline taxes on the OECD subgroup of our sample shows that the ordering of countries according to their taxes is the same for either tax measure.[20]

After selecting countries according to the availability of data for the variables considered in this section, our sample not only consists of all OECD countries, but also of all OPEC countries and of Brazil, Russia, India and China, among others (97 countries overall).

On this large sample, taxes on gasoline are very heterogenous. They range from the negative US-\$ -0.54 per liter in Venezuela to as high as US-\$ 1.39 per liter in Hong Kong. Other subsidizing countries (having negative tax rates) include Algeria, Angola, Irak, Iran, Kuwait, Libya, Saudi Arabia and United Arab Emirates. Countries with relatively high taxes on gasoline include most of developed countries.

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[18] All data are for unleaded Octane 95 gasoline.

[19] Computed taxes are expressed in per unit terms. Since dividing such taxes by the international producer price common to all countries yields their ad valorem equivalent, both expressions are exactly equivalent as dependent variables.

[20] Spearman's rank correlation coefficient between taxes computed from GTZ's 2008 prices for unleaded Octane 95 gasoline and IEA's 2008 exclusive-of-VAT taxes on the same product is 0.81. Moreover, the null hypothesis that the two distributions are independent can be rejected with a risk of error of 1%.

3.2 The optimum-tariff variable and gasoline taxes

According to Formula (19), the optimum-tariff dimension of optimal taxes on exhaustible-resource products lies in its last term on the right: $\frac{1}{\lambda^i}\left(\widetilde{X}_0^i - S_0^i\right) / \sum_{k=1,k\neq i}^{n} -\widetilde{X}_0^k \widetilde{\xi}_0^k$. Computing a variable that captures the optimum-tariff dimension requires to cautiously interpret this term's components and to accordingly make pragmatic choices.

First, while the optimum-tariff term inversely depends on the cost of public funds λ_i prevailing in each country, it should be clear from the analysis of Section 2 that the intervention of λ_i stems from the combination of the optimum-tariff dimension of domestic taxation with other taxation motives. Specifically, absent any binding revenue-collection commitment, λ_i would take a unitary value, as in Bergstrom (1982). It follows that the term $\left(\widetilde{X}_0^i - S_0^i\right) / \sum_{k=1,k\neq i}^{n} -\widetilde{X}_0^k \widetilde{\xi}_0^k$ is fully capturing the optimum-tariff dimension we aim at isolating out.

Second, the optimum-tariff component in any country i's tax depends on the elasticity of demand in all other countries. Although those elasticities can be computed for some countries, limits on data availability would have too high a cost in terms of the size of our sample. Following Bergstrom (1982) in his simulations, we assume here that domestic demands are isoelastic and identical across countries. Hence, demand elasticity evenly contributes to the optimum-tariff component of all countries; we are left with the country-specific part of it, $\left(\widetilde{X}_0^i - S_0^i\right) / \sum_{k=1,k\neq i}^{n} -\widetilde{X}_0^k$. In the latter expression for any country i, the denominator is the rest-of-the-world's cumulative gasoline consumption. To the notable exception of the United States, countries' domestic consumption of gasoline is often small relative to world consumption; let us assume the denominator to be common to all countries. We are left with the difference between long-run cumulative domestic consumption and production (i.e. with net long-run cumulative imports),

$$\widetilde{X}_0^i - S_0^i, \tag{20}$$

which is the most fundamental part of the optimum-tariff component of the tax.

The analysis of this term yields two immediate predictions regarding the tax-setting behavior of countries, respectively having to do with the sign and the magnitude of the optimum-tariff dimension of oil taxes. First, it predicts that the balance between cumulative quantities consumed and produced in equilibrium over the horizon determines whether the tariff component of the tax is positive or negative. If the equilibrium cumulative consumption of one country is larger than its cumulative supply (i.e. the country is a net cumulative importer), the tariff term (20) positively contributes to its domestic tax and vice versa. Secondly, the absolute-value magnitude of this term for one country is all the higher, the greater the absolute value of cumulative net imports of this country over the horizon. Thus, large net importers are expected to set higher taxes than otherwise similar countries with lower net imports or with greater net exports.

A comparison of gasoline taxes in top-importing and top-exporting countries gives a first indication that the sign of those taxes often coincides with the sign of the theoretical tariff component: all countries among the top-ten importers set positive taxes whereas 7 out of the 10 top exporters (Russia and Norway are notable exceptions) subsidize the domestic use of gasoline (Table 1).

Table 1: Top exporters and importers of oil

	(1)		(2)	
Rank	Exporters	Tax	Importers	Tax
1	Saudi Arabia	-0.40	The United States	0.00
2	Russia	0.33	Japan	0.86
3	United Arab Emirates	-0.11	China	0.43
4	Iran	-0.46	Germany	1.00
5	Kuwait	-0.32	South Korea	0.95
6	Norway	1.07	India	0.53
7	Angola	-0.03	France	0.96
8	Venezuela	-0.54	Spain	0.67
9	Algeria	-0.22	Italy	1.01
10	Nigeria	0.03	Taiwan	0.38

For columns (1) and (2), data is taken from EIA. Taxes are in US-$ per liter.

