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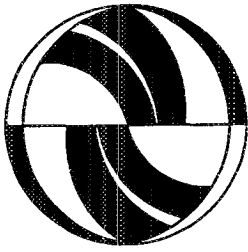
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An Emission Saved is an Emission Earned: An Empirical Study of Emission Banking for Light-Duty Vehicle Manufacturers

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An Emission Saved Is an Emission Earned:
An Empirical Study of Emission Banking
for Light-Duty Vehicle Manufacturers

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This paper presents results of an empirical study of emission banking for light-duty vehicle manufacturers. An intertemporal model of manufacturers' choices is combined with econometrically estimated abatement cost functions to simulate the cost savings and emission effects of an averaging, trading, and banking marketable permit system relative to command-and-control regulations. While the cost savings of such a system are estimated to be modest, the intertemporal emission effects may be sizable. The sensitivity of the results to discount rates, abatement cost functions, and model specifications is also explored. © 1993 Academic Press, Inc.

It is now widely agreed among economists that marketable permits are an efficient strategy for controlling environmental pollutants and an extensive literature on their properties has developed (see [5, 13] for thorough reviews). This work has identified three sources of potential cost savings: emission trading between firms, emission averaging between sources within a firm, and emission banking by polluters through time. Despite common reference to these three components, previous theoretical and empirical research on permit systems has focussed almost exclusively on the first two items, trading and averaging. This paper examines a system of averaging, trading, and banking of hydrocarbon (HC) emissions for light-duty vehicle manufacturers.

Empirical estimates of the potential cost savings from averaging and trading have often been substantial. For example, Atkinson and Lewis [1] estimated an 83% cost savings from averaging and trading, Seskin *et al.* [12] estimated a 93% savings, Maloney and Yandle [9] found a 76% savings, and McGartland and Oates [10] found savings in excess of 50%. In Tietenberg's [13] often-cited tabulation of these and other studies, he computed the ratio of control costs under command

and control relative to permit systems estimated in eight studies and found that this ratio ranged from 1.07 to 22.0. Given the potentially large savings from averaging and trading, an intriguing question is whether savings of this magnitude also apply to banking.

In addition to cost considerations, banking may have important implications for emission levels. Unlike averaging and trading, which can be designed to result in the same level of emissions as a uniform standard, banking necessarily results in different emission levels from the base standard. The degree to which firms will move emissions through time may be an important consideration in the decision of policymakers to adopt banking provisions. Thus, a question of equal importance to cost savings is how a banking scheme might affect the pattern of emission levels over time. Neither the cost savings potential nor the emissions implications of banking systems have been previously examined.

Cronshaw and Kurse (CK) [4] take an important step in the marketable permits literature by developing a theoretical model of emission banking. They present an intertemporal model of n firms, each with one emission source, facing a T-period planning horizon. Each firm is assumed to minimize the present discounted value of abatement costs and permit purchases over the entire planning horizon. CK show that the minimum cost to society and firms with banking is at least as low as the cost of a system without banking. In particular, the pattern of aggregate emissions and the price of permits depends on the discount rate, abatement costs, and cumulative aggregate allocation.

This paper provides an empirical assessment of emission banking by examining the magnitude of the cost savings from a banking system and the effect on the aggregate emission stream and permit prices through time. The application studied here is a potential banking system for HC emissions for manufacturers of light-duty vehicles in California, where a schedule of severely declining HC standards has been adopted. The tightening of standards provides an incentive for firms to reduce emissions below the standard in early years in order to accumulate credits that can be saved and used when standards are more severe.

We extend the work of CK in three important ways. First, and most importantly, we study banking in an empirical context, providing the first estimates of cost savings and emission impacts attributable to a banking system.[2] Second, although the model posited by CK is quite general, it is restricted to what we call forward banking. That is, firms are allowed to reduce emissions in the current period to use in later periods, but they are not permitted to borrow against future emission reductions. We extend their model to allow for initial "borrowing" of emissions credits in exchange for later repayment. Third, we further generalize their model by examining intra-firm averaging as well as banking and trading of emissions.

A general marketable permit system for vehicle manufacturers was considered, but abandoned, in the Federal 1990 Clean Air Act Amendments. Although no general banking system like the one envisioned here currently exists for automobile emissions, California has adopted a Low-Emission Vehicle Program which does allow a limited form of averaging, trading, and banking [2]. Scheduled to begin in 1994, the program requires manufacturers to meet a fleet average HC standard by producing any combination of vehicles which certify into five emission categories:

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[2]CK include a limited assessment of the price of permits through time based on the SO_2 emission trading program adopted in the 1990 Clean Air Act Amendments.

conventional, transitional low-emission, low-emission, ultra-low-emission, and zero-emission vehicles. For each category, manufacturers must produce vehicles which simultaneously meet the HC, nitrogen oxides (NO_x), and carbon monoxide (CO) requirements of that category. HC and NO_x emissions jointly form ground-level ozone (the primary component of smog), which is of greatest concern. To be placed in the strictest categories, manufacturers will likely be forced to produce vehicles fueled by natural gas, methanol, or electricity. Although the California system does allow for the averaging, trading, banking, and borrowing of HC emission credits, the permit system described in this paper is more general than California's program since the system studied here is based on individual vehicle emissions rather than just five vehicle categories.[3]

The next section of this paper describes the empirical banking model employed in the simulation work, and the following section reports the data used to estimate the emission control cost functions and results of this estimation. The emission control cost functions are employed in a simulation model to examine the effects of banking on the costs of meeting aggregate emission standards and the implied emission stream through time.

In the simulation work, we examine the effect of different discount rates on the cost savings and emission stream. We also perform a series of simulations to identify the cost savings attributable solely to banking, as distinct from the savings attributable to averaging and trading. To strengthen our findings, we perform sensitivity analysis on vehicle sales mix constraints and the functional form of the cost functions. Finally, we examine the implications of allowing backward banking or borrowing of emission credits in exchange for later payment.

