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Regulation of GHG emissions from transportation fuels: Emission quota versus emission intensity standard

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Abstract

Climate change mitigation requires reduction in emissions of greenhouse gases rather than mere reduction in emission intensity of the economy. Regulations such as the Kyoto Protocol, Emission Trading Scheme, and the Regional Greenhouse Gas Initiative establish an emissions target as opposed to an emission intensity target. The policies implemented till date have also largely targeted emission reduction from power plants and the industries. Recent regulations aimed at controlling greenhouse gas emissions from transportation mandate intensity target for fuels. In this paper we compare abatement cost and output under two types of regulations of transportation fuels, namely, emission intensity standard and emission quota. We do this in the context of a price-taking region, and we focus on the shortrun. We find that under an intensity standard pollution abatement cost is higher than or equal at best to that under an emission quota, while aggregate output can be higher or lower than under a quota.

1   Introduction

Some of the major greenhouse gas (GHG) policies implemented till date such as the Kyoto Protocol and the European Union's (EU) Emission Trading Scheme (ETS) mandate reduction in aggregate emissions. The Kyoto Protocol mandates national emission reduction targets, and the ETS mandates targets for emission reduction from stationary sources of pollution such as electric power plants and industrial facilities within the EU. One of the first regulations to exclusively target GHG emissions from transportation is California's Low Carbon Fuel Standard (LCFS). This policy mandates a target for GHG intensity of transportation fuels.[1]

Economic theory says that given certain conditions, a unit emission fee equal to the marginal social cost of pollution achieves the first-best (efficient) outcome, i.e, attains the optimum level of pollution at least cost [1, 2]. Difficulty in estimating the social cost of pollution leads to the pursuit of cost-effective policies, where the goal is to attain a politically chosen target level of pollution [3, 4, 5]. These policies can be implemented either by pricing pollution or by allocating pollution rights. Sometimes, instead of choosing a target level of pollution, policy-makers choose

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[1]Staff Report: Proposed Regulation to Implement the Low Carbon Fuel Standard - Initial Statement of Reasons (ISOR) Available online at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

a target level of pollution intensity, i.e, an upper limit on the quantity of pollution per unit of output. This type of policy is also more generally known as a performance-standard. Hence, when the pricing approach is infeasible, policy-makers can choose from at least two different quantity-based approaches for reducing pollution, namely, an emission target or a performance standard. It appears from practice that performance standards are the preferred form of environmental regulation [6]. Regulations such as vehicle tailpipe emission standards, corporate average fuel economy standards, and renewable fuel standards suggest that this is certainly the case for transportation. When damage depends on concentration of pollutant in the ambient environment, a performance standard such as emission intensity standard has optimal properties. When damage depends on aggregate stock of pollution emission this type of policy can be sub-optimal.

Being able to predict the effect of different types of policies on variables such as abatement cost, price, output, and pollution is necessary for making good decisions. Furthermore, while climate change requires long-term policies, the short run effects of different policies on such variables should not be ignored. Higher cost in the short run effects can generate public opposition to replace policies which may be beneficial in the long-term [5]. Hochman and Zilberman [5] compare the effects of two policy tools, namely, an emission tax and an emission standard per unit of output. They find that while as expected, both policies reduce emissions and output, surprisingly enough, taxes may in some cases lead to an increase in the emission intensity of output. With carbon taxation continuing to be politically unpopular, we focus our attention on quantity-based policies. Newell and Pizer [**?**] compare emission regulation and emission-intensity regulation (emission indexed to GDP) of GHG when there is uncertainty in abatement cost and derive conditions under which one is more efficient than the other. Since they focus on economy-wide policies, their model abstracts away from the sector-specific characteristics which can affect the relative performance of the two policies as we show in this paper.