Further comparison of actual domestic gasoline taxes with the theoretical optimum-tariff component requires computing the latter. In what follows, we discuss the theoretical quantities in (20) and the theoretical time horizon over which they are cumulated to determine what should be their empirical counterparts.

The theoretical model of Section 2 does not make any distinction between the raw resource as it is extracted and the retailed oil product which is transformed from it. This simplification is usually made on the ground that transformation processes are linear so that it can be seen as a matter of normalization. Had we modeled the transformation stage under conditions of competition, flows relative to the intermediate transformation industry would have disappeared from formulas. Therefore, the relevant supply quantity is that of the extracted resource to which the rent is attached, while the relevant consumption quantity is the normalized quantity of transformed oil products. EIA production and consumption data appropriately comprise petroleum production and the consumption of all oil products derived from it.

This simplification follows Bergstrom (1982) who noted that regardless of the oil product for which we aim at computing the theoretical tax, "the numbers needed in order to make such estimates are the shares of the world's total oil consumption consumed and produced in the country of interest" (p. 199). On the other hand, the simplification is without loss of generality only when the resource has a single transformed derivative. Gasoline is the most important, although non exclusive, of several oil products. The resulting approximation arises from the obvious difference between the theoretical tax base which covers all oil products and the tax base to which a gasoline tax is applied. Bergstrom's suggestion can be justified on the ground that gasoline taxation is very representative of the way countries tax other oil products. For instance, we find that the relation between taxes on diesel and taxes on gasoline can be considered to be monotonic increasing.[21]

As concerns the time horizon over which cumulative quantities are estimated in expressions (20) and (19), it is the entire theoretical horizon. Such variables aim at capturing the respective *long-term* position of countries on the oil market. Hence, its relevant empirical counterpart is a sufficiently long past interval of time. We proxy cumulative consumed and supplied quantities in equilibrium by the cumulative amounts consumed and supplied for as far back in history as possible, i.e. since 1980.

In the following we will denote the variable which represents the optimum-tariff

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[21] Specifically on our sample, Spearman correlation coefficient between the two variables is 0.89. The null hypothesis that their distributions are independent can be rejected with a risk of error as low as 0.01%. Diesel taxes have been computed from GTZ (2009) data in the same way as gasoline taxes.

dimension of the domestic tax on gasoline in country i by $Opt.Tariff_i$; we define it in the following fashion, which measures the difference between long-term cumulative consumption and production, in relative terms. It conserves all sign and monotonicity properties of expression (20):

$$Opt.Tariff_i \equiv ln\big(1 + \sum_{t=1980}^{2007} \widetilde{x}_0^i(t)\big) - ln\big(1 + \sum_{t=1980}^{2007} \widetilde{s}_0^i(t)\big), \tag{21}$$

where $\widetilde{x}_0^i(t)$ and $\widetilde{s}_0^i(t)$ are respectively domestic oil consumption and production of country i during year t. We thus approximate cumulative quantities of (20) by $\widetilde{X}_0^i \simeq \sum_{t=1980}^{2007} \widetilde{x}_0{}^i(t)$ and $S_0^i \simeq \sum_{t=1980}^{2007} \widetilde{s}_0{}^i(t)$, where the exclusion of year 2008 is made to mitigate any potential endogeneity of consumption terms to the 2008 tax.

Plotting these computed values against the actual tax rates clearly shows a positive relationship (Figure 1). Countries with a higher optimum-tariff component set higher taxes and vice versa. The associated correlation coefficient is 0.54.

A clearer view on this relationship is further provided by the evolution of kernel-estimated densities of actual taxes associated with the levels of the optimum-tariff component (Figure 2). The estimated density functions are uni-modal, with a high concentration around their modes. In other words, for any level of the optimum-tariff component, countries have rather similar taxation patterns. Moreover, the mode associated with each optimum-tariff level is increasing, also showing the positive relationship between this variable and the actual taxes. Countries whose optimum-tariff components are very high are concentrated around a very high level of taxation. Countries with very low optimum-tariff components are concentrated around or below the zero-tax level.

