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The effects of transport regulation on the oil market
Does market power matter?

Abstract:
Popular instruments to regulate consumption of oil in the transport sector include fuel taxes, biofuel requirements, and fuel efficiency. Their impacts on oil consumption and price vary. One important factor is the market setting. We show that if market power is present in the oil market, the directions of change in consumption and price may contrast those in a competitive market. As a result, the market setting impacts not only the effectiveness of the policy instruments to reduce oil consumption, but also terms of trade and carbon leakage. In particular, we show that under monopoly, reduced oil consumption due to increased fuel efficiency will unambiguously increase the price of oil.

Keywords: Transport regulations, oil market, monopoly, terms-of-trade effects, carbon leakage

JEL classification: D42; Q54; R48

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1. Introduction

Climate change is high on the global policy agenda, and studies like IPCC (2007) and Stern (2007) have established the need for ambitious international climate agreements and strong domestic climate policies. Early steps include the EU Emission Trading Scheme, the Kyoto Protocol, and the Copenhagen Accord; these and future efforts will have important consequences for the oil market. At the same time, energy-importing countries are concerned about energy security and oil dependence. Most developed countries are net oil importers, and the fact that one third of global oil exports come from the Middle East brings concern about macroeconomic disruption costs from the risk of oil price shocks, constraints on foreign policy (e.g., questions about human rights and democratic freedom in oil-exporting nations), and the possible funding of terrorist activities by oil revenues. Europe and the United States are expected to increase their import dependency on oil over the next decades as their own supplies are depleted (EIA 2010), whereas the Organization of the Petroleum Exporting Countries (OPEC) may increase its market share and, consequently, its market power.

Both climate change impacts and energy security call for policies to reduce the demand for oil in most oil-importing countries. These goals can be achieved through a number of different policies such as mandated biofuel shares, emissions standards, a quota system for carbon dioxide (CO_2) emissions, taxation of CO_2 emissions or energy use, support of renewable energy production, and standards for energy equipment.[1] Examples of policies that are rarely cost-effective with respect to climate change or energy security, yet often preferred by policy makers, are those that specifically target the transport sector, such as a fuel tax, a required share of biofuels in fuel consumption, and emissions standards for vehicles (see Parry et al. 2007). All are either implemented or suggested in the European Union and the United States, but to different degrees. While the U.S. has rather low tax rates by international standards, fuel taxes are relatively high in many European countries (OECD 2009). On the other hand, the United States have traditionally favored fuel economy standards, and aggressively tightened their standards in 2007 and 2009.[2] Biofuel requirements have been introduced in both the U.S. and the EU in recent years.[3]

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[1] A combination of goals will usually imply a different mix of policies than if one only had the aim of reducing greenhouse gas emissions. For instance, broad taxes are more cost-effective than fuel standards or biofuel shares if the aim is to reduce global warming.

[2] The new Corporate Average Fuel Economy (CAFE) standards for manufacturers are equivalent to 39 miles per gallon for their new car fleets and 30 miles per gallon for their light-truck fleets by 2016 (see, e.g., Parry 2009).

[3] All Member States in the EU are required to increase their share of biofuels in the transport sector to at least ten per cent in 2020 (see e.g. http://ec.europa.eu/energy/renewables/doc/sec_2008_85-2_ia_annex.pdf).

The transport sector is essential when studying the demand for oil. According to EIA (2010), transportation accounted for 53 percent of the world total liquids consumption in 2007, and the share is expected to increase to 61 percent in 2035. Also, the world's transportation systems are more than 90 percent dependent on oil and oil products, so few alternatives can compete widely with oil in the transport market today. Biofuels are obviously candidates, but are mostly uncompetitive without regulations in favor of such fuels (Brazilian ethanol being a possible exception). Coal- and gas-to-liquids are other candidates, but are too expensive today with current prices of fossil fuels. The same holds for electric cars and hydrogen cars. In the future, however, several of these technologies may become competitive versus oil, even without special treatment.

Policies to regulate transport may have different impacts in a competitive market and a market with a dominant producer. The oil market can hardly be considered competitive, as OPEC exhibits at least some degree of market power (see, e.g., Berg et al. 1997a; Alhajii 2004). Thus, in this paper we study the impacts of different types of transportation regulations in the presence of market power, and compare with the corresponding impacts in a competitive market. In particular we compare three different types of policy instruments: a fuel tax, a required share of biofuels in the transport market, and fuel efficiency.

The literature relevant for our study can be divided into two strands: one that studies regulations in the transport sector in more detail by mainly focusing on the demand side, and one that analyses the oil market by focusing on the supply side. Starting with the first strand of literature, most studies on regulations in the transportation sector are demand-side analyses (assuming fixed oil market prices) that use a utility function as the starting point to calculate optimal fuel taxes (e.g., Parry and Small 2005; West and Williams 2007; Parry 2009), measure welfare effects of fuel economy regulations (e.g., Fischer et al. 2007), or calculate costs of different regulations to meet certain levels of gasoline consumption (e.g., West and Williams 2005). Morrow et al. (2010) study the impacts of different policies to reduce oil consumption and greenhouse gas emissions from the U.S. transportation sector but assume an exogenous oil price. The large literature on fuel-efficiency standards introduces market power when examining effects of such standards under possibilities of price discrimination when consumers have different tastes (e.g., Plourde and Bardis 1999) and the effects of standards on cars sales, prices, and fuel consumption (e.g., Goldberg 1998). But these studies introduce market power in the supply of cars and not in the oil market. The economic literature on biofuels has also emerged the last few years (see, e.g., Rajagopal and Zilberman 2007 for a survey). De Gorter and Just (2007) study the effect of biofuel subsides on oil consumption in a competitive market, while Hertel et al. (2010) analyze the impacts of biofuel mandates in a global computable general equilibrium model.

A recent paper on biofuels that makes a link to the second strand of literature is Hochman et al. (2010). It focuses on the impact of biofuels when OPEC acts as a cartel. The authors specify two regions in the world—an oil-exporting and an oil-importing region—and study the different impacts on the oil price in the two regions using a static model. However, the paper does not make comparisons with other policy instruments to reduce oil consumption.

Another relevant paper on the oil market is by Berger et al. (1992), who studied the impact of international agreements to reduce CO_2 emissions on fossil fuel prices based on tradable emissions permits and an international CO_2 tax. They found that while the two instruments have the same effect on the producer price (i.e., market price) of fossil fuels in competitive fossil fuel markets, direct regulation in the form of tradable quotas tends to imply higher producer prices than an international CO_2 tax giving the same reduction in total CO_2 emissions. Strand (2009) also studies the impacts of carbon taxes and tradable permits, assuming two blocs of countries: an oil-importing region that regulates fossil fuel consumption and produces alternative fuels, and an oil-exporting region without any regulations. However, the paper focuses on strategic behavior for rent extraction, such as export taxation, rather than effects of market power.

Some studies of carbon taxation consider intertemporal supply under different market settings (e.g., Berg et al. 1997b), but few studies compare policy instruments in an intertemporal setting when market power is taken into account. For instance, Sinn (2008) studies different policy measures from an intertemporal supply-side perspective for a non-renewable resource but does not consider market power on the supply side.

In this paper, we combine the two strands of literature. Instead of focusing on the preferences of consumers, we study the importance of the supply side of the oil market for the effects of transport regulations. We do not consider intertemporal optimization on the supply side but rather focus on market power. Our interest is on the effects on the price and quantity of oil consumption under different market settings. We find that particularly price effects can be dramatically different under market power compared to in a competitive market, especially if fuel efficiency standards are raised. Price effects are important, and not just for distributional reasons (i.e., who bears the burden of the policy, consumers or producers). Assuming, for instance, that transport regulations follow from a climate treaty, signatory countries may be concerned about increased emissions in non-signatory countries due to a *lower* oil price (a phenomenon called *carbon leakage*; see Felder and Rutherford, 1993). It is also widely known that environmental regulations may affect terms of trade (Krutilla 1991), and oil-importing countries may worry about policy measures that can *increase* the oil price. Therefore, we compare the effects on the oil price of different regulations under different market settings.

The paper is organized as follows. In the next section, we use a static model for a closed economy to study the impacts of the different policy instruments in a competitive market and a monopoly market. While both forms are too simplistic in describing the oil market, they represent useful indicators of the effects of transport regulations when market power is introduced. In the third section, we extend the analysis to an open economy to further study volume effects, as well as changes in terms of trade and carbon leakage, from regulations in the transport sector. The final section concludes.

2. Transport regulations in a closed economy

To focus on the effects of market power, we use a static partial equilibrium model, starting with a closed market. A natural interpretation is to think of this as the global oil market. Nevertheless, we will also discuss implications for a single oil-importing country, and in the following section, we will model an open market explicitly. As the substitution possibilities are small in the transport market, we implicitly keep prices of other energy goods constant.[4]

We study different transport regulations to reduce fossil fuel consumption and hence CO_2 emissions under the assumption that they are widely introduced. If we think of the global oil market, these regulations could be the outcome of an international climate agreement. So far it seems more realistic to consider such regulations within a single country or a group of countries than the entire globe as not all countries are likely to sign a climate agreement, and that is why we examine an open economy in the next section. The analysis of a closed market will still give useful insight, to a situation where a large part of the oil market becomes regulated.