Our interest is in comparing an emission intensity standard and an emission quota in a sector-specific or product-specific context, namely transportation fuel. With quantity-based policies there is a growing tendency to allow trading of pollution rights between regulated entities [**?**]. The LCFS policy also allows trading of emission credits/permits between firms. However, policies that do not permit trading of pollution rights are also common such as the Clean Air Act standards for toxics. In the model we use here, we assume no trading between firms. While this simplifies the mathematical exposition, it does not affect the conclusions which will hold even when trading is considered. The differences between the two policies stem from a fundamental characteristic of each policy, which is not affected by whether trading of pollution rights is allowed or not. We focus on a price-taking region and assume linear technologies, i.e., production function is fixed

proportion. We focus on the short run and so we assume that capacity is fixed. We find that an emission quota is more cost effective or in the worst case as cost effective as an emission intensity standard for achieving a given level of emission reduction. We also find that aggregate output from the region can be higher or lower than under a quota.

2   Model and analytic results

We model the behavior of fuel-producing firms facing environmental regulation. As mentioned earlier, we focus on a price-taking region, with a number of competitive price-taking producers who produce a homogeneous product, transportation fuel. The market price of the finished fuel is p. Firms convert inputs to output in fixed proportion. Firms are heterogenous, differing in capacity q_i^0 which we assume is fixed, in marginal cost c_i^0 (constant for a given firm), and in the pollution intensity of output γ_i^0. We also assume that $\frac{\partial c_i^0}{\partial \gamma_i} < 0, \frac{\partial^2 c_i^0}{\partial \gamma_i^2} > 0$, i.e., cleaner fuels are costlier to produce.Using this notation, profit π_i^0 and pollution Z_i^0 can be expressed as,

$$\pi_i^0 \;\; = \;\; (p - c_i^0)q_i^0$$
$$Z_i^0 \;\; = \;\; \gamma_i^0 q_i^0$$

A firm can reduce emissions in any of the following ways.

1. *Adopt cleaner inputs*: A firm can reduce emissions by adopting technology that reduces emission intensity (for instance switch to newer vintage that is more efficient) or adopt cleaner energy as in input (for instance switch from using coal to using natural gas).

2. *Blend with cleaner fuels*: Fuels differing in pollution intensity can be blended to produce a fuel with intermediate level of pollution intensity. In fact policies such as the LCFS and the Renewable Fuel Standard (RFS) mandated envision that blending gasoline (or diesel) with cleaner biofuels will be the principal mechanism for reducing GHG emissions from transportation.

3. *Cut production*: A firm can reduce its total emissions by simply reducing its output. However, if firms have to reduce the pollution intensity of output, then it is not sufficient to merely reduce output.The firm has to consider this in conjunction with one of the options above.

Henceforth, we refer to these choices simply as option A, option B, and option C respectively.[2] The two types of regulations we consider impose different constraints on firms. An emission intensity

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[2]These options are named such that, option A implies adoption, option B implies blending and option C implies cutting or reducing output.

standard, while limiting the maximum allowable emissions per unit of output, does not restrict the aggregate emissions per facility. The converse is true for an aggregate quota.

The optimization problem of a firm with fixed capacity is,

$$\max_{\Delta\gamma_i, \Delta q_i^*, \Delta q_i} \pi_i = \{\underbrace{p(q_i^0 + \Delta q_i + \Delta q_i^*)}_{\text{Revenue}} - \underbrace{(c_i^0 + \Delta c_i(\Delta\gamma_i))(q_i^0 + \Delta q_i)}_{\text{Production cost}} - \underbrace{(p + c_i^t)\Delta q_i^*}_{\text{Blending cost}}\},$$

subject to the constraint that, the average emission intensity is less than the emission intensity standard, $\overline{z}$

$$\frac{\gamma_i^0 q_i^0 + \Delta\gamma_i q_i + \gamma_i^* \Delta q_i^*}{q_i^0 + \Delta q_i + \Delta q_i^*} \leq \overline{z}$$

or *subject to the constraint that*, total emissions are below the quota, $\overline{Z_i}$ [3]

$$Z_i^0 + \Delta\gamma_i q_i + \gamma_i^* \Delta q_i^* \leq \overline{Z_i}$$

It is worth pointing out that generally intensity standards are uniform across all firms (not indexed by i), while the emission quotas tend to be firm-specific (indexed by i). Holding output constant, any arbitrary level of emission intensity can be translated into an equivalent level of emissions. Similarly, any given level of intensity reduction can be translated into an equivalent level of emission reduction and vice versa. Therefore, for any firm i, and producing output q_i^0 before regulation, we can write, $\overline{Z_i} = \overline{z} * q_i^0$ (or $\Delta Z_i = Z_i^0 - \overline{z} * \overline{q_i}$).