AN EMPIRICAL MODEL OF EMISSION BANKING

The system envisioned here allows averaging, trading, and banking of HC emission credits by vehicle manufacturers. Initially, we examine only forward banking; later we extend the model to include borrowing against future emission reductions. In particular, manufacturers are assumed to face a fleetwide average standard (i.e., their sales-weighted average emissions cannot exceed the given standard). Manufacturers are allowed to meet this standard by averaging emissions within their fleet, by trading with other manufacturers, or by banking. We examine trading in HC emissions since our model is patterned on California's Low Emission Vehicle Program, which allows for categorical emission trading of HC (but not NO_x or CO) credits.

To generate emission credits, manufacturers can choose from two forms of pollution abatement: they can reduce the amount of HC emissions per vehicle by installing additional pollution abatement equipment, or they can change their vehicle sales mix and sell more vehicles with lower emission characteristics. A manufacturer that more than meets its average emission requirement in any year earns credits that can be sold to other firms or banked for future use or sale.

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[3] Furthermore, California's system places restrictions on vehicle manufacturers' ability to bank and borrow emissions. For example, banked emissions are discounted by 25, 50, 75, and 100% after 1, 2, 3, and 4 model-years, and starting with the 1998 model-year, emissions can be borrowed only 1 year in advance [3].

Suppose there are n vehicle types, k manufacturers, and T time periods. The equilibrium emission levels and number of vehicles from a marketable permit system that allows unrestricted averaging and trading, and banking (but not borrowing), assuming that all gains from trade are exhausted, can be characterized as the solution to the nonlinear program.

$$\min_{HC_{ijt}, V_{ijt}} \sum_{i=1}^{n} \sum_{j=1}^{k} \sum_{t=1}^{T} \beta_t C_{ij}(HC_{ijt}, X_{ijt}) V_{ijt} \tag{1}$$

s.t.

$$\sum_{i=1}^{n} \sum_{j=1}^{k} HC_{ijt} V_{ijt} + I_t \leq \overline{HC_t} \overline{V}, \qquad t = 0, \ldots, T, \tag{2}$$

$$B_{t+1} = B_t + I_t, \qquad t = 0, \ldots, T, \tag{3}$$

$$\sum_{i=1}^{n} \sum_{i=1k} V_{ijt} = \overline{V}, \qquad t = 0, \ldots, T, \tag{4}$$

$$B_t \geq 0, \qquad B_0 = 0, \qquad t = 0, \ldots, T, \tag{5}$$

where C_{ij} is the abatement cost function for vehicle class i for manufacturer j, HC_{ijt} is the level of HC emissions from vehicle class i and manufacturer j in time period t, X_{ijt} is other explanatory variables, V_{ijt} is the number of vehicles from class i sold by manufacturer j in year t, r is the interest rate, $\beta_t = 1/(1 + r)^t$ is the discount factor in year t, I_t is the investment into or out of the emission bank, B_t is the stock of emissions in the bank at time t, $\overline{HC_t}$ is the fleet average HC emission standard in year t, and $\overline{V}$ is the total current sales of vehicles.

The first constraint in the cost minimization problem represents the emission standard and the possibility for banking emissions. This constraint says that the sum of current emissions by all manufacturers plus the flow of emissions invested in the bank must be no more than the fleetwide emissions standard for that year. Note that the investment can be positive or negative, although the non-negativity constraint on the bank in the initial period also forces the initial investment to be non-negative. The second constraint defines the stock of the emission bank in each year and says simply that the total amount banked in any year equals the amount in the bank the previous year plus the level of investment in the previous year. By setting the initial stock to zero ($B_0 = 0$) and requiring that the stock be non-negative in each year ($B_t \geq 0$), borrowing against future emission reductions is disallowed. This restriction is relaxed later.

The third constraint restricts the total number of vehicles sold in each year to be the same as the total number sold in the base year of the simulation (1990). Such a constraint is necessary if manufacturers are allowed to reduce emissions by selling different mixes of vehicles, i.e., by letting V_{ijt} be a choice variable. Thus, a manufacturer may be able to reduce fleetwide emissions by selling more small-cylinder vehicles and fewer large-cylinder vehicles. An implicit assumption in allowing manufacturers to adjust the sales mix is that the marginal profit on these vehicles remains unchanged.

Most previous studies of permit system trading have taken output of individual firms as fixed. Thus, firms have only one form of abatement, reducing emissions per unit of output.[4] In the case of automobile emissions, an assumption of fixed output levels seems untenable. It is more reasonable to assume that manufacturers may alter their mix of vehicles (presumably in favor of smaller, less-polluting vehicles) in order to meet the required average emission standard.

The approach adopted here is to make the number of vehicles manufacturers produce in each category (V_{ij}'s) endogenous to their decision, but to allow only limited changes in the vehicle output mix. This simplification allows output mix changes, but does so in an ad hoc manner. The approach assumes that there is no change in profits per vehicle (i.e., no penalty) when manufacturers change sales mixes. Since this cannot be correct for large changes, we limit changes in the sales mix to be within 20% of the current position. Although not a complete depiction of firm decision making, this approach seems far superior to ignoring output changes altogether. In the section on sensitivity analysis below, we examine the importance of the 20% limit on our results.

To more accurately depict firms' choices regarding output mix would require imposing additional costs on manufacturers for changing the sales mix. The logic would follow that of Difiglio et al. [6], who estimated producer surplus losses from specified fuel economy targets that require alterations in the sales mix of vehicles between domestic car manufacturers. Their approach works by assuming that manufacturers bear the full economic cost of vehicle mix changes by finding a set of prices that will leave consumers indifferent to the changes in vehicle mix. That is, manufacturers are assumed to compensate consumers fully for their lost surplus from reductions in vehicle size. This approach would require adding an additional cost to manufacturers for altering their vehicle sales mix.