The demand-side regulations we consider are the following:

[4] In the future, given significant progress for alternative transportation technologies, this assumption may become less valid. To simplify the analysis throughout the paper, we further ignore oil consumption outside the transport sector.

i) A *fuel tax* interpreted as a tax t per unit of oil consumed.
ii) A required *share of biofuels* such that for each unit of oil that is sold, one also needs to sell a units of biofuel (e.g., gasoline mixed with ethanol).[5]
iii) An *efficiency standard* interpreted as a binding minimum average vehicle efficiency m, measured as miles per gallon (mileage).

We will compare the effects of these policy instruments in a competitive market (C) and a monopoly market (M), assuming throughout the paper that the changes in t, a, or m are the same in the two market settings. In the next section we also consider a market with a dominant firm and a competitive fringe.

2.1. The demand for oil

Let us start by defining the consumption of transport services, measured in miles driven (q), as a function of mileage (m), oil consumption for transport use (x), and biofuel requirements (a). Then we have

$$(1) \qquad q = m \cdot x + m \cdot ax = m(1+a)x .$$

To drive a mile, one can use oil and/or biofuels as the fuel source.[6] As oil is measured in gallons, $m \cdot x$ is the number of miles driven on oil and $m \cdot a \cdot x$ is the number of miles driven on biofuels. Alternatively, $(1+a)x$ is the blended fuel. We see that for a given consumption of transport services q, increased mileage or share of biofuels means that the consumption of oil is reduced accordingly.

Now, let us turn to the demand for oil. To do this, assume that an increase in m increases mileage by the same percentage rate for all transport consumers, so that an increase in m has the same effect on the demand function for all quantities of oil. Moreover, we disregard any costs related to making cars more fuel efficient and costs related to supplying the necessary amount of biofuels. We assume the government covers these costs, not consumers or producers in the oil market. Thus, we assume that the

[5] Alternatively, there is a required share of biofuels interpreted as a fraction $\hat{a}$ of total transport fuel consumption, where $a = \hat{a}/(1-\hat{a})$.

[6] We disregard other alternative transport technologies, such as electricity and hydrogen, as they are usually not regulated through any policy measures studied here.

price of biofuels is equal to the price of oil — e.g., that gasoline is mixed with biofuels when sold at a gas station.[7]

Let $P_q(q)$ denote the inverse demand function for transport services — i.e., the price consumers are willing to pay for an extra mile as a function of miles driven. Furthermore, $P_x(x)$ denotes the inverse demand function for oil facing the producer(s) of oil. Note that the consumer price of oil is then $P_x(x) + t$ — i.e., the producer price plus the fuel tax. Consequently, we have

$$(2) \qquad P_q(q) = \frac{P_x(x) + t}{m}.$$

Thus, the price per mile driven is equal to the consumer price of oil per gallon divided by the mileage. From (1) and (2) we can write the inverse demand function for oil facing the producer(s) of oil:

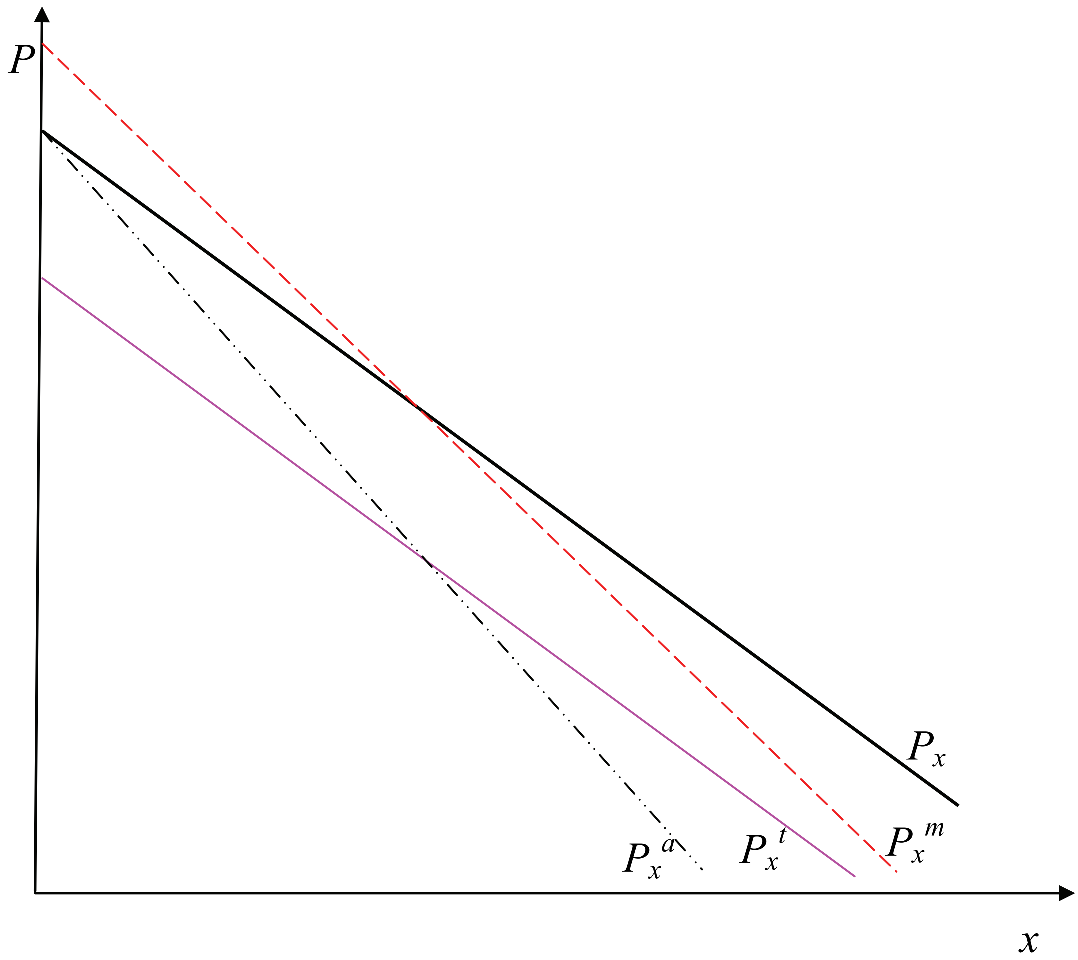
$$(3) \qquad P_x(x) = mP_q(m(1+a)x) - t,$$

where we assume $P_q'(q) < 0$ and thus $P_x'(x) < 0$.

Equation (3) shows quite clearly that the three different policy instruments affect the inverse demand function for oil very differently. This is illustrated for a linear demand function in Figure 1, where P_x^i and $i=a,m,t$ are the new demand functions under the different regulation schemes. A fuel tax, t, shifts the inverse demand function downward, while a higher required share of biofuels, a, makes the function steeper, with the same maximum price as before.

[7] This also follows the assumption in Hochman et al. (2010) that biofuels and gasoline are supplied to the same price. If we assumed, for instance, that the oil producer has to buy the biofuels at a price different than its marginal costs and then supply the blend in the market, a change in the blending requirement, *a*, would also give a change in the marginal cost of the blended fuel.

Figure 1. Impacts of different policy instruments on the demand for oil



Increased efficiency, *m*, also makes the inverse demand function steeper, but the maximum price (if finite) increases because it becomes cheaper to drive a mile if prices are unchanged. Thus, as opposed to the two other instruments, increased efficiency may *increase* oil demand for some (high) price levels.[8] To see this, note first that with higher mileage one does not need as much gasoline to drive the same distance as before, which lowers oil demand. This is particularly relevant when consumers' price responsiveness is low (e.g., at low prices). On the other hand, if consumers are price responsive, the lower cost of driving a mile will stimulate demand for transport. This is called the *rebound effect* in

[8] The demand curves will not cross if the price elasticity is constant. In this case, the new demand function will either be above or below the old one. One example where the P_x^m-curve will be below the P_x-curve for all x is $P_x = x^{-k}$, where $k < 1$ (i.e., price elasticity below one in absolute value).

the literature (see, e.g., Portney et al. 2003; Small and Van Dender 2007).[9] If the rebound effect is very strong, which may be the case if consumers are very price responsive (see the next subsection), transport volumes may be stimulated to such a degree that even demand for gasoline increases.

2.2. Quantity effects

Consider first the quantity effects of the different policies in competitive and monopoly markets. For simplicity we assume that $a = t = 0$ and $m = 1$ initially. In other words, we study the effects of introducing transport regulations where there are no prior regulations. To simplify the notation we use $P(x)$ instead of $P_x(x)$.

2.2.1. Competitive oil market

Assume that a representative, profit-maximizing producer faces a cost function $c(x)$, with the following properties: $c'(x) > 0$ and $c''(x) \geq 0$. As shown in the appendix (equation (A4)), we get the following effects of the different instruments in a competitive market:

(4)

i) $$\frac{dx^C}{dt} = -\frac{1}{c''(x) - P'(x)} < 0,$$

ii) $$\frac{dx^C}{da} = \frac{xP'(x)}{c''(x) - P'(x)} < 0, \text{ and}$$

iii) $$\frac{dx^C}{dm} = \frac{P(x)\left(1 + \frac{1}{\varepsilon(x)}\right)}{c''(x) - P'(x)},$$

where $\varepsilon(x) = \frac{P(x)}{xP'(x)}$ (price elasticity of demand).[10]

Not surprisingly, and also shown in earlier studies, oil consumption drops if either a tax or a required share of biofuels is introduced. On the other hand, we notice from (4) iii) that the effect of increased mileage on oil consumption is ambiguous, also shown in Figure 1. If the marginal cost function crosses above the intersection of the P_x- and the P_x^m curves, oil consumption increases when mileage is

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[9] The crossing demand functions can also be seen from equation (3). Increasing m has two effects as m is multiplied with $P_q(q)$ and also increases q everything else given. As $P'_q(q) < 0$, we see that $P_x(x)$ may either increase or decrease for an increase in m.