The decision variables for the firm are, $\Delta\gamma_i$, the amount by which it lowers emission intensity of its own processes by adopting new technology or by switching fuels (option A), Δq_i^*, the quantity of output it procures from other sites for blending (option B), and Δq_i, the amount by which the firm lowers its own production (option C). Since we assume linear technologies, the firm will choose only of the options to reduce pollution (i.e., corner solution). Therefore the decision variable effectively is the discrete choice of selecting one among the three options for reducing pollution. The firm will choose the most cost-effective option. We describe the economics of each option below.

- Option A (Adopt): Let us assume that the firm i has K discrete choices to reduce emission intensity, with each choice having constant marginal cost. If choice k, $k \in 1..K_i$ involves a cost Δc_{ik} and reduces emissions intensity by $\Delta\gamma_{ik}$, the average cost (AC) of pollution

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[3]Equivalently, the constraint under a quota can also be expressed as

$$\Delta\gamma_i q_i + \gamma_i^* \Delta q_i^* \geq \Delta Z_i, \text{ where } \Delta Z_i = Z_i^0 - \overline{Z_i}$$

reduction for the kth choice is,

$$AC_A = min\{\frac{\Delta c_{ik}}{\Delta \gamma_{ik}}\} \ k \ \in 1..K_i$$

- Option B (Blend): A firm can blend dirty fuel it produces with a cleaner fuel produced either by itself at a different location (Option B_{own}) or by another firm (Option B_{market}).

    Option B_{own}: Let c_i^* represent the cost of producing the cleaner fuel with $p - c_i^* > 0$ (the firm earns positive profits on the clean fuel), c_i^t the the cost of transporting it to the site producing the dirty-fuel and γ_i^* the pollution intensity of clean fuel. Let the firm blend the dirty and clean fuels in the ratio $(1-\alpha)$ and α respectively. The average cost of pollution reduction by blending with clean fuel purchased in the market is,

    $$AC_{B_{own}} = \frac{c_i^t}{\gamma_i^0 - \gamma_i^*}$$

    Option B_{market}: Here we assume the firm purchases the clean fuel at the market price p and transports it at a cost c_i^{t*} to its facility for blending with its fuel. The pollution intensity of clean fuel is γ_i^* ($\gamma_i^* < \gamma_i^0$). Let the firm blend the dirty and clean fuels in the ratio $(1-\alpha)$ and α respectively. The average cost of pollution reduction by blending with clean fuel purchased in the market is,

    $$AC_{B_{market}} = \frac{p + c_i^{t*} - c_i^0}{\gamma_i^0 - \gamma_i^*}$$

    Corollary: The average cost of pollution reduction by blending is independent of the blend ratio. (See appendix for detailed derivation).

- Option C (Cut production): Lowering output by one unit lowers pollution by a quantity γ_i^0 and lowers profit by an amount $p - c_i^0$. This implies that average cost of pollution reduction by decreasing output is,

    $$AC_C = \frac{p - c_i^0}{\gamma_i^0}$$

Table 1 summarizes the cost-effectiveness of each option available to a firm. These support the following propositions.

Proposition 1: Under emission quota, firms will prefer to reduce output rather than blend with cleaner fuels from the market.

Table 1: Comparison of a firm's choices for emission reduction when production capacity is fixed