Interestingly, the strong relation between actual taxes and the optimum-tariff variable stems less from the consumption and production components of the latter than from their combination. Taken in isolation, neither cumulative consumption nor cumulative production are related to actual taxes in a way that is comparable with their combination as per the optimum-tariff variable.[22]

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[22] In Table 5 of Appendix A, cumulative consumption and cumulative production are respectively denoted by *Cum.Cons* and *Cum.Prod.* To have these variables suitable for comparison with $Opt.Tariff$,

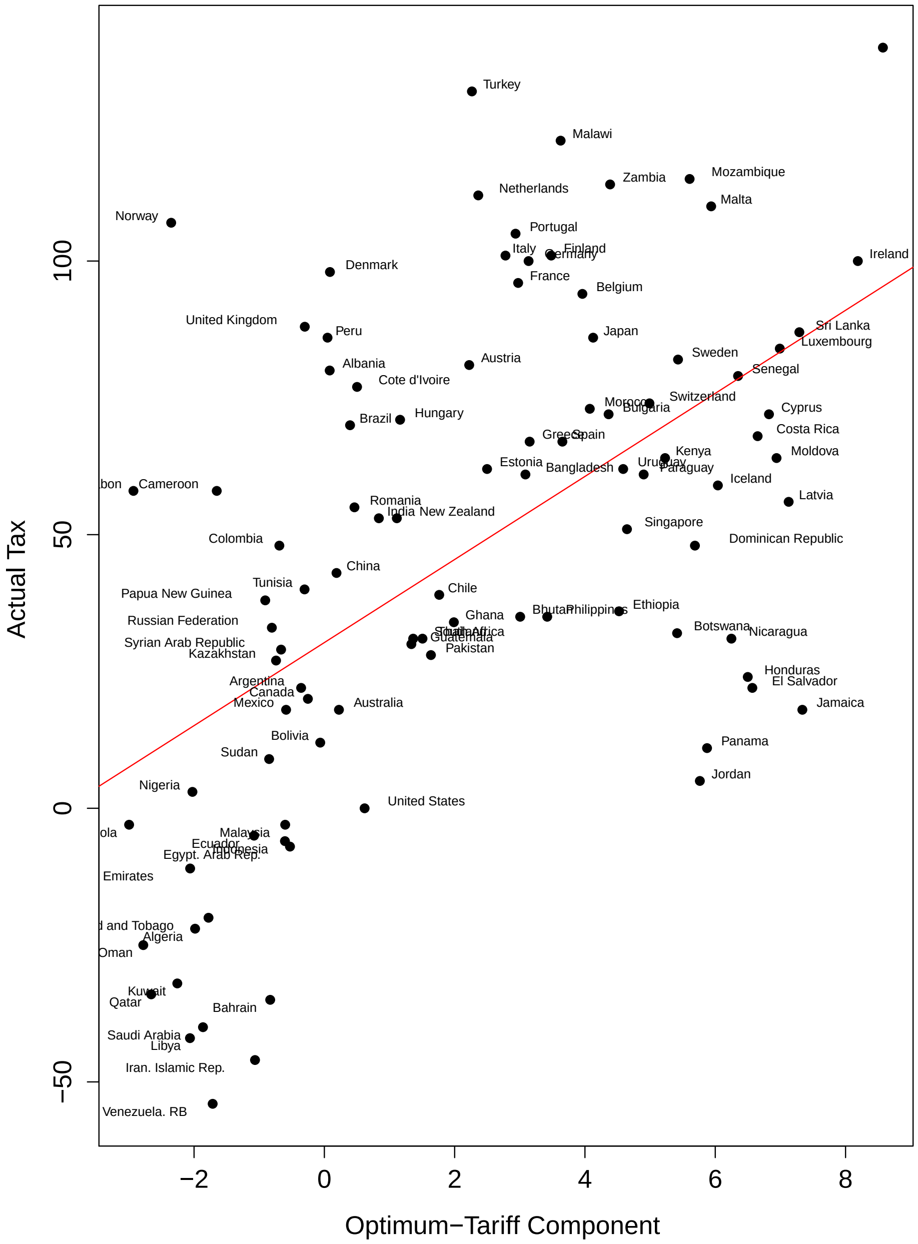

Figure 1: Scatter plot for computed optimum-tariff components and actual taxes

In the sequel, we address the question of how well the optimum-tariff-component

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they are transformed with the log operator in the same way as per the optimum-tariff variable. We find that only cumulative production is correlated with actual taxes. The associated correlation coefficient is 0.44 in absolute value, to be compared with the 0.54 correlation coefficient associated with the relation between taxes and the optimum-tariff variable. Their combination as per the optimum-tariff variable thus enhances their relation to actual taxes.