While creative, this approach is not worthwhile to pursue here for several reasons. First, to accurately measure the economic loss, Difiglio et al. must assume that production costs across vehicles and manufacturers are equal. In the context of our study, this is an extremely poor assumption since sales mix shifts occur between large European and small domestic vehicles, which have very large differences in production costs. Second, since we require costs for different manufacturer groups and vehicle sizes, we would need to gather consumer preference data from a number of different studies. Combining our data with the data from a number of separate studies would provide little confidence in the results. A final reason we have decided not to pursue this approach is that we know the direction of bias: not including lost producer surplus creates cost savings larger than they otherwise would be. This occurs because including sales mix costs with abatement costs would mean that for any given sales mix change, the cost savings would be smaller would be smaller than predicted by our model, which has a zero sales mix penalty. This issue is discussed further in the section on sensitivity analysis.

Currently, manufacturers more than meet emission standards in order to create a safety margin that accounts for uncertainty in actual in-use emissions. To be sure that the permit system does not generate more emissions than the current command-and-control (CAC) system, the 1990 certified emission levels are used in place of the actual 1990 standard. That is, manufacturers are required to preserve

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[4] Maloney and Yandle [9] do, however, examine the effects of allowing firms to close or relocate

the current safety margin under the permit system.[5] Additionally, the same percentage safety margin is assumed to persist as standards tighten through time. Consequently, the fleetwide average emission standard in the first constraint contains this safety margin.

Finally, the CAC costs can be represented as

$$\sum_{i=1}^{n} \sum_{j=1}^{k} \sum_{t=1}^{T} \beta_t C_{ij}\left(\overline{HC}_t, X_{ijt}\right)\overline{V}_{ij},$$ (6)

where $\overline{V}_{ij}$ are the number of vehicles of class i produced by manufacturer j in 1990. Equation (6) simply represents the present value of the aggregate cost of meeting the declining standards if each vehicle must individually meet the standard. The permit system cost will be compared to (6) to give a measure of relative cost savings.

DATA AND COST FUNCTIONS USED IN THE STUDY

The estimation of the cost savings, the emission stream, and the price of permits associated with the banking system requires cost functions that differ between vehicle manufacturers and cylinder sizes. To distinguish among vehicle types, vehicles are divided into three categories based on cylinder size: small (4–5 cylinders), medium (6–8 cylinders), and large (10–12 cylinders).

To estimate the emission control cost functions, data on vehicle emissions and control costs are needed. The data on vehicle emissions are the certified emission levels of HC for the engine families certified in California in 1990. In the certification process, manufacturers provide the California Air Resources Board with detailed information on emission control cost systems used in their engine families. Emission control cost data are based on the retail prices of emission control parts collected from automobile dealers in the Sacramento area. Once the prices of each of the parts associated with a particular engine family were totalled, they were discounted by the dealer's markup and the manufacturer's markup to recover an estimate of the costs to manufacturers. Finally, an estimate of the costs associated with assembly and installation was added to obtain the total costs of emission control per vehicle. Details of the data collection procedure and construction of the control costs are contained in Wang [14].

The emission control cost data were combined with the emission certification data to yield 378 observations. The certification data provide emissions data and information on the miles-per-gallon achieved by the vehicle in city driving. To estimate separate cost functions by manufacturer and cylinder size, the data were first divided into three broad manufacturer groups: European, Japanese, and

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[5]Hahn and Axtell [7] present an insightful theoretical model that incorporates a penalty function for violating the standard. They demonstrate conditions under which the safety margin is preserved in a permit system. Our simpler approach assumes that the same safety margin will prevail with a permit system as under CAC or that the margin will be eliminated and regulators, in response, will tighten the standard by the amount of the margin.

TABLE I

Cost Function Estimates[a]

Variable	Japanese	European	American
Constant	7.00	7.36	6.01
	(59.25)	(30.45)	(43.23)
ln HC	−0.06	−0.24	−0.15
	(−1.32)	(−2.34)	(−3.96)
MPG	−0.01	−0.03	−0.01
	(−2.17)	(−2.34)	(−1.96)
Medium	0.14	0.21	0.26
	(3.36)	(2.85)	(5.97)
Large	0.36	0.70	0.54
	(4.29)	(5.15)	(9.25)
Number of Observations	133	64	181
Adjusted R^2	0.31	0.58	0.60

[a]The dependent variable is the natural logarithm of abatement costs.

American. For each group, the following cost function was estimated;

$$\ln C = \alpha + \beta \ln HC + \gamma \, MPG + \delta_1 MED + \delta_2 LARGE + \varepsilon, \tag{7}$$

where C is cost, MPG is miles per gallon, MED and LARGE are dummy variables indicating whether the observation is for a medium or large-cylinder vehicle, Greek letters indicate coefficients, and subscripts are omitted for convenience. To keep the functions as simple as possible, only MPG was used as an explanatory variable additional to HC. MPG is highly correlated with vehicle weight and other factors that affect emission control.

Kling [8] examines the implications of a variety of functional forms and cost function specifications on cost savings estimates associated with a static model of emission averaging and trading. The function employed here is chosen for illustrative purposes. Although different functional forms yield somewhat different answers, Kling finds that functional form differences yield relatively small differences in cost savings. Additionally, Kling experimented with more disaggregated functions obtaining up to 36 separate abatement cost functions and found that cost savings increased by only 1–2%.

Results from OLS estimation of Eq. (7) are contained in Table I. Signs of the coefficients are as expected and generally significant. The t statistics are reported in parentheses below the coefficient estimate. The dummy variables on cylinder size are used to construct cost functions that differ by vehicle cylinder size as well as manufacturer. Thus, the results in Table I define nine cost functions; for each of three manufacturer groups, there are three cylinder sizes. The cost functions have slopes and intercepts that differ by manufacturer and intercepts that further differ by cylinder size.