Option	Profit (π_i^1)	Loss in profit per unit of output ($\pi_i^0 - \pi_i^1$)	Emission reduction ($Z_i^1 - Z_i^0$)	Reduction in emission intensity	Average cost of abatement
Adopt (A)	$p - c_{ik} + \Delta c_{ik}$	Δc_{ik}	$\Delta \gamma_{ik}$	$\Delta \gamma_{ik}$	$\frac{\Delta c_{ik}}{\Delta \gamma_{ik}}$
Blend with own clean fuel (B_{own})	$p - [(1-\alpha)c_i + \alpha(c_i^* + c_i^t)]$	αc_i^t	$\alpha(\gamma_i^0 - \gamma_i^*)$	$\alpha(\gamma_i^0 - \gamma_i^*)$	$\frac{c_i^t}{(\gamma_i^0 - \gamma_i^*)}$
Blend with clean fuel from market (B_{market})	$p - [(1-\alpha)c_i + \alpha(p + c_i^{t*})]$	$\alpha(p + c_i^{t*} - c_i^0)$	$\alpha(\gamma_i^0 - \gamma_i^*)$	$\alpha(\gamma_i^0 - \gamma_i^*)$	$\frac{(p + c_i^{t*} - c_i^0)}{(\gamma_i^0 - \gamma_i^*)}$
Cut production (C)	-	$p - c_i^0$	γ_i^0	0	$\frac{p - c_i^0}{\gamma_i^0}$

Proof: Comparing the average cost of abatement for option B_{market} and option C shown in table 1 we can see that,

$$AC_{B_{market}} > AC_C \ \forall \ c_i^t > 0, \ \gamma_i^* > 0 \text{ and } \gamma_i^* < \gamma_i^0$$

Consider a more realistic assumption, that cleaner fuel is costlier or that there is positive to cost of physically blending different fuels to produce the final fuel. We can see that this only makes cost of blending option to increase further relative to option C.

Proposition 2: For any given firm, abatement costs under an emission intensity standard is equal to or greater than abatement cost under an emission quota.

Proof:

Case 1: Firm produces both dirty and clean fuels.

The cost of achieving compliance with an emission intensity standard is,

$$C_{ub} = \min\{AC_A, AC_{B_{own}}\}$$

The cost of achieving compliance with a quota is,

$$C_{quota} = \min\{AC_A, AC_{B_{own}}, AC_C\}$$

$$\text{If } AC_C \ < \ AC_{B_{own}} \text{ and } AC_C < AC_A$$
$$\text{then } C_{ub} \ > \ C_{quota}$$
$$\text{else } C_{ub} \ = \ C_{quota}$$

This implies that $C_{ub} \geq C_{quota}$

Case 2: Firm produces only dirty fuel

The cost of achieving compliance with an emission intensity standard is,

$$C_{ub} = \min\{AC_A, AC_{B_{market}}\}$$

The cost of achieving compliance with a quota is,

$$C_{quota} = \min\{AC_A, AC_C\}$$

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Since $AC_C < AC_{B_{market}}$ this again implies that $C_{ub} \geq C_{quota}$. Therefore an emission intensity standard is costlier or equal at-best to a emission quota for a regulated firm. The intuition behind the proposition is that the choice set under an emission quota has more lower cost options than the choice set under an emission intensity standard.

Lemma: An increase in output price (or equivalently a reduction in cost of an input) increases the cost of abating emissions by reducing output relative to the cost of abating emissions by other means. To the extent that this is true, the inefficiency of an intensity standard relative to a quota will decrease.

Proposition 3: Aggregate output under an emission quota can be higher or lower than that under an intensity standard depending on the cost-effectiveness of reducing emissions by reducing output relative to that through technology adoption and through blending with clean fuels, holding production capacity of firms fixed.

Proof: If technology adoption and blending with clean fuels are both unprofitable ($\pi_i^1(A) < 0$ and $\pi_i^1(B) < 0$) then emission intensity standards will force inefficient firms to exit. However, under an emission quota inefficient firms can reduce output and continue to operate. If the production capacity of firms is fixed (i.e., efficient firms cannot increase output to make up for the reduction in capacity due to exit of inefficient firms), then emission quotas will result in higher output than or at least the same amount of output as under intensity standard.

If technology adoption or blending with clean fuels is not costly enough to force firms to exit ($\pi_i^1(A) > 0$ or $\pi_i^1(B) > 0$), and if lowering output is still the cheapest abatement option ($AC_A > AC_C$ and $AC_B > AC_C$), then emission intensity standard will result in higher output than or at least the same amount of output as under quota. This is because even though reducing output is the cheapest abatement option, firms cannot lower their emission intensity by doing so.