[10] Note that $x(P)$ is the demand function for oil, which is the inverse of $P(x)$.

raised; otherwise it will fall. Furthermore, we see from (4) iii) that the direction of change in consumption depends on the size of the price elasticity of demand.

As a reference point to the analysis in a monopoly market, we summarize these conclusions in a proposition:

Proposition 1: *In a competitive oil market, introducing fuel taxes and biofuel requirements will reduce oil consumption. Increased fuel efficiency will increase oil consumption if and only if the price elasticity in the market equilibrium is above one in absolute value.*

Proof: This is easily seen from (4) i)–iii).

Most recent empirical analyses seem to conclude that price elasticities are rather low in absolute value and most likely below one in the short run (e.g., Hughes et al. 2006; Parry 2009). Thus, if the oil market can be viewed as a competitive market, introducing an efficiency standard for transportation will most likely reduce total consumption of oil in the short run. This is also the empirical conclusion for the U.S. by Small and Van Dender (2007). In the long run, however, the price elasticity can be quite high (see, e.g., Sterner 2007).[11]

2.2.2. Monopoly market

To see the effect of transport regulations when market power is introduced, we confront the conclusions above with an analysis of a market with a monopoly on the supply side. As we will use linear demand and marginal cost functions in Section 3, we will also briefly report the results for linear functions.

As shown in the appendix (equations (A9)), the quantity effects of the different policy instruments are as follows in a monopoly market:

[11] If the price elasticity is above unity at high prices (e.g., as with linear and concave demand functions), a gradual increase in unit production costs over time due to resource scarcity will increase the likelihood that increased mileage will stimulate consumption.

$$(5)\qquad \text{i)}\quad \frac{dx^M}{dt} = -\frac{1}{c''(x) - 2P'(x) - xP''(x)} = -\frac{1}{\Gamma(x)} < 0\,,$$

$$\text{ii)}\quad \frac{dx^M}{da} = \frac{2xP'(x) + x^2P''(x)}{c''(x) - 2P'(x) - xP''(x)} = \frac{xP'(x)\big(2 + \gamma(x)\big)}{\Gamma(x)}\,, \text{ and}$$

$$\text{iii)}\quad \frac{dx^M}{dm} = \frac{P(x) + 3xP'(x) + x^2P''(x)}{c''(x) - 2P'(x) - xP''(x)} = \frac{xP'(x)\big(3 + \varepsilon(x) + \gamma(x)\big)}{\Gamma(x)}\,,$$

where $\gamma(x) = x\frac{P''(x)}{P'(x)}$, and $\Gamma(x) = c''(x) - 2P'(x) - xP''(x) > 0$ (by the second order condition). In a monopoly market we recall that $\varepsilon(x^M) \leq -1$ for the marginal revenue (*MR*) to be positive.[12]

We notice that the value of $\gamma(x)$ is crucial for the impact of the policies. This parameter is the elasticity of $P'(x)$ with respect to x and characterizes the curvature of the demand function. Throughout the paper we will distinguish between three cases: i) $\gamma > -1$, which means that the inverse demand function is either concave ($\gamma > 0$), linear ($\gamma = 0$), or "slightly convex" ($-1 < \gamma < 0$), in the sense that the price derivative does not change too fast when x changes; ii) $-2 < \gamma < -1$, in which case we will refer to a "quite convex" inverse demand function; and iii) $\gamma < -2$, which means that the inverse demand function is "very convex."[13]

From equations (5) we first observe that a tax will unambiguously reduce consumption of oil, just as in the competitive market. In the linear case of $P''(x) = 0$, we can easily show that the relative output reduction will be the same in the two market settings.

Further, a required biofuel share will reduce oil consumption if and only if the inverse demand function is not very convex ($\gamma > -2$). In the linear case, the relative output reduction will be bigger in a monopoly market than in a competitive market (unless marginal costs are constant). The reason is that the demand function becomes steeper, and thus the monopolist finds it profitable to reduce output

[12] As mentioned above, empirical studies find the short-run price elasticity to be less than one (in absolute value) in the oil market. However, this does not rule out market power in this market. If the oil market can be characterized as having a dominant producer (OPEC) and a competitive fringe (see, e.g., Hansen and Lindholt, 2008), it is profitable for a dominant producer to adjust its production to a level where the price elasticity of the residual demand is larger than one (in absolute value). This elasticity will be larger than the demand elasticity (in absolute value), so we may still have a dominant producer in the oil market even if the demand elasticity is "low." Also, Hochman et al. (2010) argue that import demand elasticities observed by OPEC countries are much larger than price elasticities observed in macro, and they set these to be above one in absolute value. In section 3.2, we will investigate the model with a dominant producer.

[13] Note that γ is a function of x — i.e., it is not necessarily constant. We have ruled out $\gamma = -1$ and $\gamma = -2$. For $\gamma = -2$, dP/dx is not defined for $da>0$; see equation **(7)** below. For $\gamma = -1$, we see from **(6)** and **(7)** below that dP/dx is similar in a monopoly and a competitive market for both $dt>0$ and $da>0$.

relatively more than in the tax case. However, for more convex inverse demand functions ($\gamma < -2$), oil consumption will actually increase. Thus, whereas a required share of biofuels always reduces consumption in a competitive market, oil consumption will actually increase in a monopoly market if the inverse demand function is very convex. Notice, however, that a very convex inverse demand function typically (but not necessarily) will lead to negative marginal revenue even for low values of x, which makes this outcome (i.e., increased oil consumption) rather unlikely.[14]

As for the competitive market, the effect of increased fuel efficiency on oil consumption is generally ambiguous in a monopoly market. The sign of the numerator in (5) iii) depends on the sum of γ and the price elasticity ε. As $\varepsilon < -1$ in a monopoly market, we see that if the inverse demand function is very convex ($\gamma < -2$), oil consumption will increase when fuel efficiency is increased.[15] Oil consumption can also increase with $\gamma \geq -2$ if $\varepsilon + \gamma < -3$. Nevertheless, a more realistic scenario may be that $-2 < \varepsilon < -1$ and $\gamma > -1$, so that the numerator in (5) iii) is negative, in which case oil consumption decreases.

The conclusions can be summarized by the following proposition:

Proposition 2: *With a monopoly supplying oil,*

- *introducing fuel taxes will reduce oil consumption;*
- *introducing a biofuel requirement will reduce oil consumption if the inverse demand function is not very convex ($\gamma > -2$), but otherwise increase consumption ($\gamma < -2$); and*
- *increasing fuel efficiency will reduce oil consumption if the inverse demand function is not very convex and not very price elastic ($\varepsilon + \gamma > -3$), but otherwise increase consumption ($\varepsilon + \gamma < -3$).*

Proof: See equation (5) and the text above.

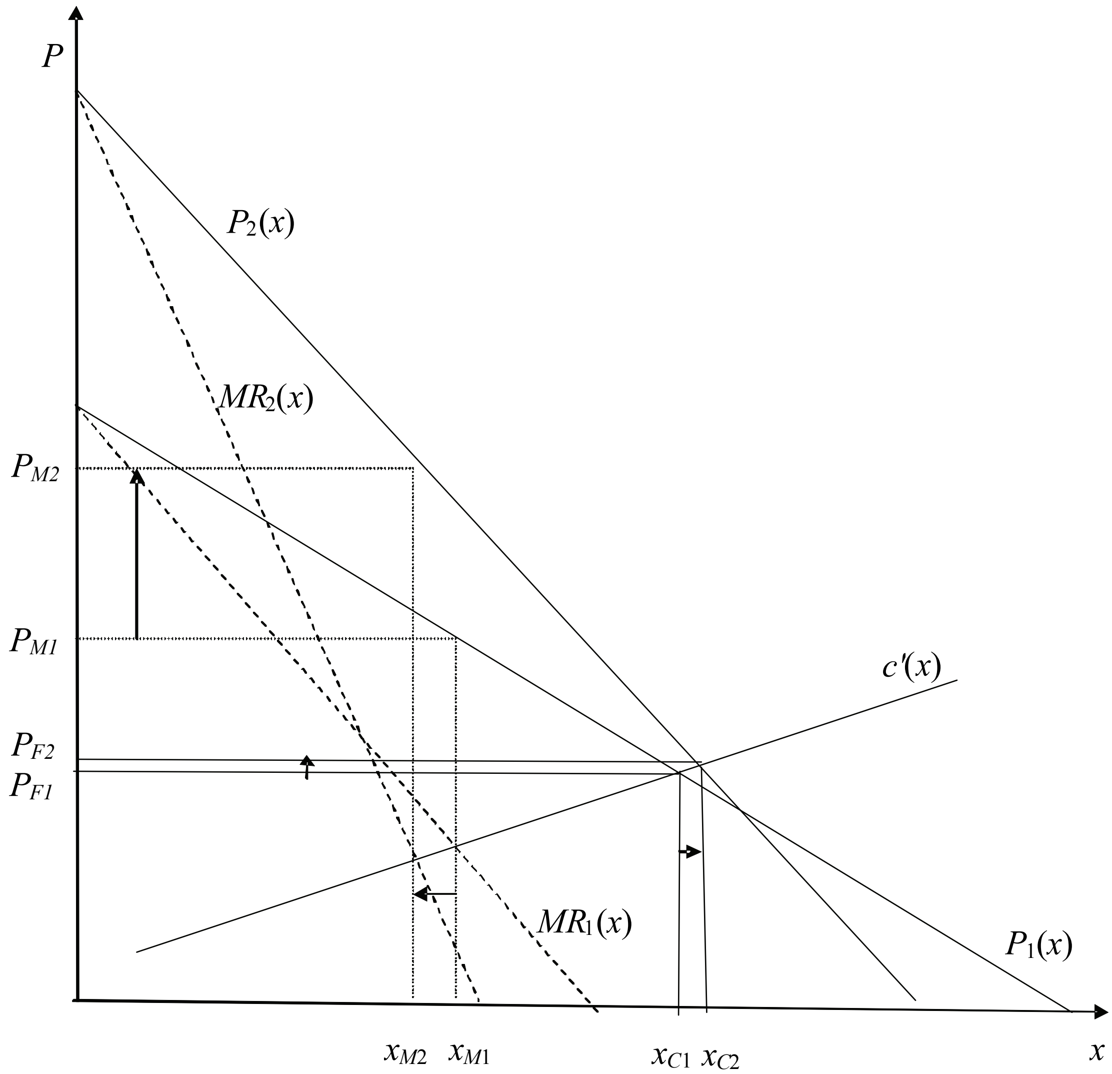
An example of increased fuel efficiency in the oil market is shown in Figure 2. We have here assumed that the price elasticity is above one in absolute value in the competitive outcome, so that higher fuel efficiency will increase oil demand in this market setting (from x^{C1} to x^{C2}). On the other hand, it will decrease oil demand (from x^{M1} to x^{M2}) in the presence of a monopoly. This is not accidental. In the