The final data requirement for the study is the emission standards that firms must meet. As mentioned previously, California has adopted HC emission standards for light-duty vehicles that decline severely over time. The standard in 1990 was 0.39 g per mile (gpm), and the standard is set to drop to 0.25 gpm in 1994. It

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TABLE II

Percentage Cost Savings Estimates from Averaging, Trading, and Banking

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Discount rate	Averaging, Trading, and banking (%)	Averaging and trading (%)	Banking (%)	Averaging and banking (%)	Averaging (%)
0.00	11.78	8.27	3.93	5.94	2.10
0.05	9.92	8.23	1.91	3.95	2.09
0.10	8.83	8.20	0.73	2.79	2.08
0.15	8.38	8.17	0.24	2.31	2.07

will continue to fall each year, reaching 0.157 in 1998 and 0.62 by 2003, which represents just 16% of the 1990 standard.

SIMULATION SCENARIOS AND RESULTS

In the simulations, t runs from 1990 to 2009. We run the simulation through 2009 since there will be effects of banking past the last tightening of standards, depending on the discount rate used.

The Effect of the Discount Rate

In the first set of simulations, we compute the cost savings of the averaging, trading, and banking system over a uniform set of standards (the CAC cost in Eq. (6)). We also examine the emission stream over time resulting from banking and contrast it to the emission levels that would occur in the CAC solution.

There are three separate effects from the discount rate: two that can be termed accounting and one real. The first accounting effect is that, as the discount rate increases, the present value of costs of both CAC and the permit system will fall. In particular, the CAC costs for discount rates 0, 5, 10, and 15% are $15,986, $10,199, $7,130, and $5,372 million, respectively. A second accounting effect can be seen in the third and sixth columns in Table II, where the percentage cost savings with the discount rate. In these two cases there is no banking occurring, and therefore, the optimal solution for emissions and vehicles is identical for all interest rates. The percentage cost savings change in these cases only because the percentage cost savings is a weighted sum whose weights change with the interest rate.[6] Since this last effect is small (0.1% at most in Table II) and of little economic content, we ignore it except to note its presence.

[6]The weighting effect can most easily be seen in the two-time period, one-vehicle case,

% cost savings

$$= 1 - \left[C_1(HC^*)V_1^* + (1/(1 + r))C_2(HC^*)V_7^* \right] / \left[C_1(\overline{HC})\overline{V}_1 + (1/(1 + r))C_2(\overline{HC})\overline{V}_2 \right],$$

where the asterisks represent optimized values of the variables, and the bars indicate the CAC baseline values. The percentage cost savings can either increase or decrease with changes in the discount rate, depending on which period has the larger relative cost savings from optimal HC and vehicle allocations compared to CAC costs

More interestingly, the percentage cost savings falls as a real effect of increases in the discount rate when there is banking. When the future is discounted, there is less incentive to avoid higher future costs implied by the tightening emission standards; hence, there is less incentive to bank current emissions. That is, the additional flexibility implied by banking is less valuable to firms with higher discount rates, so firms will bank less and the cost savings will be smaller.

The averaging, trading, and banking model (Eqs. (1)–(5)) is estimated using the set of cost functions outlined in the previous section for the discount rates of 0, 5, 10, and 15%.[7] Table II contains the results of the four simulations. The first column reports the discount rate used, and the second column reports the percentage cost savings from averaging, trading, and banking compared to the CAC system. In this case the percentage cost savings ranges from about 8 to 12%.

Explanation for the Magnitude of the Cost Savings

At this point it is worth discussing the relatively small magnitude of the cost savings reported here relative to those found in other studies of permit systems. This appears due to the fact that the combination of consumer preferences and regulatory incentives for fuel-efficient vehicles has already led to higher sales of lower priced, small-cylinder vehicles. Since these are the vehicles with the lowest emission control costs per vehicle, the situation for automobile emissions differs from the prototypical permit system studied in that the CAC baseline already employs lower cost sources more extensively than high-cost sources. That is, the number of vehicles in each category effectively acts as a weighting scheme. With the current array of vehicles, low-cost sources are already more heavily weighted than high-cost sources. Thus, there is less room for reallocation from high-cost to low-cost sources and, correspondingly, smaller cost savings result.

To examine the magnitude of this weighting effect, we ran a set of simulations where the CAC baseline was arbitrarily set to have the same number of vehicles and emissions in each category. In this case the cost savings estimates roughly quadrupled for each of the four interest rates. The savings increased from about 12 to 45% when $r = 0\%$, from about 10 to 43% when $r = 5\%$, from about 9 to 42% when $r = 10\%$, and from about 8 to 41% when $r = 15\%$. Thus, the current CAC system has already appropriated significant cost savings benefits by utilizing low-cost sources more extensively than high-cost sources. This finding is in the spirit of the Oates et al. [11] work, which notes that CAC approaches may not always be substantially inferior to incentive-based systems.

Banking Pattern and Emission Streams

Independent of the cost savings, it is also useful to examine the banking patterns and implied emission streams resulting from the ability of firms to bank emissions. Figure 1 contains a plot of the stock of emissions banked and the investment into the bank when the discount rate is zero. As seen from the figure, in the initial years (1990–1998), investment into the bank is positive and the stock rises each