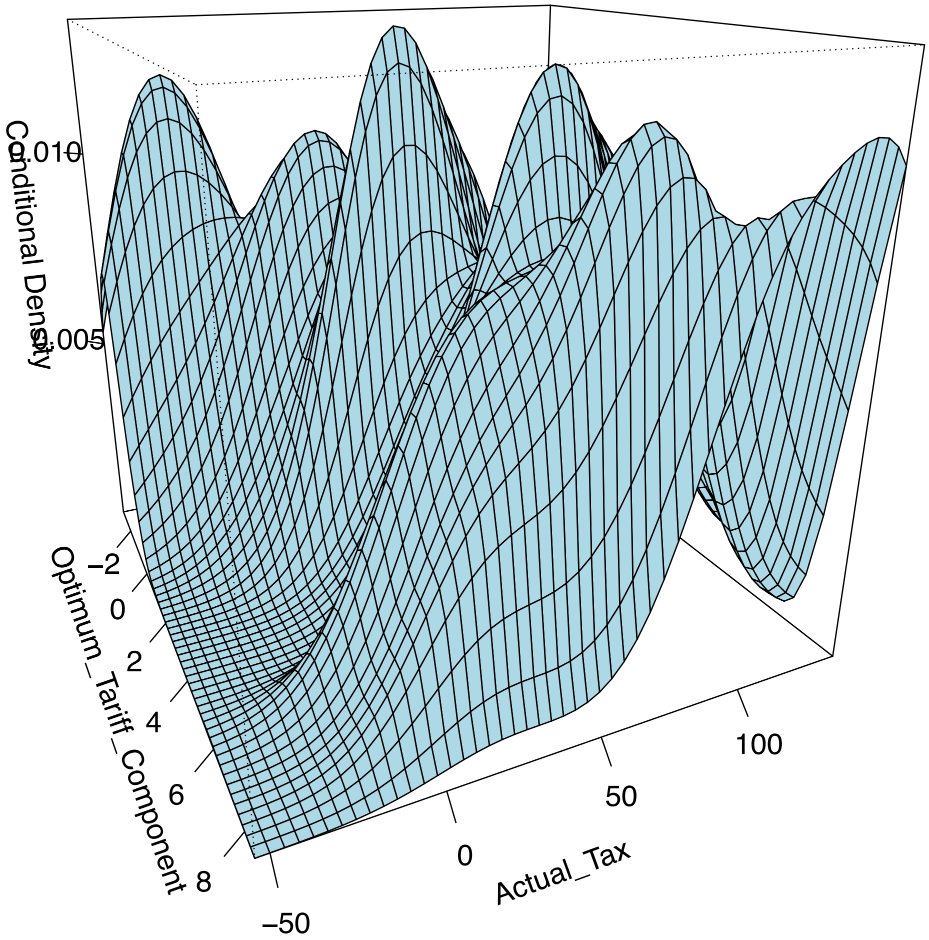

Figure 2: Conditional density

variable we have computed from Section 2 explains domestic gasoline taxes in a regression analysis. The main objective is to confirm the strong relation found when the two variables are taken in isolation by showing that it survives the introduction of the factors considered and/or demonstrated to be of importance by the existing empirical studies on the topic.

3.3 Regression analysis

Our empirical strategy consists in estimating a model with three sets of explanatory variables. For reference, we first include the main variables the related empirical literature has considered and/or shown to be crucial to explain the distribution of domestic taxes on oil products. This baseline model is meant to replicate their empirical analyses to our data set. To this model, we will then include the optimum-tariff variable, which is the variable of main interest here. Last, we will introduce additional controls so as to further assess the robustness of the relation between the optimum-tariff variable and the actual taxes.

All explanatory variables are lagged by one year compared to the 2008 tax on gasoline in order to mitigate any potential endogeneity issue. Moreover, the Ramsey (RESET) test as well as the Swilk-Shapiro test for residuals' normality will be applied to all our linear models so as to provide evidence against any specification errors.

3.3.1 Data

From the previous section, we inherit the 2008 domestic taxes on gasoline final consumption, which will be denoted by "Tax" in the regression equation. We also inherit the computation of the optimum-tariff variable *Opt.Tariff*, which represents the optimum-tariff dimension of taxes.

As our theoretical Section 2 shows with the equilibrium tax Formula (19), domestic taxes on oil products not only consist of an optimum-tariff component, but also of a Ramsey-tax term and of a Pigovian-tax term. Those two components represent the public-finance view adopted by most of the empirical studies on domestic taxation of oil products consumption.

The Ramsey term corresponds to governments' need to raise commodity-tax levies to secure public revenues. While several variables may be suitable to represent how much countries are subject to such needs, the recent crisis highlights that state financial constraints are much related to the level of their indebtment. In line with Hammar et al. (2004), we thus use the debt-over-GDP ratio (denoted $Debt/GDP$) as representing this taxation motive, at the expense of Rietveld and van Woudenberg's (2005) and Liddle and Lung's (2008) public-expenditure variable, which turned out to be less powerful. All the above studies consistently find that the raising-revenue motive best explains gasoline taxes.

There are several externalities arising from oil use. The two most cited effects are related to pollution emissions, whether they cause global or local damages, and to the risk of local road congestion. Following the literature, we focus on those two external effects. While several pollutants are released from the consumption of gasoline, their emissions must all chemically be proportional to each other. Countries' respective contributions to CO_2 emissions thus equivalently represent emissions of other pollutants, as well as fuel products total consumption – a measure preferred by Hammar et al. (2004). We choose this variable and simply denote it by CO_2. As far as congestion is concerned, we follow the common practice of using the density of cars, here computed per kilometer of road (variable $Vehicles$). So far, the literature has not found evidence that externality-correction motives are relevant to oil products taxation.