[14] One example is $P(x) = x^{-2}$, in which $\gamma = -3$ and $MR = -x^{-2}$. On the other hand, a demand function where we get higher oil consumption by introducing biofuel requirements is $P(x) = Min\ (3\ ;\ 2 + x^{-2})$. The intuition here is that marginal revenue increases in x. An interior solution requires, however, that $c'(x)$ increases faster than $MR(x)$.

[15] The reason is the same as for biofuels; the marginal revenue will increase in x in this case.

special linear case, we can show that we will never get higher x^M and lower x^C for the same set of demand and cost functions. Again, the reason is that the demand function becomes more inelastic with increased fuel-efficiency standards, making it more profitable for the monopolist to reduce supply. If we rather assumed a marginal cost curve lying below the crossing point for the two demand curves (which we know is equivalent to inelastic demand in the competitive outcome), oil demand would decrease in the competitive case, too. On the other hand, if the marginal cost curve were lying above the crossing point for the two *MR*-curves, we would get higher demand in both cases.

Figure 2. Impacts of emissions standards in the oil market



To sum up the quantity effects in competitive and monopoly markets (see Table 1), the effects of regulations become somewhat more ambiguous with market power. Still, in most realistic cases, the analysis suggests that oil consumption will fall irrespective of policy instrument and market setting studied above. Moreover, it is difficult to state in general terms whether the quantity reductions are largest in a competitive or a monopoly market. The brief discussions of the special linear case may indicate, however, that the relative output reduction may be biggest in the monopoly market except in the tax case, as the demand functions become more inelastic when introducing biofuel shares and fuel efficiency.

Table 1. Quantity effects of policy instruments in competitive (*C*) and monopoly (*M*) markets

	Fuel tax	Biofuel share	Efficiency standard
C	Negative	Negative	Negative if $\varepsilon(x^C) > -1$ Positive if $\varepsilon(x^C) < -1$
M	Negative	Negative if $\gamma(x^M) > -2$ Positive if $\gamma(x^M) < -2$	Negative if $\varepsilon(x^M) > -3 - \gamma(x^M)$ Positive if $\varepsilon(x^M) < -3 - \gamma(x^M)$

2.3. Price effects

Let us now turn to the price effects of the different policy instruments in the two market settings. In a closed market, price effects are of interest with respect to distributional issues—i.e., to what degree are monopolists able to charge a mark-up over marginal costs. Thus, the analysis may shed light on which policy instruments large oil producers would prefer and lobby for, given that oil consumption will have to come down.

If we think of the closed market as consisting of different countries agreeing on a common policy to reduce oil consumption, changes in P can be interpreted as terms-of-trade effects for the different countries. Thus, if a country is importing oil, it would like P to fall as much as possible when x is reduced to improve its terms of trade.

2.3.1. Competitive market

We will analyze the price effect by calculating the price change relative to the change in consumption. In a competitive market, it is obvious from the first-order condition (5) that we must have

$$(6) \qquad \frac{dP^C}{dx^C} = c''(x),$$

irrespective of which policy instrument is used. This gives the following proposition, which is useful as a reference for the analysis in the next subsection:

Proposition 3: *With standard assumptions under competitive markets ($c''(x) > 0$), producer price and quantity always move in the same direction when one of the policy instruments are used. Moreover, the relative price effect (i.e., dP/dx) is independent of instrument choice.*

Proof: This follows from equation (6).

2.3.2. Monopoly market

In a monopoly market, however, the price effect depends highly on the instrument choice. It is straightforward to show (by total differentiation of (3) and inserting from (5)) that we get the following price effects:

(7)

$$\text{i)} \quad \left.\frac{dP^M}{dx^M}\right|_{dt>0} = c''(x) - P'(x)\big(1+\gamma(x)\big),$$

$$\text{ii)} \quad \left.\frac{dP^M}{dx^M}\right|_{da>0} = \frac{c''(x)}{2+\gamma(x)}, \text{ and}$$

$$\text{iii)} \quad \left.\frac{dP^M}{dx^M}\right|_{dm>0} = \frac{c''(x)\big(1+\varepsilon(x)\big) + P'(x)\big[1-\varepsilon(x)\big(1+\gamma(x)\big)\big]}{3+\varepsilon(x)+\gamma(x)},$$

where we know that $\varepsilon(x^M) \leq -1$ in a monopoly market.

We immediately see that the value of $\gamma(x)$ is crucial for the comparisons of the price effects, but so is the third derivative of the cost function. Note that x will always be higher in a competitive market than with monopoly. Thus, the sign of $c'''(x)$ for $x \in [x^M, x^C]$ determines whether $c''(x)$ will be higher or lower with monopoly compared to a competitive market.

Let us first look at the tax case. We notice that the price reduction (relative to the output reduction) can be either bigger (e.g., if $\gamma > -1$ and $c'''(x) \leq 0$) or smaller (e.g., if $\gamma < -1$ and $c'''(x) \geq 0$) in a monopoly market than in a competitive market. In the special linear case ($\gamma = 0$), the price reduction will be biggest in a monopoly market. On the other hand, if $\gamma < -1$, it is possible that the producer price increases if the inverse demand function is sufficiently steep compared to the marginal cost function.

The explanation is that the fuel tax moves consumption toward a more inelastic part of the demand function, making it profitable for the monopolist to decrease production more substantially.

Consider now an increase in the biofuel share. Again we see that the relative price reduction can be either bigger (e.g., if $-2 < \gamma < -1$ and $c'''(x) \leq 0$) or smaller (e.g., if $\gamma > -1$ and $c'''(x) \geq 0$) in a monopoly market than in a competitive market. However, as we see, the conditions on γ for whether the price effect is bigger or smaller is completely turned around compared to the tax case. Thus, in the special linear case ($\gamma = 0$), the price reduction will be smallest in a monopoly market. It also follows that the price reduction in a monopoly market will be smaller with a biofuel share than with a tax. As explained above, the demand curve facing the monopolist becomes steeper (more inelastic) only in the former case, and thus it becomes more profitable to withhold production. If the inverse demand function is very convex ($\gamma < -2$), we know from the discussion in Section 2.2.2 that oil consumption will increase when a biofuel share is imposed. Equation (7) ii) shows that the price will decrease also in this case. Thus, the price will unambiguously fall if a biofuel share is introduced. The reason is that the new demand function will always be below the old one.

Last but not least, if fuel efficiency is increased, it can be shown that the price of oil will always increase as long as oil consumption decreases.[16] This effect, which is shown in Figure 2 in the linear demand case, is completely opposite of the price effect in a competitive market, where the price and quantity always move in the same direction (see equation (6)). If increased fuel efficiency stimulates oil consumption, the price effect is ambiguous and depends on the marginal cost and inverse demand functions.

We can summarize the conclusions in the following proposition:

Proposition 4: *With a monopoly supplying oil,*

- *introducing fuel taxes will reduce the producer price if $\gamma > -1$ but possibly increase the producer price if $\gamma < -1$ and the inverse demand function is sufficiently steep compared to the marginal cost function;*
- *introducing a biofuel requirement will always reduce the producer price; and*
- *increasing fuel efficiency will increase the producer price if oil consumption decreases but may either increase or decrease price if oil consumption increases.*

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[16] Note that x^M decreases if $3 + \varepsilon + \gamma > 0$; see (5) iii). Thus, the denominator in (7) iii) is positive. The first term in the numerator is negative since $\varepsilon \leq -1$, and the second term is also negative when $3 + \gamma + \varepsilon > 0$.

Proof: This follows from equation (7) and the discussion above.