[7]The model is solved using the non-linear programming algorithm in GAMS.
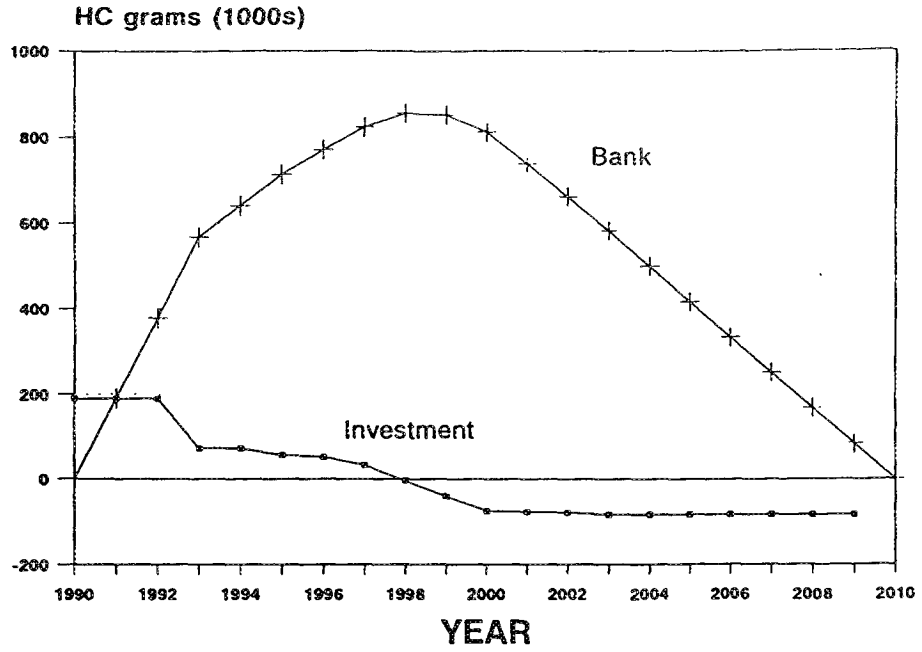
HC grams (1000s)

FIG. 1.   Investment and bank levels when the discount rate = 0%
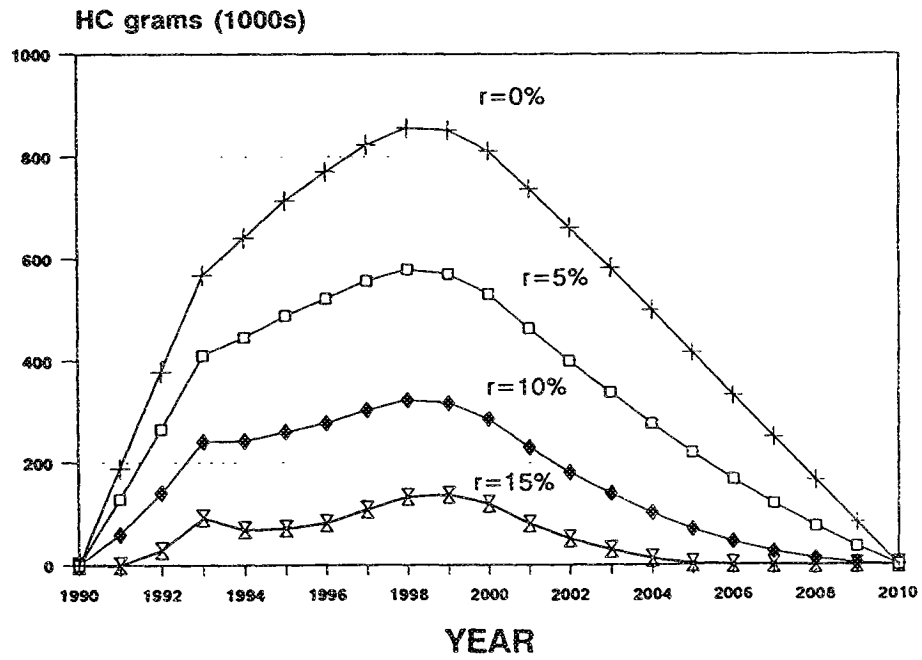
HC grams (1000s)

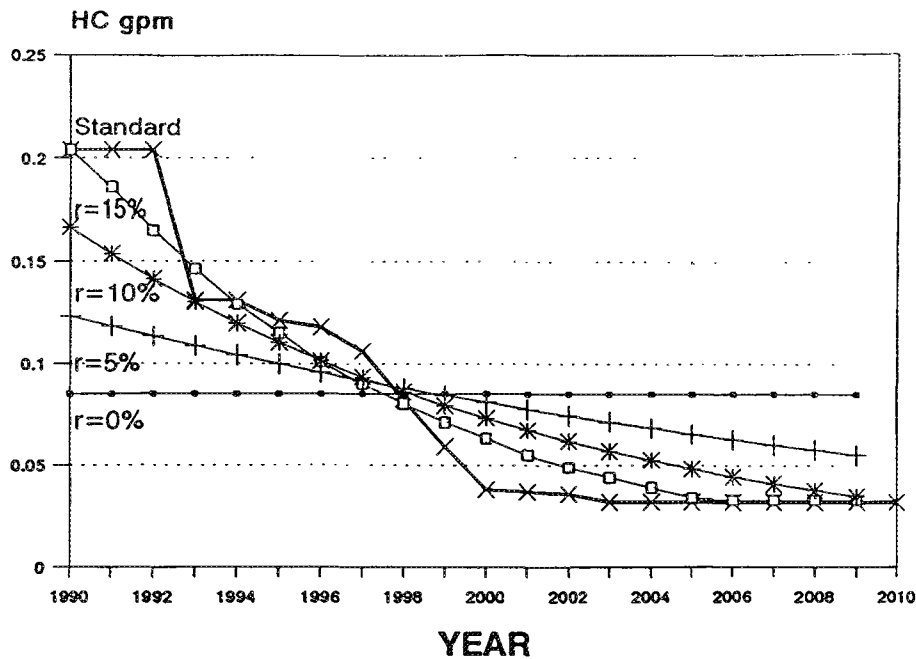FIG. 2.   Bank levels under four different discount rate scenarios.

HC gpm

Fig. 3. HC emission streams under four discount rate assumptions.

year. After 1998, emissions are withdrawn from the bank so that investment is negative and the bank is depleted through 2010.