As mentioned in the introduction, there is another famous factor of domestic taxation, having to do with the tax competition between neighboring countries, in the spirit of Kanbur and Keen (1993). In line with Rietveld and van Woudenberg, we use a weighted average of prices in neighboring countries to represent countries' pressure arising from border tax competition ($Neighborprice$). For each country, the weight attached to each neighbor's gasoline price is taken as the fraction of former's total border length shared with the latter. While Rietveld and van Woudenberg find this variable to be crucial, they also show that its explanatory effect is unconditional on countries' market exposure. On the ground of their finding, and for simplicity, we exclusively include the $Neighborprice$ variable to represent border tax competition.

Oil rents accruing from oil production generally provide top oil-producing countries with a substantial source of government revenue that is absent in oil-poor countries. The presence of such rents may enhance the influence of the local oil sector over policy makers, in particular regarding tax decisions. Rietveld and van Woudenberg (2005) include a dummy variable for OPEC membership to account for the presence of such rents, which proved to have crucial explanatory power. As one can anticipate, their variable captures some important aspect of the optimum-tariff variable, at least much of its sign. We follow Rietveld and van Woudenberg and include the same challenging variable (denoted $OPEC$). In the same spirit, we will consider an index representing the stability of countries' political system to take account of their vulnerability to external influences or lobbying activities (*Polrights*).

The OPEC-membership variable might also capture some distributional objectives which are specific to top oil-producing countries. It has been presumed that such objectives may account for the extraordinarily low level of taxes in those countries which could redistribute part of the oil rents in this fashion. In fact the redistributive dimension of domestic taxes on oil products has been more generally argued to be relevant, regardless of the presence of producer rents (see Cremer et al., 2003, for an application to France). A serious account of these distributional concerns is impossible on a large scale[23], but to the extent that inequalities can be expected to magnify them. On this ground, we include the Gini coefficient (variable *Gini*), the most standard measure of income inequality. Last, we include GDP per capita (denoted *GDP* for simplicity) to capture tax differences arising from any kind of income effects.

Appendix A gives a more accurate description of the data, provides summary statistics on all variables (Table 4) and shows their pairwise correlation coefficients (Table 5); no multicollinearity issues are detected.

3.3.2 Regression equations

To show how robust is the relation between the optimum-tariff variable and actual domestic taxes on gasoline, we further consider it in the following regression analysis.

A linear regression equation is extended step by step so as to identify the respective explanatory contribution of several sets of exogenous variables. As a reference, we first isolate out the main variables considered and/or shown to be of importance by the existing literature. We then include the variable of main interest: the optimum-tariff variable. Last, we include several other control variables.

Formally, the complete regression equation writes

$$Tax_i = \alpha + \beta X_i' + \gamma Opt.Tariff_i + \delta Z_i' + \varepsilon_i, \tag{22}$$

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[23] Cremer et al.'s (2003) application suggests that such considerations should involve each country's joint distribution of residents' incomes and consumption patterns, as well as a measure of its inequality aversion.

where Tax is the variable to be explained, X the vector of baseline variables ($Debt/GPD$, CO_2, $Vehicles$, $Neighborprice$ and $OPEC$), $Opt.Tariff$ the optimum-tariff variable of interest, and Z a vector consisting of additional controls ($Gini$, $Polrights$ and GDP). Moreover, α is a scalar and β, γ and δ are vectors of coefficients of the relevant dimension.

All models are estimated in STATA by the method of least squares with (Huber-White) heteroskedasticity-consistent standard errors. To all regressions are applied the Ramsey (RESET) test for specification errors (variables omission, functional forms misspecification, and correlation between exogenous variables and errors) as well as the Shapiro-Wilk test for residuals' normality.

3.3.3 Results

Table 2 shows the estimation results of the main models.

Baseline models

The estimation of the baseline model, which excludes the optimum-tariff variable, is decomposed as per Columns (1) and (2). This decomposition is meant to highlight that absent the $OPEC$ variable, the coefficient associated with $Debt/GDP$ is significantly different from zero at the 1% level. This is consistent with the common finding that the revenue-raising motive best explains taxes on oil products. When the $OPEC$ dummy is included however we find that the role of $Debt/GDP$ completely vanishes. Also in line with previous findings, the effects of the two variables capturing Pigovian taxation motives (respectively CO_2 and $Vehicles$) are statistically insignificant and sometimes take the unexpected sign. Moreover, in both columns, the coefficient associated with $Neighborprice$ is significantly different from zero (10% significance level), which suggests border tax competition to play some role.

When included as in Column (2), the OPEC-membership variable has a substantial, positive and statistically significant (1% level) impact on domestic taxes. Moreover, its inclusion drastically improves the variance explained by the linear model. As suggested earlier, this variable partly captures the sign dimension of the optimum-tariff variable.