Given a monopoly market, there are several policy implications to be drawn from the price effects in Proposition 4. A government may prefer the oil price to decrease or increase depending on the country's situation. We will return to this after discussing the open economy with a dominant producer, as this is a more relevant market situation, and because price effects are particularly important in an open economy due to terms-of-trade effects and carbon leakage.

Table 2 sums up the price effects of the three policy instruments for the different market assumptions, showing that the direction of change depends significantly on the market setting.

Table 2. Price effects of policy instruments in competitive (*C*) and monopoly (*M*) markets

		Fuel tax	Biofuel share	Efficiency standard
C	$dx^C < 0$	Negative	Negative	Negative
	$dx^C > 0$	N/A	N/A	Positive
M	$dx^M < 0$	?	Negative	Positive
	$dx^M > 0$	N/A	Negative	?

3. Transport regulations in an open economy

In the preceding section, we learned that the price effect of reducing oil consumption is independent of the policy instrument in a competitive market but highly dependent on the instrument choice in a monopoly market. In particular, whereas a biofuel share and, most likely, a fuel tax will reduce the producer price of oil in a monopoly market, increased efficiency will increase the price, given that the instrument leads to lower oil consumption. In this section, we will explore this issue further in an open economy with either a monopolist or a dominant firm with a competitive fringe. As the analysis becomes more complicated in an open economy, we will make a number of simplifying assumptions and also present some numerical illustrations. The analytical derivations and expressions are left to the appendix, whereas their implications are discussed in the main text below.

Consider now that the world is divided into two oil consuming regions: Region *A* and *B*. Region *A* imports oil from Region *B*, which has a dominant firm (*D*) and a competitive fringe (*F*) with linear marginal cost functions.[17] Both regions are assumed to have linear transport demand functions. Moreover, we disregard transport regulations in Region *B*.

It turns out that is difficult to derive analytical and interpretable expressions in the case of a dominant firm with a competitive fringe (except in the tax case). Thus, in the first subsection below we consider a monopoly market and examine the effects of the policy instruments in this market setting. We also present some numerical illustrations. Then, in Subsection 3.2, we present some numerical illustrations showing how the existence of a competitive fringe affects the results.

3.1. Monopoly market

As shown in the appendix (equations (A17)-(A19)), a fuel tax and a biofuel share will unambiguously reduce the producer price of oil and consumption in Region *A*, and thus increase consumption in Region *B*, causing carbon leakage. Increased fuel efficiency, however, will unambiguously increase the producer price of oil and hence reduce consumption in Region *B*. The effects on consumption in Region *A* are ambiguous and depend on the steepness of the demand curve in Region *B* as well as the marginal costs of the monopolist. These results are consistent with the results found in Section 2 in the case of a closed market.[18]

Let us examine more closely in which cases increased fuel efficiency will reduce fuel consumption in Region *A*. Define Region *B* to be large compared to Region *A* when oil demand is higher in region *B* than *A*. Examination of equation (A17) in the appendix reveals that the sign of dx_A/dm more likely will be positive when Region *A* is small compared to Region *B* (e.g., let $\beta_2 \to 0$). Thus, a small country facing a monopolist on the world market should not introduce fuel-efficiency standards if it aims to reduce its consumption (given the simple model framework used here). The explanation is that the equilibrium price in a monopoly market with linear demand functions will be above the intersection between the old and new demand curve shown in Figure 1. As Region *A* is small, the demand curve in Region *B* will be relatively flat in comparison; thus the small region has little influence on the price, and consumption will increase.

If the two regions are equally large, increased fuel efficiency will reduce oil consumption in Region *A* if and only if the two demand curves are substantially (i.e., 3.6 times) steeper than the marginal cost function of the monopolist. Moreover, consumption in Region *A* will always increase if the marginal

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[17] Conclusions regarding prices and consumption will not change if the competitive fringe is located in region *A*.

[18] A closed market can be seen as a special case of an open market with Region *B* becoming infinitely small.

cost function is at least twice as steep as the demand function in Region *A*, irrespective of the size of Region *B*. The intuition is that the marginal cost curve then crosses above the intersection between the old and new marginal revenue curve (see Figure 2). On the other hand, if Region *B* is small compared to Region *A*, consumption will decrease in the latter region if the marginal cost curve is not too steep compared to the demand curve in Region *A*. In the limit, when Region *B* is infinitely small, we notice that the results are consistent with the findings for a closed market in Section 2.

The main results can be summarized in the following proposition:

Proposition 5: *Consider a world consisting of two regions (A and B), with a monopoly in Region B supplying oil, and linear demand and marginal cost functions. Increased fuel-efficiency standards in Region A will then*

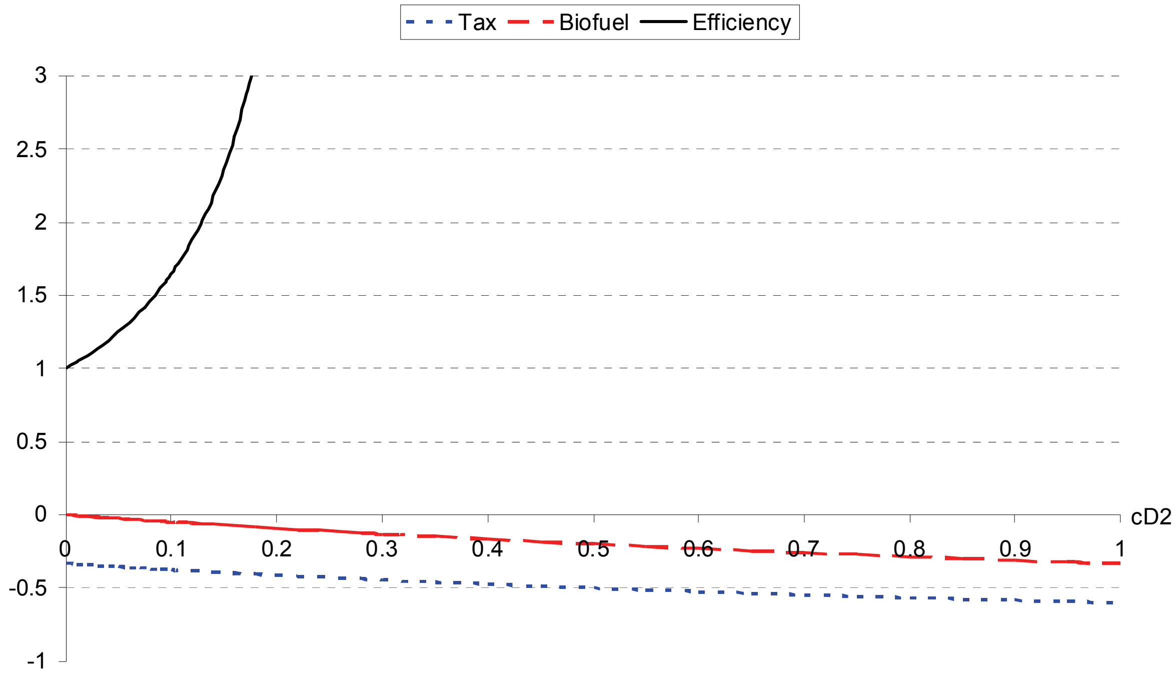
- *increase oil consumption in this region if Region A is sufficiently small compared to Region B, or if marginal costs of the oil producer are sufficiently high; and*
- *increase the producer price of oil.*

Proof: This follows from the discussion above.

Now focus on the situations where the policy instruments lead to reduced oil consumption in Region *A*. We know from above that the fuel tax and the biofuel share will reduce the producer price of oil, whereas fuel efficiency will increase the price. But how much will it change relative to the consumption reduction, and how does it depend on demand and marginal cost functions? In Figure 3, we assume that the two regions are of the same size, and vary the steepness of the marginal cost function (denoted c_{D2}, cf. the appendix).[19]

[19] When $c_{D2} = 0.5$, the marginal cost curve of the monopolist (dominant firm in Figures 5-6) and the global demand curve have the same steepness.

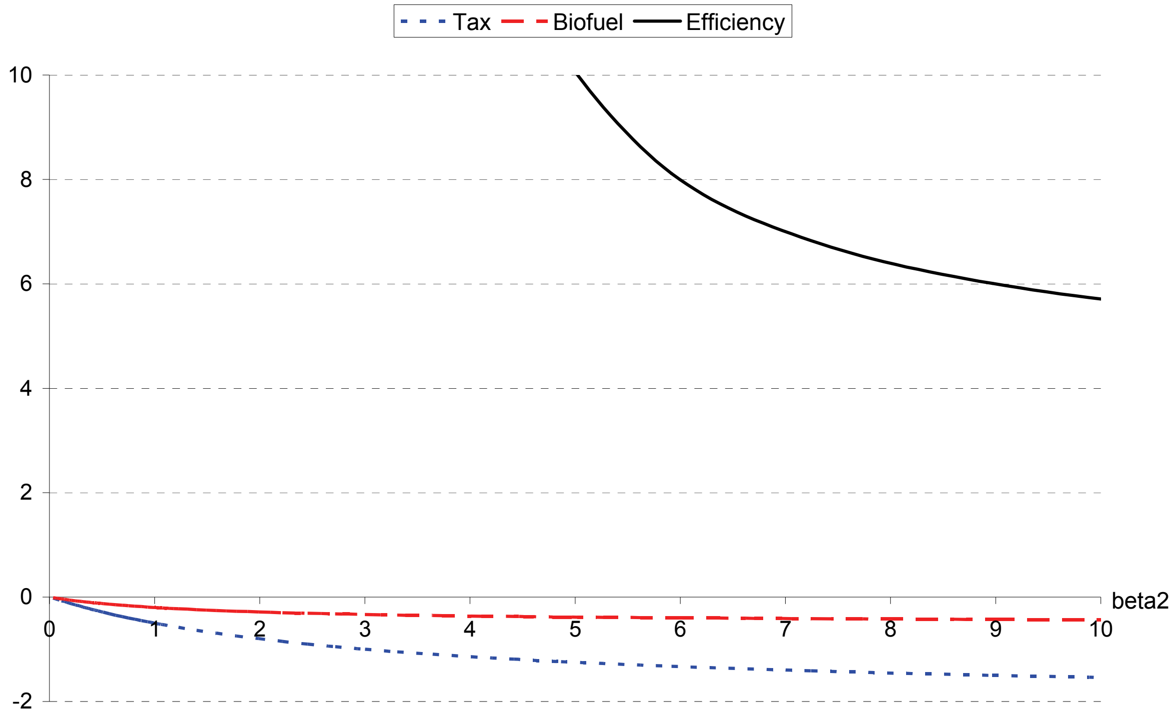
Figure 3. Effects on the producer price of oil (dP/dx_A) under different policy instruments