Figure 2 shows the aggregate level of emissions banked under the four different discount rate assumptions. As anticipated, a discount rate of 0% generates the largest number of banked emissions and a rate of 15% generates the fewest. The use of a high discount rate dramatically discourages banking, because the costs of future emission reductions are more heavily discounted by the firms and there is less incentive to bank.

Of particular interest to an environmental authority is the effect that banking has on the emissions stream. As noted previously, the inclusion of banking differs from averaging and trading in that it may have large effects on emission levels through time. The level of HC emissions in each year under the four discount rate assumptions is plotted in Fig. 3 and contrasted with the standards (adjusted by the safety margin) each year. Banking has the effect of smoothing the emissions stream over time. That is, firms voluntarily reduce emissions in early periods below the allowable standard in exchange for the right to exceed future, stricter standards. If the discount rate is zero, firms will allocate an equal number of emissions to each time period. At higher discount rates, firms will allocate more emissions to the present but will still generate an emission stream smoother than the one prescribed by the standards.

As CK note, if firms use banking to smooth emissions over time and if marginal damages from pollution are increasing, banking generates lower total damages from pollution. For example, suppose in a two-period setting that the standard is lower in the second period than the first, and if allowed to bank, firms would equalize emissions between the two periods. This reallocation will take units from the first period, where marginal damages are greatest, and put them into the

second period, where, from convexity of the damage function, marginal damages are lower, yielding lower total damages. In terms of our application, this effect is amplified since vehicles have an average life of 10 years; thus, emission reductions in earlier model years may yield substantial initial benefits.[8]

The size of current emission reductions is substantial. Our model predicts that if such a banking system had been installed in 1990, firms would have reduced emission by 58% in that year at a discount rate of 0%. Even with a discount rate of 5 or 10%, emission reductions would have been quite substantial at 41 and 20%, respectively.

Unless there are threshold effects, a strong case can be made for allowing banking from a benefit–cost perspective since in addition to reducing damages, it also reduces firms' costs (otherwise firms would not bank). Based on the emission streams reported in Fig. 3, there may be substantial emission benefits from banking.

Cost Savings Attributable to Banking

The results in Table II contain the percentage cost savings associated with the combined effects of banking, averaging, and trading relative to the CAC baseline. To further examine the source of the cost savings and determine the marginal cost savings attributable solely to banking, we ran several additional sets of simulations allowing: (1) just averaging and trading, (2) just banking, (3) just banking and averaging, and (4) just averaging. Each of the four additional simulations require revising the constraints in the cost minimization problem (Eqs. (1)–(5)) to restrict the system to allow the specified combination of averaging, trading, or banking.

The purpose of this exercise is to estimate the incremental savings from banking under three systems: when banking is used alone (no averaging or trading is allowed), when banking is used in combination with averaging (no trading is allowed), and when banking is used in combination with both averaging and trading. Additionally, we can also examine the cost savings attributable to each individual component of the permit system, averaging, trading, and banking.

Table II also contains the percentage cost savings estimates associated with these different simulations. For the systems that do not contain banking (third and sixth columns), the percentage of savings changes only slightly with changes in the discount rate. When the ability to shift emissions through time is removed, the rate at which firms discount future costs no longer affects the choice of emission levels or vehicles mixes; hence, the numbers change only due to the accounting effects mentioned earlier.

Comparisons between various numbers in the table yield many interesting insights. First, the difference between the percentage cost savings reported in the second and third columns represents the incremental savings attributable to banking when averaging and trading are also allowed. Likewise, the difference between the fifth and sixth columns represents the incremental costs savings due to banking if only averaging is allowed. The fourth column represents the cost savings from banking if neither averaging nor trading is allowed. These comparisons indicate that the increment to banking is about the same regardless of whether

averaging or trading is allowed. When the discount rate is 0, banking yields an additional 3.5 to 4% cost savings. When the rate is 5%, the savings are about 1.7 to 1.9%, at 10%, the savings are 0.6 to 0.7%, and at 15%, the savings are a negligible 0.2%.

These results demonstrate that the incremental savings from banking are not highly dependent on whether averaging and trading are also allowed and they again highlight the importance of the discount rate in the returns to banking. At high discount rates, firms are not concerned about the higher future abatement costs implied by tightening standards and consequently do not take advantage of the opportunity to bank. Thus, there are few savings associated with banking.

A second interesting feature of the results is the proportion of the total cost savings due to banking. This is particularly useful given the relatively small total cost savings found in this study. When the discount rate is 0, averaging, trading, and banking yield about 11.8% savings over CAC. Of that total, about 3.5% is due to banking; hence, banking yields about 33% of the cost savings. When the discount rate is 5%, this figure drops to 17%. At a 10% discount rate, only 7% of the savings is due to banking, and at a 15% rate, only 3% is due to banking. If banking generates the same proportion of cost savings in other permit systems as found here, the absolute cost savings could be more substantial, depending on the discount rate.

Overall, results from Table II indicate that averaging generates savings of about 2%, trading generates savings of about 6%, and banking generates savings ranging from about 0 to 4%, depending on the discount rate employed. At $r = 0$, trading is responsible for about 50% of the total savings, averaging accounts for about 17% of the savings, and banking accounts for about 33% of the total savings. In contrast, at $r = 15\%$, trading generates about 72% of the savings, averaging about 25%, and banking about 3% of the total savings.

Borrowing vs Banking

The previous sets of results require that all banking be forward; that is, a firm must first save emissions before using them. In this section we report the results of allowing firms to borrow against future emission reductions as well as to bank. This is a feature of the California Low Emission Vehicle Program, which allows vehicle manufacturers to receive debits which must be made up in the subsequent model year [3]. In terms of our model, B_t is allowed to take on negative values, but there is an added constraint that the bank must be back to zero in the $T + 1$ period, otherwise firms would borrow an infinite quantity of permits and the problem becomes unbounded.[9]

In the situation presented here, firms have a potential incentive to borrow only when the discount rate is positive. With tightening emission standards through time and a zero discount rate, firms will have no incentive to delay abatement. However, with a positive discount rate, they may find it desirable to put off costs into the future by borrowing.