3 Numerical example

We illustrate the theoretical model using representative data on cost and emissions for ethanol production in the United States (see table 3). Ethanol biorefineries use either coal or natural gas as the source of energy for producing ethanol from corn. The GHG intensity of ethanol produced from corn using coal is higher than that for ethanol produced from corn using natural gas ($89gCO_2e/l$ and $61gCO_2e/l$ respectively).[4] We consider two policies, an emission intensity standard that requires the GHG intensity of ethanol to be below $75gCO_2e/l$ and a quota that

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[4]gCO_2e/l refers to grams of carbon-di-oxide per liter of ethanol.

Table 2: Input parameters to the simulation for various scenarios

Scenarios*	I	II	III	IV	V
Price of ethanol ($/liter)	0.628	0.942	0.628	0.628	0.942
Coal-based ethanol production cost ($/liter)	0.430	0.430	0.430	0.430	0.430
Ethanol transportation cost - rail ($/liter)	0.050	0.050	0.050	0.100	0.075
Ethanol transportation cost - road ($/liter)	0.130	0.130	0.130	0.260	0.195
Energy used in biorefining (MJ/liter)	13.85	13.85	13.85	13.85	13.850
GHG intensity of coal-based corn ethanol in gCO2e/liter	89	89	89	89	89.000
GHG intensity of gas-based corn ethanol in gCO2e/liter	61	61	61	61	61.000
Price of coal energy ($/MJ)	0.0020	0.0020	0.0020	0.0020	0.002
Price of natural gas energy ($/MJ)	0.0105	0.0105	0.0262	0.0105	0.010

* Scenarios are the following,
I: Base case - see appendix for further explanation
II: Ethanol price is 50% higher than base case
III: Natural gas is 2.5X costlier relative to coal than base case
IV: Transportation cost is 2X than base case
V: Ethanol price and transportation cost are 1.5X of base case

Table 3: Calculated average cost of abatement in $/gCO_2e for each option

Scenarios	I	II	III	IV	V
Option A - Switching from coal to gas	0.0042	0.0042	0.0119	0.0042	0.0042
Option B_own	0.0032	0.0032	0.0032	0.0064	0.0048
Option B_market	0.0103	0.0215	0.0103	0.0135	0.0231
Option C	0.0022	0.0057	0.0022	0.0022	0.0057

Table 4: Minimum cost of compliance under each policy

1. Firm produces dirty and clean fuel					
Scenarios	**I**	**II**	**III**	**IV**	**V**
Cost under intensity standard	0.0032	0.0032	0.0032	0.0042	0.0042
Cost under emission quota	0.0022	0.0032	0.0022	0.0022	0.0042
Relative cost of intensity standard	145%	100%	145%	188%	100%
2. Firm produces only dirty fuel					
Cost under intensity standard	0.0042	0.0042	0.0103	0.0042	0.0042
Cost under emission quota	0.0022	0.0042	0.0022	0.0022	0.0042
Relative cost of intensity standard	188%	100%	463%	188%	100%

requires a 15.7% reduction in emissions by the coal-producing firm (assuming no change in firm's output)[5]. Coal-using biorefineries can either switch to natural gas as the source of heat (option A), blend with own cleaner gas-based ethanol, in case it owns such a facility (option B_{own}), blend with gas-based ethanol purchased in market (option B_{market}) or simply reduce output (option C) (see table 3). For option A we assume switching is comprised only of difference in fuel cost but no fixed-cost.This is not a realistic assumption. Yet we do so, because our purpose is to only illustrate the model and not to rule out any option. The option chosen by a representative firm under either policy in different economic situations and the least-cost policy given a situation is shown in table 3. Table 3 shows that firms will incur significantly higher cost under an emission intensity standard policy. We can see that the incentive to blend increases with increase in the fuel price or switching cost. However, fuel price increase will likely raise transportation cost which decreases the incentive to blend. Therefore, the net effect is ambiguous. Comparing scenarios I and II we can see that an increase in output price reduces the incentive to reduce output in order to reduce pollution and thereby decreases the inefficiency of an intensity standard relative to a quota.