The figure shows that the price reduction will be consistently and significantly larger if a tax is imposed than if a biofuel share is imposed. This holds more generally, unless the marginal cost function is several times steeper than the aggregate demand curve (which we find highly unlikely). In line with Section 2, this is due to steeper demand functions with biofuel shares than with a tax. The figure further demonstrates that the steeper the monopolist's marginal costs are, the more the price drops when consumption is reduced by a fuel tax or a biofuel share. This is intuitive, as it is less profitable for the monopolist to reduce its supply if marginal costs drop significantly. The figure also shows that the price effect is much bigger when fuel efficiency is enhanced and can be very big relative to the consumption reduction when c_{D2} approaches the point where increased fuel efficiency no longer reduces consumption, cf. the discussion above.

In Figure 4 we assume that the steepness of the marginal costs equal the steepness of global demand, and vary the relative size of Region *A* compared to *B* (denoted β_2, cf. the appendix). We see that the price reduction under a tax or a biofuel share increases with the relative size of Region *A*. For instance, if Region *A* is two times bigger than Region *B* ($\beta_2 = 2$), the price reduction is 50–60 percent higher than if the regions are equally big ($\beta_2 = 1$). Moreover, when Region *A* is very small compared to the rest of the world ($\beta_2 \rightarrow 0$), we see that the price reduction is negligible, which is consistent with the discussion leading up to Proposition 5.

Figure 4. Effects on the producer price of oil (dP/dx_A) under different policy instruments when $c_{D2} = \beta_2 / (1 + \beta_2)$ in a monopoly market



On the other hand, if fuel efficiency is increased, we see again that the price increase (relative to the consumption reduction) can be very big close to the point where increased fuel efficiency no longer reduces consumption (cf. the discussion above). However, as we increase the relative size of Region A, the price increase is reduced. This is mainly because the policy instrument becomes more effective in reducing consumption when the region is large, so the relative price increase falls.

3.2. Dominant firm with competitive fringe

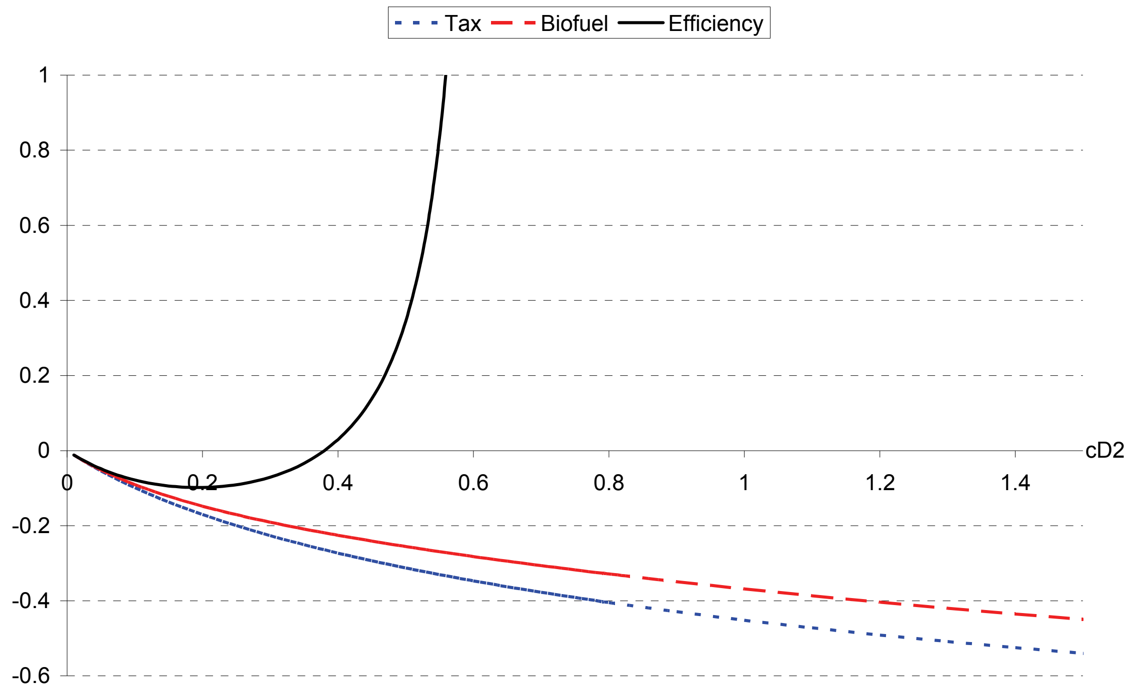
As it is difficult to derive interpretable expressions in the case with a dominant firm and competitive fringe, in this subsection we will present only some numerical illustrations that show how the existence of the fringe can influence on the results discussed above.

In the figures below, we have assumed that the fringe can produce half as much as the dominant firm at a given marginal cost level. In the market equilibrium, however, it will supply more than one-third of the market, and possibly more than 50 percent, depending on the parameters of the cost and demand functions. The existence of the fringe increases the likelihood that increased fuel efficiency in Region A will reduce consumption in that region. On the other hand, it is now possible that the price of oil can fall.

Figure 5 corresponds to Figure 3, where the regions are of the same size. Figure 5 shows that the existence of the fringe significantly changes the terms-of-trade effect for Region *A* if fuel efficiency is increased. If the marginal cost curves are rather flat (low c_{D2}), higher fuel efficiency will *decrease* the price of oil because the fringe will react quite significantly to a change in the price, and thus the dominant firm will not reduce its supply that much. If the curves are steeper (but not too steep), we get the same qualitative result as in the monopoly case, i.e., a higher oil price. In the tax case, the price reduction is much smaller than in Figure 3 if the marginal cost curves are flat, which again is explained by the fringe's responsiveness.

Let us calibrate this simple, linear model to the current oil market, assuming that a common policy instrument is introduced in the United States and the European Union, which together has about 40 percent of global oil consumption (BP 2010). OPEC currently has a market share around 40 percent of global supply. We assume that non-OPEC and OPEC unit production costs amount to 40–100 and 20–40 percent of the oil price, respectively. Then we obtain the effects shown in Table 3 of the three policy instruments.[20]

Figure 5. Effects on the producer price of oil (dP/dx_A) under different policy instruments when $\beta_2 = 1$ in a dominant firm model



[20] The parameter values of this model are $c_{D1} = 0.1$, $c_{F1} = 0.2$, $c_{D2} = 0.3$, $c_{F2} = 0.6$, and $\beta_2 = 0.7$ (cf. the appendix).

Table 3. Simulated effects of policy instruments in the current oil market, when joint consumption in the United States and the European Union is reduced by 5 percent

	Fuel tax	Biofuel share	Efficiency standard
Oil price	-1.0%	-0.8%	+3.9%
Oil consumption, rest of world	+1.0%	+0.8%	-3.7%
Oil production, OPEC	-1.9%	-2.4%	-17%
Oil production, non-OPEC	-1.1	-0.9%	+4.4%

We notice that a fuel tax and a biofuel requirement have similar effects, with somewhat stronger price reduction in the former case. The effects of increased fuel efficiency are strong, with substantial reduction in OPEC supply and a significant increase in the oil price. This result, however, is very sensitive to small variations in the parameters of the model and reflects that increased fuel efficiency has small effects on U.S. and EU oil consumption in this model, such that a 10 percent reduction in consumption requires a major increase in efficiency. Thus, the results of increased fuel efficiency should be interpreted with particular caution; they suggest that it might be extra difficult to predict the market outcome of raising fuel efficiency in some major oil-consuming countries. Still, we should expect higher oil prices and/or very limited reductions in fuel consumption.

Finally, in what way do these findings influence the optimal choice of policy instrument in Region *A*? As mentioned before, policymakers in the region may be concerned about both terms-of-trade effects and carbon leakage in Region *B*. The costs of the different policies obviously matter as well, but this is not the topic of this analysis. Disregarding also domestic distributional aspects, the "international (net) benefits" ($d\Omega$) for Region *A* of policy instrument *i* can then be expressed as:

$$(8) \qquad \left.\frac{d\Omega}{dx_A}\right|_{di>0} = x_A \left.\frac{dP}{dx_A}\right|_{di>0} + \tau \left.\frac{dx_B}{dx_A}\right|_{di>0},$$

where τ denotes the shadow price of increased consumption abroad (i.e., carbon leakage).