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[9] It is important to emphasize that the borrowing allowed in this model is much more extensive than that allowed under the California LEV regulations. Moreover, the implementation of an extensive borrowing program could lead to severe commitment problems where firms which do not meet current standards lobby for, and possibly receive, a relaxation of future standards.
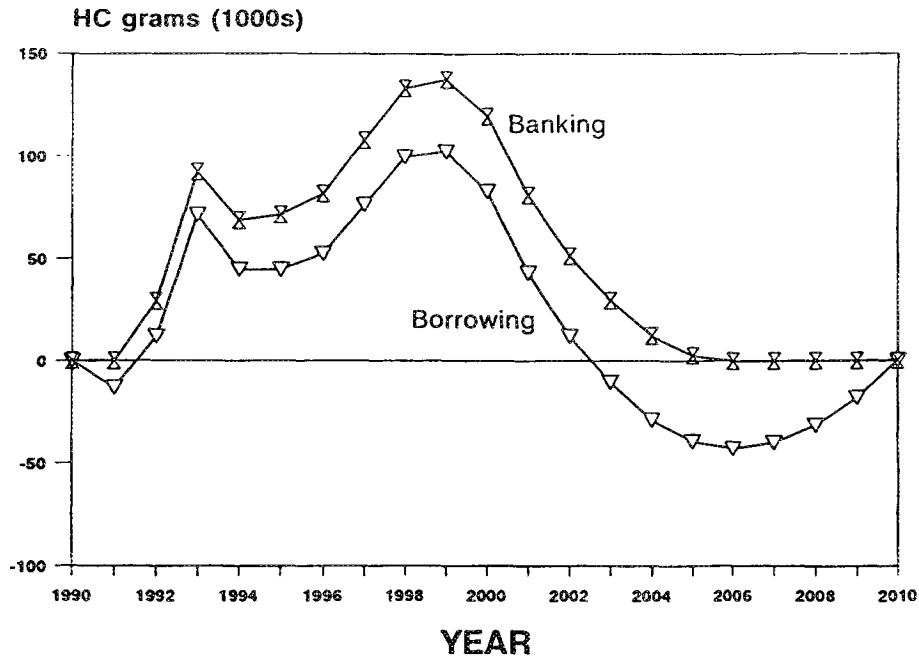
HC grams (1000s)

FIG. 4. Bank levels from banking vs borrowing ($r = 15\%$).

Results for the four discount rates are consistent with the above reasoning. Only in the case of a 15% discount rate did the ability to borrow have any effect on firms' choices. Hence, the cost savings are the same for the 0, 5, and 10% discount rate cases and only slightly greater (8.41% compared to 8.38%) for the 15% rate when borrowing is allowed. Figure 4 shows the level of the bank when borrowing is not allowed and contrasts it to the case when borrowing is allowed at $r = 15\%$. With borrowing, the first year's investment is negative, causing the bank to have a negative balance. Then firms invest in positive quantities, so that balances become positive, but balances are below those that prevail when no borrowing is allowed. After 1999, firms begin to draw down the bank in both cases, but in the case of borrowing, firms actually draw the bank down to a negative balance before paying back the bank beginning in 2006 to end with a zero balance by 2010. The negative balances with borrowing from 2003 to 2010 occur because the standard remains unchanged over this period. Without a declining standard, firms have the incentive to delay expenditures on pollution control by borrowing.

The emission streams associated with these two cases do not differ substantially. When borrowing is allowed, firms emit slightly more in early years and reduce emissions slightly further in later years.

PERMIT PRICE PATHS

If firms cannot bank, there will be different present value permit prices in every period. However, as CK show, when only forward banking is allowed, the present value of permits must be non-increasing. If this were not the case, firms could
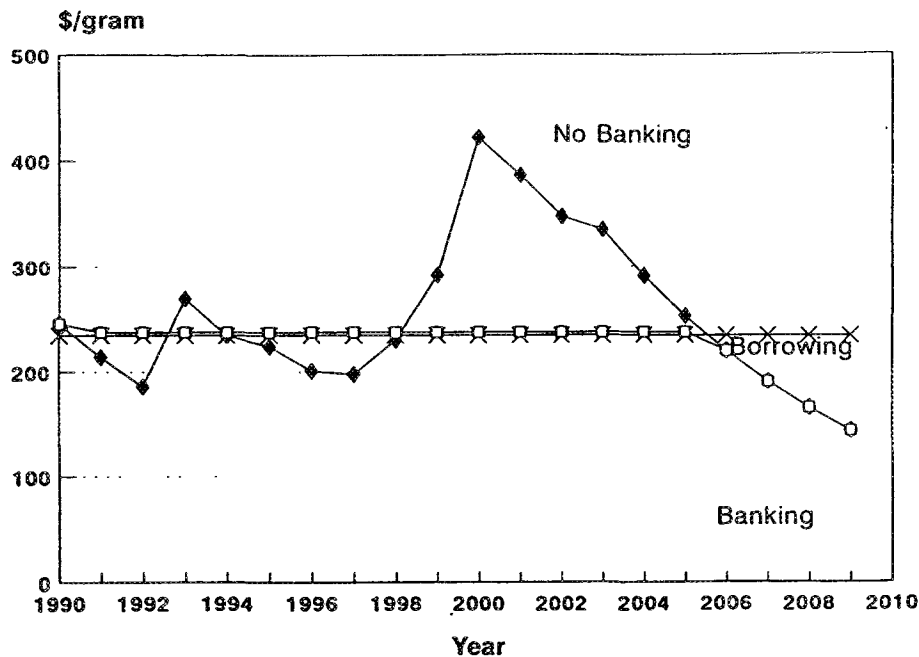
Fig. 5. Present-value permit prices, forward banking, borrowing, and no banking ($r = 15\%$).

reduce their costs by purchasing permits in early periods and selling them later at a higher present value price. Furthermore, CK note that if the present value of permits falls between periods t and $t + 1$, no firm will carry any permits forward to period $t + 1$. These theoretical results are borne out empirically by our data. The present value prices for 0, 5, and 10% discount rates were constant over the entire time horizon at \$677, \$441, and \$311 per gram of HC, respectively. These prices apply to both the banking and the borrowing cases given that the borrowing solution was identical to the banking solution for these three discount rates.