4 Discussion

For a price-taking region, a more efficient policy is one which imposes lower cost on producers to achieve a given level of emission reduction. Emission quotas impose lower or in the worst case the same cost as emission intensity standards in the short-run (when capacity is fixed). The higher efficiency of quotas stems from the fact it provides firms, the additional option of achieving compliance by lowering output whereas the latter does not. The numerical example illustrates how the abatement cost may differ between the two policies under different economic conditions. Although our application has been in the context of transportation fuels, the result is true for GHG emissions from other products too.

The efficiency gained through the option to reduce output will be higher if there is variability in macro-economic circumstances. During a period of low or negative economic growth (like during the current recession) when producer margins are small (or demand is low), pollution reduction is more easily achieved through lower production (or consumption) without necessarily lowering emission intensity which requires adopting new and costlier technologies.[6] On the other hand,

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[5]We can see that if there is no change in output, the two regulations imply the firm's fuel has the same pollution intensity on average($\frac{89-75}{89} = 15.7\%$)

[6]Gasoline consumption in the US in the year 2009 is expected to be 7% lower compared to 2007. This represents a reduction of about 10.7 billion gallons of gasoline. If a megajoule of corn ethanol reduces GHG emissions 18% relative to a megajoule of gasoline (ignoring indirect emissions such as that from land use change because of increased corn production), about 88 billion gallons of ethanol would be required to achieve the same amount of GHG reduction that will be achieved simply from reduction in demand. This represents about 14-fold increase in ethanol consumption in the US and 7-fold increase in global production of ethanol.

during periods of high economic growth, quotas will serve as a binding cap on aggregate emissions which under an emission intensity regulation may increase due to higher output (or consumption). Thus an emission intensity standard can lead to a higher-than optimal level of abatement during difficult economic times and an increase in emissions during good economic times.

Our results hold even when we allow for emission trading (which we have not considered) under either policy. Performance-based standards such as emission intensity standards by definition tend to be uniform across firms. Emission quotas on the other hand tend to be polluter-specific. Often they require that polluters reduce emissions by a certain percentage relative to emissions at a certain time (e.g, reduction targets under Kyoto Protocol). While emission trading has come to be accepted in the case of emission quotas, there has been limited experience with market-based emission intensity standards. The program that led to the phase-down of lead in gasoline is an example of a market-based performance standard which was highly cost-effective compared to performance-standard which did not allow trading and banking.[7]. Emission trading reduces the inefficiency of both an intensity standard and an emission quota when there is heterogeneity across firms. Irrespective of tradability of pollution rights, firms cannot simply reduce output under an intensity standard. Therefore an emission quota with trading i.e., a cap and trade policy will be more flexible than a performance-standard with trading. Furthermore, provisions such as banking and borrowing of permits will improve the flexibility of both quotas and intensity standards but not make intensity standards more flexible than emission quotas. It can also be shown that an intensity standard that varies with time will for the same reason be less flexible than an aggregate emission quota that varies with time.

Emission quotas reduce the likelihood of blending of clean and dirty fuels. In the worst case simple blending may result in no real emission reduction compared to the pre-policy situation. For instance, gasoline from oil sands (which is more carbon intensive than gasoline from crude oil) can be blended with ethanol from cellulosic sources to achieve the same emission intensity as blending gasoline from crude oil with corn based biofuels. [8] The incentive to blend decreases with an increase in the cost of clean fuels or an increase in cost of transporting fuels. Since both oil sands and cellulosic biofuels are costlier relative to oil, under an emission quota, where a firm is likely to find it cheaper to reduce output than to blend two costly fuels.

In future work we will address some of the limitations of our model. One is exogeneity of prices.

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[7]Policies such as CAFE standards for automobile manufacturers and Renewable portfolio standards for electricity also allow either trading or banking or both. But these are not emission policies.

[8]There are parallels to be drawn here to auto manufacturers adjusting the mix of small (efficient) and large (inefficient) cars in their fleet, rather than improving the fuel economy of each model in order to comply with CAFE. Furthermore, some manufacturers began producing flex-fuel cars, cars capable of running on $E85$ in addition to gasoline, in order to take advantage of the extra mileage credits provided for such vehicles. Although extra credits for flex-fuel cars was based on on the assumption that these would run on $E85$ 50% of the time; estimates seem to suggest that flex fuel vehicles are run on $E85$ less than 1% of the time.