If carbon leakage is not important, we are left with $x_A \cdot dP/dx_A$, the latter part of which we have discussed above. But what if $\tau > 0$? Figure 6 shows how the international benefits depend on the steepness of the marginal cost curves relative to the aggregate demand curve. Note that we only show the outcome of cases where demand in Region *A* is reduced. The shadow price τ has been set, somewhat ad hoc, to respectively 10 percent or 100 percent of the producer price in the figure.[21]

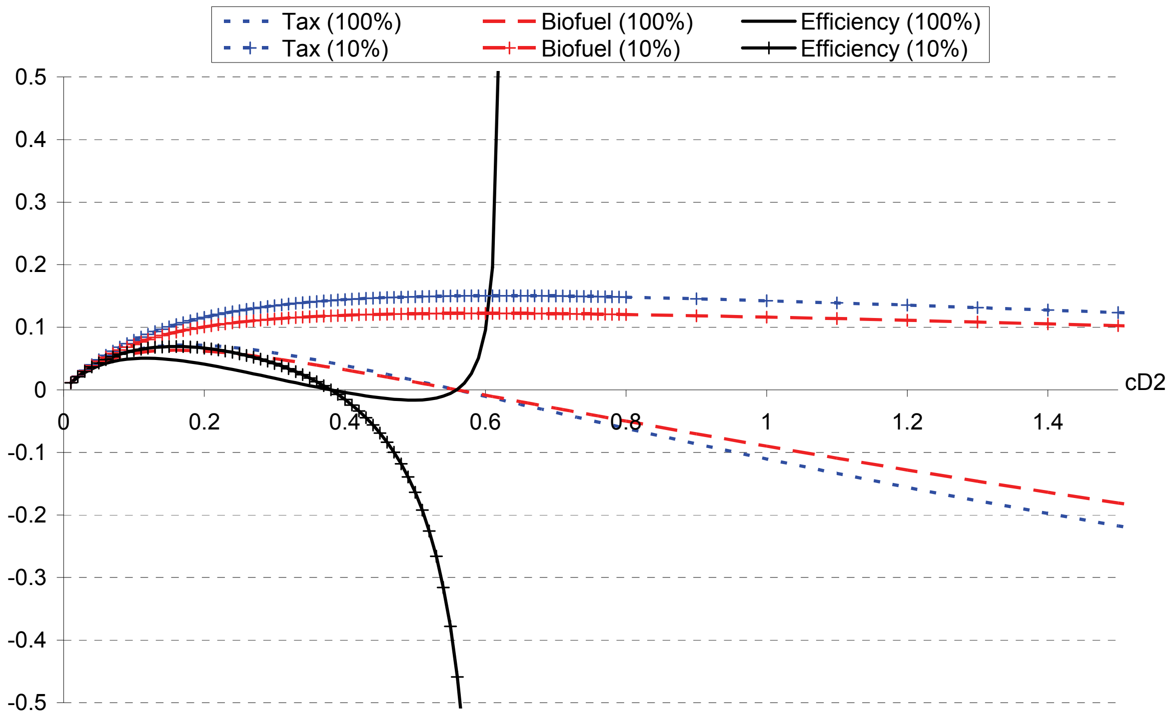
The figure shows that if marginal costs are rather flat, the different policy instruments fare quite similarly. The reason is again that the fringe responds significantly to any price changes, and hence the dominant firm has little room to maneuver. When marginal costs are steeper, we see that the total international benefits are very dependent on τ, i.e., how much we value carbon leakage. This is particularly important for the benefits of increased fuel efficiency. Remember that this policy reduces the oil price if the marginal cost curves are flat, but increases the price if the curves are moderately steep (and increases consumption for even steeper curves). Thus, the carbon leakages are respectively positive and negative.[22] A fuel tax fares best when the shadow price of foreign emissions is not too high. Then the terms-of-trade benefits from reduced oil price dominate over the leakage effect. Similar effects are seen for biofuel requirements.

How large are the net benefits shown in Figure 6 compared to the benefits of reduced domestic consumption, disregarding costs of the policy? The answer to this depends on the valuation of domestic reductions. If, for instance, we assume that Region *A* values domestic and foreign consumption reductions equally much (e.g., due to greenhouse gas emissions), the domestic benefits will be at most 0.07 (if τ is 10 percent of price) and 0.7 (100 percent) in the figure. Thus, we see that the international (net) benefits are at least comparable with the domestic benefits and possibly more important.

[21] As a comparison, the average EU ETS price in 2009 amounted to about $8 per barrel of oil, i.e., about 13 per cent of the world oil market price that year.

[22] This explains why the fuel-efficiency curves intersect around $c_{D2} = 0.35$, with international benefits equal to 0.

Figure 6: Effects on international (Net) benefits ($d\Omega/dx_A$) under different policy instruments when β_2 = 1 in a dominant firm model



4. Conclusions

This paper has shown that the effects of different policy measures to reduce oil demand in the transport sector depend significantly on the market structure. In a competitive market, a fuel tax and a biofuel requirement will always reduce oil demand, whereas the outcome of higher fuel-efficiency standard is more ambiguous due to the well-known rebound effect (though empirical studies suggest reduced oil consumption). If a monopoly supplies the oil market, the consumption effects become ambiguous also under a biofuel requirement. Nevertheless, in most realistic cases, oil consumption will decrease under all these policy instruments, and most likely even more than in a competitive market if biofuel requirements or increased fuel efficiency are implemented.

More interestingly, the price effects depend significantly on the market setting, especially if fuel efficiency is increased. In a closed economy, the producer price always move in the same direction as the consumption if the market is competitive, so a lower consumption level always goes along with a lower producer price. Moreover, the price effects are independent of policy instrument as long as the instruments are fine-tuned to produce the same reduction in oil consumption. However, with a monopoly on the supply side, the price effects depend highly on the choice of policy instrument, as well as on the curvature of the demand and cost functions. In particular, and rather counter intuitive, increased fuel-efficiency standard will unambiguously *increase* the price of oil as long as consumption is decreased. This result, which holds for any downward-sloping demand and upward-sloping marginal cost functions, is quite opposite to the effect with perfect competition. The reason is that higher fuel efficiency makes the demand curve steeper, giving the monopolist more incentives to cut back on its supply.

In an open economy, we show that (now assuming linear demand and marginal cost functions) with monopoly on the supply side, the price of oil will still increase if one region increases its fuel efficiency. If this region is relatively small, it will most likely experience increased oil consumption in this case. Existence of a competitive fringe producing oil, however, increases the likelihood of reduced oil consumption, and the price of oil may fall if the fringe's supply is rather price elastic.

Price effects are important for a number of reasons. A regulating body may for instance care about the distribution effects between oil producers and consumers. In addition, an oil-importing country may worsen its terms of trade if the oil price rises, and vice versa for an oil-exporting country. The effects on the oil price may also be important if an international climate treaty is in place. If not all countries have signed the treaty, a lower oil price may increase oil demand in non-signatory countries and lead to carbon leakages. Thus, the signatory countries may favor instruments that increase the oil price.

It is hard to make policy recommendations based on the analysis as policymakers' preferences with regard to consumption and price effects may contrast. Moreover, other (potentially more important) issues come into play too when choosing between policy instruments, such as cost-effectiveness, which is not considered in this paper. If we assume that the regulator only cares about reduced oil consumption, a fuel tax is the safest alternative because it will always decrease consumption. Increased fuel efficiency is the most uncertain instrument, especially if the region in question is small and there is market power on the supply side.

If the regulator cares much about price effects, we have seen that in a competitive market, lower oil consumption always goes hand-in-hand with a lower oil price. This gives preferred terms-of-trade effects for an oil-importing country but induces carbon leakage and undermines attempts to reduce global carbon emissions. If there is market power on the supply side, and the policymakers are concerned about too high mark-up for big oil producers or their oil import bill, they should avoid fuel-efficiency standards as the main policy instrument to reduce oil consumption because this policy quite possibly will increase the price of oil. They should rather choose a fuel tax, or, if the inverse demand function is quite convex, a biofuel standard. If policymakers prefer high prices, e.g., due to concern about carbon leakage, the conclusions naturally become completely turned around. The same reasoning can be applied to big oil producers, who would find it in their interest to lobby for fuel-efficiency standards rather than fuel taxes and biofuel shares.

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Appendix

Closed, competitive market

The outcome of a closed, competitive market is derived by considering the oil producers' maximization problem when the price is taken as given:

(A1) $$Max\left[P(x)x - c(x)\right].$$

This gives the well-known first-order condition,

(A2) $$P = c'(x).$$

Inserting from (3) and then differentiating (setting $a = t = 0$ and $m = 1$) gives the following equation:

(A3) $$\left(c''(x) - P'(x)\right)dx = \left(P(x) + xP'(x)\right)dm + xP'(x)da - dt.$$

Thus, we get the following effects of the different instruments in a competitive market:

(A4)

i) $$\frac{dx^C}{dt} = -\frac{1}{c''(x) - P'(x)} < 0,$$

ii) $$\frac{dx^C}{da} = \frac{xP'(x)}{c''(x) - P'(x)} < 0, \text{ and}$$

iii) $$\frac{dx^C}{dm} = \frac{P(x)\left(1 + \frac{1}{\varepsilon(x)}\right)}{c''(x) - P'(x)},$$

where $\varepsilon(x) = \frac{P(x)}{xP'(x)}$ (price elasticity of demand).