Introducing the optimum-tariff variable

Table 2: Regression results

	(1)	(2)	(3)	(4)
Debt/GDP	0.44***	0.15	0.11	0.094
	(0.15)	(0.15)	(0.14)	(0.12)
CO_2	-0.0000038	-0.0000048	-0.0000025	-0.0000021
	(0.0000035)	(0.0000030)	(0.0000031)	(0.0000045)
Vehicles	-0.046	0.041	0.031	0.0014
	(0.074)	(0.057)	(0.048)	(0.056)
Neighborprice	0.17*	0.15*	0.100	0.074
	(0.098)	(0.087)	(0.080)	(0.078)
OPEC		-80.1***	-61.1***	-53.8***
		(9.60)	(11.1)	(11.8)
Opt.Tariff			4.22***	3.43**
			(1.42)	(1.40)
Polrights				-4.01**
				(1.88)
GDP				0.00012
				(0.00022)
Gini				-0.60*
				(0.32)
α	15.6	34.9**	29.9**	69.4***
	(14.4)	(13.8)	(12.7)	(20.7)
N	97	97	97	97
$Adj.R^2$	0.066	0.35	0.41	0.46
RESET	0.06	0.77	0.15	0.33
Swilk	0.96	0.80	0.82	0.69

Standard errors are given in parentheses below coefficient estimates.
Models are estimated with least squares using STATA.
Heteroscedasticity-robust standard errors are used.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

As the optimum-tariff variable is included, estimation results are shown in Column (3). Despite the *OPEC* variable, *Opt.Tariff* proves to have a statistically significant impact on domestic taxes (1% significance level). Accordingly, it further increases the explanatory power of the model. The finding confirms the strong relation between taxes and the optimum-tariff variable and supports the hypothesis that the optimum-tariff dimension of domestic taxes fundamentally contributes to explain the distribution of domestic taxes on oil products.

While OPEC-membership retains its crucial role, the magnitude of its impact is markedly reduced at the *Opt.Tariff*'s introduction. The remark validates our intuition that the $OPEC$ dummy captures some dimension of *Opt.Tariff*. Another model is estimated in Appendix B (See Column (5) of Table 6), which further consolidates the intuition: the exclusion of $OPEC$ from the exhaustive model (with all controls) both lowers the level at which the optimum-tariff's effect is significant, and substantially increases the magnitude of this effect.

Last, the insignificance of $Debt/GDP$, CO_2 and $Vehicles$ survives the introduction of *Opt.Tariff*, while the level at which the effect of $Neighborprice$ is significant now exceeds 10%.

Additional controls

As Column (4) shows, the significant impacts of both *Opt.Tariff* and $OPEC$ hold true even after including our additional controls. Among them, *Polrights* turns out to have a significant negative effect (5% level). Interestingly, the coefficient associated with the Gini index is found to be significantly different from zero (10% level). Thus, its negative sign gives some ground to the view that intra-country inequalities negatively affect domestic taxes applied on the consumption of oil products. The exhaustive model of Column (4) is consistent with the model of Column (3) regarding the insignificance of $Debt/GDP$, CO_2, $Vehicles$ and $Neighborprice$.

Overall, the additional controls are found to complement rather than to compete with the most important factors identified in Column (3).

4. CONCLUSION

Although famous and initially very influential, the old optimum-tariff theory had not received empirical support until recently. In their major contribution, Broda, Limão and Weinstein (2008, p. 2032) pointed at this lack of evidence and challenged the commonly controversial status of the theory by first showing the relevance of its basic predictions. Prior to World Trade Organization membership, as they find, countries were setting significantly higher import tariffs on inelastically-supplied imports, the tariff variation being better explained by countries' market power.

Our contribution is not about tariffs *strictio sensu*, but still brings strong evidence of the relevance of optimum-tariff arguments. On low-supply-elasticity markets, the optimum-tariff theory has implications even when countries are subject to current restrictions on tariff decisions (Friedlander and Vanderdorpe, 1968; Dornbusch, 1971; Keen, 2002). In such contexts, while domestic taxes may still pursue revenue-raising or corrective objectives, they further acquire an optimum-tariff dimension.

The non-renewable character of oil implies a long-run supply inelasticity. According to the theory, taxes on oil derivatives should acquire an optimum-tariff dimension, magnified by the fixity of reserves. This is the reason why forces at work in many theoretical contributions to the taxation of non-renewable resources are reminiscent of optimum-tariff arguments. Our highly stylized model neatly connects the exhaustible-resource-taxation theoretical literature with the optimum-tariff theory while also integrating ingredients considered to be fundamental by the related empirical literature. From the model's comprehensive results, we have isolated out the optimum-tariff dimension of domestic taxes on oil products. On that ground, we have simulated a variable capturing this dimension and have tested its relation with actual taxes.

This paper first brings evidence of the optimum-tariff dimension of domestic taxes on oil products hitherto completely ignored by the related empirical literature: even after controlling for factors identified by previous contributors as being empirically important for the taxation of oil products, our results are strongly supportive of the view that the optimum-tariff dimension of those taxes plays a fundamental role.