If the region implementing the policy is large then there will be price-effects of regulation which cannot be ignored and these effects may vary under different policies. The assumption of fixed capacity is another limitation. While this is reasonable in the short to medium term, addressing climate change requires long term policies. We have also not considered administrative costs which can differ significantly for different types of regulations.

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APPENDIX

A. Derivation of average cost of emission reduction by blending

Let the firm blend the dirty and clean fuels in the ratio $(1 - \alpha)$ and α respectively.

GHG emissions per unit of blend is,

$$\gamma_i^1 = (1 - \alpha)\gamma_i^0 + \alpha\gamma_i^*$$

Reduction in GHG emissions with respect to unblended fuel, γ_i^0,

$$\Delta\gamma_B = \gamma_i^0 - \gamma_i^1 = \gamma_i^0 - (1 - \alpha)\gamma_i^0 + \alpha\gamma_i^* = \alpha(\gamma_i^0 - \gamma_i^*)$$

Option B_{own}:

The cost of producing one unit of blended fuel,

$$c_i^1 = \underbrace{(1 - \alpha)c_i^0}_{\text{production cost of dirty fuel}} + \underbrace{\alpha(c_i^* + c_i^t)}_{\text{production and transport cost of clean fuel}}$$

Incremental cost in selling blend as opposed to selling as separate fuels ,

$$\Delta C_{B_{own}} = c_i^1 - c_i^0 = (1 - \alpha)c_i^0 + \alpha(c_i^* + c_i^t) - (1 - \alpha)c_i^0 - \alpha c_i^* = \alpha c_i^t$$

$\Rightarrow$ Average cost of reducing GHG emissions by blending own fuels,

$$AC_{B_{own}} = \frac{\Delta C_{B_{own}}}{\Delta\gamma_B} = \frac{\alpha c_i^t}{\alpha(\gamma_i^0 - \gamma_i^*)} = \frac{c_i^t}{\gamma_i^0 - \gamma_i^*}$$

Option B_{market}:

The cost of producing one unit of blended fuel,

$$c_i^1 = \underbrace{(1 - \alpha)c_i^0}_{\text{production cost of dirty}} + \underbrace{\alpha(p + c_i^{t*})}_{\text{cost of clean-fuel purchased and transported for blending}}$$

Incremental cost of blend compared to own dirty-fuel,

$$\Delta C_{B_{market}} = c_i^1 - c_i^0 = (1 - \alpha)c_i^0 + \alpha(p + c_i^{t*}) - c_i^0 = \alpha(p + c_i^{t*} - c_i^0)$$

$\Rightarrow$ Average cost of reducing GHG emissions by blending own fuel with fuel from market,

$$AC_{B_{market}} = \frac{\Delta C_{B_{market}}}{\Delta \gamma_B} = \frac{\alpha(p + c_i^{t*} - c_i^0)}{\alpha(\gamma_i^0 - \gamma_i^*)} = \frac{p + c_i^{t*} - c_i^0}{\gamma_i^0 - \gamma_i^*}$$

B. Data sources for numerical illustration

1. Price of ethanol $= 0.67 * P_g + 0.5$, where, $P_g(= \$2.8/gallon)$, is the average retail price for regular, conventional (non-reformulated) gasoline in the US in 2007. We assume that ethanol is priced for energy relative to gasoline, 0.67 is the correction for energy content, 0.5 is the 50 cent/gallon is the excise tax credit

2. Coal-based ethanol production cost: OECD estimate for ethanol production cost [7]

3. Ethanol transportation cost by rail: [8]

4. Ethanol transportation cost by road: [8]

5. Energy used in biorefining: EBAMM model estimate
   $http://rael.berkeley.edu/ebamm/$

6. GHG intensity of coal-based corn ethanol: EBAMM model estimate

7. GHG intensity of gas-based corn ethanol: EBAMM model estimate

8. Price of coal energy: average delivered price to industries in US for 2007 $http://www.eia.doe.gov/cneaf/coal/pa$

9. Price of natural gas energy - average US commercial price in 2007 $http://tonto.eia.doe.gov/dnav/ng/ng\_pri\_sum$