Closed, monopoly market

A monopolist also considers the maximization problem in (A1) but does not take the price as given. This gives the standard first-order condition,

(A5) $$MR(x) = xP'(x) + P(x) = c'(x),$$

and the second-order condition,

(A6) $$\Gamma(x) = c''(x) - 2P'(x) - xP''(x) > 0 .$$

From (3) we find that $P'(x) = m^2(1+a)P_q'(m(1+a)x)$. Differentiating this expression gives the following:

(A7) $$dP' = (1+a)\left[2mP_q' dm + m^2 P_q''\left((1+a)xdm + mxda + m(1+a)dx\right)\right] + m^2 P_q' da .$$

Inserting from (3) in (A5) and then differentiating, using (A7), $a = t = 0$, $m = 1$, $P' = P_q'$, and $P'' = P_q''$ (see equation (2) for $a = t = 0$ and $m = 1$), gives the following expression:

(A8) $$\begin{aligned}&\left(c''(x) - 2P'(x) - xP''(x)\right)dx = \\ &\left(P(x) + 3xP'(x) + x^2P''(x)\right)dm + \left(2xP'(x) + x^2P''(x)\right)da - dt.\end{aligned}$$

Thus,

(A9)

i) $$\frac{dx^M}{dt} = -\frac{1}{c''(x) - 2P'(x) - xP''(x)} = -\frac{1}{\Gamma(x)} < 0 ,$$

ii) $$\frac{dx^M}{da} = \frac{2xP'(x) + x^2P''(x)}{c''(x) - 2P'(x) - xP''(x)} = \frac{xP'(x)\left(2 + \gamma(x)\right)}{\Gamma(x)}, \text{ and}$$

iii) $$\frac{dx^M}{dm} = \frac{P(x) + 3xP'(x) + x^2P''(x)}{c''(x) - 2P'(x) - xP''(x)} = \frac{xP'(x)\left(3 + \varepsilon(x) + \gamma(x)\right)}{\Gamma(x)},$$

where $\gamma(x) = x\frac{P''(x)}{P'(x)}$, and $\Gamma(x) > 0$ is given from (A6).

Open market with monopolist or dominant producer and competitive fringe

Given the open market described in Section 3, and using equation (3), the consuming regions have the following inverse demand functions for oil, where $\alpha_1 > 0$, $\alpha_2 > 0$, $\beta_1 > 0$, $\beta_2 > 0$ and subscript $i = A,B$ represents the variable of region i:

(A10) $$P(x_A) = m(\alpha_1 - \alpha_2 m(1+a)x_A) - t \text{ and}$$

(A11) $$P(x_B) = \beta_1 - \beta_2 x_B .$$

Here P denotes the world market price of oil. Moreover, we have used that $q_B = x_B$ (as we disregard transport regulations in Region B). We normalize price and quantity units so that $\alpha_1 = \alpha_2 = 1$. Moreover, we assume that $\beta_1 = 1$ — i.e., the choke price is identical in the two regions at $m = 1$.

The marginal costs of producer j is specified as

(A12) $$c_j'(x_j) = c_{j1} + c_{j2} \cdot x_j .$$

We assume that $c_{j1} < 1$ to ensure positive production of oil. The fringe has the same first-order condition as in a competitive market; see equation (A2). Note that a monopoly market emerges as a special case if $c_{F2} \to \infty$.

We will refer to demand in Region B minus fringe production as the residual demand in region B (x_B^D). From equations (A2), (A11), and (3), we have that x_B^D is given by

(A13) $$P(x_B^D) = \beta_1^D - \beta_2^D x_B^D ,$$

where $\beta_1^D = \dfrac{c_{F2} + \beta_2 c_{F1}}{\beta_2 + c_{F2}}$ and $\beta_2^D = \dfrac{\beta_2 c_{F2}}{\beta_2 + c_{F2}}$.

The total residual demand facing the dominant firm (x^D) consists of x_B^D and x_A. From equation (A13) and (A10) we find that

(A14) $$P(x^D) = \frac{1}{\phi_3(m,a)}\left[\phi_1(m,a,t) - \phi_2(m,a)x^D\right],$$

where $\phi_1(m,a,t) = \beta_1^D m^2(1+a) + \beta_2^D m - \beta_2^D t$, $\phi_2(m,a) = \beta_2^D m^2(1+a)$ and $\phi_3(m,a) = \beta_2^D + m^2(1+a)$.

By using the first-order condition of a dominant firm, which is the same as for a monopolist (equation (A5)), we can derive the following expressions for the equilibrium price and residual demand in this market as functions of the policy instruments:

(A15) $$P = \frac{\phi_1(m,a,t)\phi_2(m,a) + \phi_1(m,a,t)\phi_3(m,a)c_{D2} + \phi_2(m,a)\phi_3(m,a)c_{D1}}{2\phi_2(m,a)\phi_3(m,a) + \phi_3(m,a)^2 c_{D2}}, \text{ and}$$

(A16) $$x^D = \frac{\phi_1(m,a,t) - \phi_3(m,a)c_{D1}}{2\phi_2(m,a) + \phi_3(m,a)c_{D2}}.$$

Equilibrium consumption in the two regions and fringe production then follows from the equations above.

In a monopoly market, we have that $\beta_1{}^D = 1$ and $\beta_2{}^D = \beta_2$. This is easily seen by letting $c_{F2} \rightarrow \infty$ in the expressions for $\beta_1{}^D$ and $\beta_2{}^D$. The steepness of the inverse aggregate demand curve is then given by $\beta_2 / (1 + \beta_2)$. We make a final simplification by assuming that $c_{D1} = 0$.[23]

We find that the three different policy instruments affect consumption and producer price in the following way:

(A17)

i) $$\frac{dx_A}{dt} = -\frac{\beta_2{}^2 + 2\beta_2 + \beta_2 c_{D2} + c_{D2}}{(\beta_2 + 1)(2\beta_2 + c_{D2}\beta_2 + c_{D2})} < 0,$$

ii) $$\frac{dx_A}{da} = -\frac{\beta_2(2\beta_2 + c_{D2})}{(2\beta_2 + c_{D2}\beta_2 + c_{D2})^2} < 0, \text{ and}$$

iii) $$\frac{dx_A}{dm} = \frac{2\beta_2 c_{D2}{}^2 + 3\beta_2{}^2 c_{D2} + \beta_2{}^3 c_{D2} + 2\beta_2 c_{D2} + c_{D2}{}^2 + \beta_2{}^2 c_{D2}{}^2 - 2\beta_2{}^3}{(\beta_2 + 1)(2\beta_2 + c_{D2}\beta_2 + c_{D2})^2}.$$

[23] This can also be viewed as a normalization, if we first subtract c_{D1} from α_1 and β_1 and then normalize prices and quantities so that $\alpha_1 - c_{D1} = 1$, $\beta_1 - c_{D1} = 1$ (and $\alpha_2 = 1$). In Figures 5-6 we have assumed that $c_{F1} = c_{D1} = 0$, which is not merely a normalization, but simplifies the comparison with Figure 4.

i) $\frac{dx_B}{dt} = -\frac{1}{\beta_2}\frac{dP}{dt} = \frac{\beta_2 + \beta_2 c_{D2} + c_{D2}}{(\beta_2 + 1)(2\beta_2 + c_{D2}\beta_2 + c_{D2})} > 0$,

(A18) ii) $\frac{dx_B}{da} = -\frac{1}{\beta_2}\frac{dP}{da} = \frac{\beta_2 c_{D2}}{(2\beta_2 + c_{D2}\beta_2 + c_{D2})^2} > 0$, and

iii) $\frac{dx_B}{dm} = -\frac{1}{\beta_2}\frac{dP}{dm} = -\frac{\beta_2 c_{D2} + 2\beta_2^{\ 2} + c_{D2}^{\ 2} + 2\beta_2 c_{D2}^{\ 2} + \beta_2^{\ 2} c_{D2} + \beta_2^{\ 2} c_{D2}^{\ 2}}{(\beta_2 + 1)(2\beta_2 + c_{D2}\beta_2 + c_{D2})^2} < 0$.

i) $\left.\frac{dP}{dx_A}\right|_{dt>0} = \frac{\beta_2^{\ 2} + \beta_2^{\ 2} c_{D2} + \beta_2 c_{D2}}{\beta_2^{\ 2} + 2\beta_2 + \beta_2 c_{D2} + c_{D2}} > 0$,

(A19) ii) $\left.\frac{dP}{dx_A}\right|_{da>0} = \frac{\beta_2 c_{D2}}{2\beta_2 + c_{D2}} > 0$, and

iii) $\left.\frac{dP}{dx_A}\right|_{dm>0} = \frac{\beta_2\left(\beta_2 c_{D2} + 2\beta_2^{\ 2} + c_{D2}^{\ 2} + 2\beta_2 c_{D2}^{\ 2} + \beta_2^{\ 2} c_{D2} + \beta_2^{\ 2} c_{D2}^{\ 2}\right)}{2\beta_2 c_{D2}^{\ 2} + 3\beta_2^{\ 2} c_{D2} + \beta_2^{\ 3} c_{D2} + 2\beta_2 c_{D2} + c_{D2}^{\ 2} + \beta_2^{\ 2} c_{D2}^{\ 2} - 2\beta_2^{\ 3}}$.