APPENDICES

A Data Description

Table 3: Data

Abbreviation	Variable	Motive	Year	Source
Tax	Tax on gasoline: Gasoline retail price minus normal gasoline sales price, in US-$ Cents		2008	GTZ (2009)
Dieseltax	Tax on diesel: Diesel retail price minus normal diesel sales price, in US-$ Cents		2008	GTZ (2009)
Opt.Tariff	Optimum-tariff component: Computed from historical crude oil consumption and supply data	Optimum tariff	1980- 2007	EIA
Debt/GDP	Debt (% of GDP)	Revenue raising	2007	CIA Factbook (2008)
Vehicles	Vehicles per km roadway	Congestion	2007 or most recent	World Bank and other sources
CO_2	CO_2 emissions in kt	Pollution	2007	World Bank
Neighborprice	Average price in neighboring countries: weighted averaged gasoline retail prices in neighboring countries where the weights are determined by the length of adjacent borders, in US-$ Cents		2008	GTZ (2009) and CIA Factbook (2009)
OPEC	Dummy variable for OPEC membership			
GDP	GDP per capita, PPP corrected (constant 2005 international $)	Control	2007	World Bank
Polrights	Political rights indicator, discretely coded with categories from 1 to 7; 1 representing the most free and 7 representing the least free country	Control	2007	Freedom in the World Survey (2008), The Heritage Foundation
Gini	Gini index	Control	2007 or most recent	CIA Factbook (2008), World Bank and Global Peace Index
Cum.Cons	$\sum_{t=1980}^{2007} \widetilde{x}_0^i(t)$: cumulative consumption of petroleum products for country i		1980-2007	EIA
Cum.Prod	$\sum_{t=1980}^{2007} \widetilde{s}_0^i(t)$: cumulative crude oil production for country i		1980-2007	EIA

Notes on the data:

- Fuel prices refer to the pump prices of the most widely sold grade of gasoline. Prices have been converted from the local currency to US-$. The difference between the observed gasoline price at gas stations and the "normal gasoline sales price" (see GTZ) is used as proxy for the tax on gasoline.
- Consumption and supply: data exclusively on gasoline are not available. Some countries underwent geopolitical changes during the period 1980-2007 (Germany and the UDSSR). Consumed and supplied quantities were calculated for those regions as follows.
  - Germany: sum of East and West Germany for the years 1980-1990.

  - UDSSR: Estonia, Kazakhstan, Latvia, Moldova and Russia. Consumed and supplied quantities are extrapolated backwards for the years 1980-1991. The extrapolation is based on a ratio computed from the production/consumption in each country in the year before the fall of the UDSSR (1992) over the fraction of total consumption/production of the UDSSR in its last year (1991).

- Total oil supply: some countries reported a negative number for supply. This is due to a refinery loss; oil supply data are made up of four components: crude oil (including lease condensate), natural gas plant liquids, other liquids, and refinery processing gain (loss). Some countries do not have any domestic oil production, but might have refinery gain (loss). Countries with a negative number report a refinery loss. As these numbers are very low; they are set to zero.[24]
- Total consumption of oil products: the sum of all petroleum products supplied and of crude oil burned directly. For each petroleum product, the amount supplied is calculated by adding production, imports and net withdrawals from primary stocks, and subtracting exports.
- Vehicles per km roadway: this variable was computed as follows. Motor vehicles per 1000 people from World Bank database (use most recent value). Motor vehicles include cars, buses, and freight vehicles but do not include two-wheelers. The total number of motor vehicles is calculated using population data from the World Bank. Data on km motorway is taken from the CIA Factbook (2008).
- Political rights indicator: edition 2008 provides data for year 2007.
- Gini index: most of the data are reported by the CIA Factbook (2008). Countries not covered by this data source were filled with data from the World Bank (e.g. Bhutan, Gabon, Qatar, Syrian Arab Republic and Trinidad and Tobago) and the Global Peace Index (e.g. Bahrain, Libya, Kuwait, Oman, Saudi Arabia, Sudan, United Arab Emirates), respectively.
- Neighborprice: it is in country i is the weighted average of gasoline prices in countries bordering country i. The weight attached to any neighboring country j corresponds to the fraction of total border length shared between country i and country j.

Table 4: Summary statistics

Variable	**Mean**	**Std. Dev.**
Tax	46	44
Dieseltax	16	46
Opt.Tariff	2	3
Debt/GDP	43	30
CO_2	279097	913585
Vehicles	52	67
Neighborprice	89	49
OPEC	0.11	0.32
Polrights	3	2
GDP	17200	16417
Gini	40.3	10.0
Cum.Cons	8.3	1.8
Cum.Prod	6.1	4.0
N	97	

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[24] Refinery processing loss: the volumetric amount by which total refinery output is less than input for a given period of time. This difference is due to the processing of crude oil into products which, in total, have a higher specific gravity than the crude oil processed.

Table 5: Cross-correlation table

Variables	Tax	Dieseltax	Opt.Tariff	Debt/GDP	CO_2	Vehicles	Neighborprice	OPEC	Polrights	Gini	GDP	Cum.Cons	Cum.Prod
Tax	1.000												
Dieseltax	0.894	1.000											
	(0.000)												
Opt.Tariff	0.538	0.496	1.000										
	(0.000)	(0.000)											
Debt/GDP	0.239	0.189	0.198	1.000									
	(0.018)	(0.064)	(0.052)										
CO_2	-0.075	-0.004	-0.138	0.021	1.000								
	(0.466)	(0.972)	(0.176)	(0.837)									
Vehicles	-0.092	-0.100	-0.073	-0.004	-0.050	1.000							
	(0.369)	(0.329)	(0.478)	(0.970)	(0.626)								
Neighborprice	0.117	0.156	0.132	-0.286	-0.030	-0.131	1.000						
	(0.253)	(0.128)	(0.198)	(0.005)	(0.768)	(0.200)							
OPEC	-0.588	-0.522	-0.469	-0.319	-0.051	0.240	0.017	1.000					
	(0.000)	(0.000)	(0.000)	(0.001)	(0.623)	(0.018)	(0.867)						
Polrights	-0.509	-0.612	-0.463	-0.113	0.067	0.055	-0.111	0.394	1.000				
	(0.000)	(0.000)	(0.000)	(0.272)	(0.513)	(0.594)	(0.278)	(0.000)					
Gini	-0.194	-0.300	0.023	-0.059	0.050	-0.106	-0.062	0.011	0.151	1.000			
	(0.057)	(0.003)	(0.823)	(0.565)	(0.628)	(0.304)	(0.543)	(0.919)	(0.140)				
GDP	0.107	0.198	-0.007	-0.015	0.067	0.483	-0.059	0.136	-0.331	-0.457	1.000		
	(0.298)	(0.052)	(0.945)	(0.884)	(0.512)	(0.000)	(0.568)	(0.185)	(0.001)	(0.000)			
Cum.Cons	-0.053	0.065	-0.280	0.133	0.510	0.152	-0.074	0.091	-0.141	-0.196	0.308	1.000	
	(0.606)	(0.527)	(0.006)	(0.195)	(0.000)	(0.138)	(0.470)	(0.377)	(0.167)	(0.054)	(0.002)		
Cum.Prod	-0.444	-0.359	-0.905	-0.096	0.334	0.124	-0.136	0.406	0.299	-0.105	0.142	0.662	1.000
	(0.000)	(0.000)	(0.000)	(0.350)	(0.001)	(0.226)	(0.184)	(0.000)	(0.003)	(0.307)	(0.165)	(0.000)	

B Regression Result

Table 6: Regression results

	(1)	(2)	(3)	(4)	(5)
Debt/GDP	0.44***	0.15	0.11	0.094	0.21*
	(0.15)	(0.15)	(0.14)	(0.12)	(0.12)
CO^2	-0.0000038	-0.0000048	-0.0000025	-0.0000021	0.00000023
	(0.0000035)	(0.0000030)	(0.0000031)	(0.0000045)	(0.0000049)
Vehicles	-0.046	0.041	0.031	0.0014	-0.023
	(0.074)	(0.057)	(0.048)	(0.056)	(0.057)
Neighborprice	0.17*	0.15*	0.100	0.074	0.051
	(0.098)	(0.087)	(0.080)	(0.078)	(0.082)
OPEC		-80.1***	-61.1***	-53.8***	
		(9.60)	(11.1)	(11.8)	
Opt.Tariff			4.22***	3.43**	5.11***
			(1.42)	(1.40)	(1.40)
Polrights				-4.01**	-6.50***
				(1.88)	(1.98)
GDP				0.00012	-0.00013
				(0.00022)	(0.00022)
Gini				-0.60*	-0.75**
				(0.32)	(0.33)
α	15.6	34.9**	29.9**	69.4***	75.7***
	(14.4)	(13.8)	(12.7)	(20.7)	(20.6)
N	97	97	97	97	97
Adj.R^2	0.066	0.35	0.41	0.46	0.37
RESET	0.06	0.77	0.15	0.33	0.33
Swilk	0.96	0.80	0.82	0.69	0.56

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Columns (1)-(4) are equivalent to those of Table 2; in Table B, they are completed with Column (5). This column presents the estimation results for the exhaustive model of Section 3, exclusive of the dummy variable for OPEC membership ($OPEC$).

The main conclusion from these results concerns the effect of the exclusion of $OPEC$ on the role of *Opt.Tariff*. It has been drawn in Section 3. It is also worth commenting on its effect on the role of *Polrights* and *Gini*. At the exclusion of $OPEC$, both variables turn out to have stronger effects. Moreover, the levels at which their coefficients are significantly different from zero is reduced.

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