At a discount rate of 15%, the results found for the forward banking and borrowing cases diverge. Figure 5 contains the price paths for a 15% discount rate under the following three systems: when only forward banking is allowed, when both forward banking and borrowing are allowed, and when no banking is allowed. In the case where firms may borrow as well as bank, the present value of permits must be constant across all time periods. In CK's model, the present-value price falls when stocks reach zero, but when borrowing is allowed, permit prices must equilibrate in all periods. This follows from the fact that if a present-value price is lower in any period, firms will purchase permits in that period and sell them when prices are higher.

Figure 5 shows the constant present-value price of permits when forward banking and borrowing are allowed, the constant or declining present-value price when only forward banking is allowed, and the no banking case where present-value price varies considerably between periods. When only forward banking is allowed, the present-value price falls between 1990 and 1991, corresponding to no firms holding inventories in 1990; the price then remains constant until 2006, at which time the bank of emissions is driven to zero and the present-value price declines unit the terminal period. The present-value price when firms can borrow (\$235 per

TABLE III

Percentage Cost Savings Sensitivity Analysis for Averaging, Trading, and Banking

Discount rate	Double-log model: Vehicle mix limits					Semi-log model: Vehicle mix limits				
	0%	5%	10%	20%	30%	0%	5%	10%	20%	30%
0.00	6.18	7.58	8.98	11.78	13.19	7.97	9.47	10.96	13.88	16.69
0.05	4.19	5.26	7.06	9.92	12.79	7.48	8.96	10.43	13.31	16.10
0.10	2.99	4.45	5.91	8.83	11.75	7.56	9.00	10.42	13.24	16.01
0.15	2.46	3.94	5.42	8.38	11.32	7.91	9.32	10.71	13.48	16.20

gram) is less than the present-value price when only forward banking is allowed ($238 per gram) until 2006, when the present-value price begins to fall in the forward-banking case.

SENSITIVITY ANALYSIS

The simulation model employed allows trading of both emissions per vehicle and the number of vehicles produced by each manufacturer in each vehicle class by 20%. To test the model's sensitivity to the assumption of a 20% change in vehicle sales mix, we ran simulations for the basic model with averaging, trading, and banking for all interest rates when the sales mix was allowed to change 0, 5, 10, and 30%, respectively. These results are shown under the double-log heading in Table III. As can be seen, allowing vehicle mix changes to vary 10 to 30%, decreases and increases, respectively, the percentage cost savings 2 to 3% across all interest rates. These modest changes suggest that the model is relatively insensitive to the restriction of limiting changes in the vehicle sales mix to 20%.

Even when the model is limited to 0% changes in the vehicle sales mix, there are still 6–8% cost savings at $r = 0$. Note that the results in this first column provide a lower bound to cost savings obtainable even if a complete model incorporating costs of changing the vehicle sales mix were employed. Manufacturers would undertake changes in the vehicle sales mix only if such changes were an efficient way to meet emission standards. Further, results from the sensitivity analysis also provide an upper bound from cost savings as long as the sales mix change that would result from such a model did not exceed 30%. This is so since for any given vehicle sales mix change, our model yields cost savings greater than those that would result from a model that has a penalty for vehicle sales mix changes. Thus, the results in Table III provide an estimate of the lower bound (0% sales mix changes) and a very high estimate (30% sales mix changes) of the percentage cost savings fromsuch a trading system.

To test the sensitivity of the results to the functional form of the cost function, a number of simulations were also run with a semi-log form. In this specification, the logarithm of emission control costs is explained by the levels of the same explanatory variables used before, but HC enters in its absolute level rather than logged. These results are shown in Table III. The percentage cost savings is generally 2 to 4% larger with the semi-log cost functions across all interest rates and vehicle sales mix limits. These results indicate that moving from the double-log to the semi-log

form of the cost function does not substantially change the quantitative results, nor does it affect the qualitative conclusions.

FINAL REMARKS

We have studied the effects of emission banking for light-duty vehicles sold in California for the 20-year period from 1990 through 2009. To our knowledge, this is the first empirical study of emission banking, averaging, and trading. As theory suggests, increases in the discount rate reduce incentives to bank and correspondingly the cost savings associated with banking. This study estimates the magnitude of these changes.

In addition to examining the consequences of higher discount rates, we also examine the cost savings attributable to each component of a permit scheme: averaging, trading, and banking. In this study, the largest gains came from trading (about 6%), while the gains from averaging are about an additional 2%. The additional gains from banking range from near 0 to 4%, depending on the discount rate. A major implication of these findings is the critical dependence of the cost savings from banking on the discount rate. High rates imply few cost savings benefits from banking.

In contrast to the relatively small cost savings estimates found, emission reductions in early years of the banking system may be large, although the magnitude of such effects also depends on the discount rate. Whereas environmentalists often disparage incentive-based systems that include only averaging and trading because they fear the worsening of air quality, this may be a case where an incentive-based system may yield greater environmental benefits than a CAC system. Further, since the cost savings estimates are relatively small, the environment may be a larger benefactor of an emission banking system than automobile manufacturers.

Finally, we examined the empirical implications of allowing borrowing as well as banking and found that no borrowing was optimal for discount rates below 15%. At this rate, a small amount of borrowing was undertaken, yielding a small amount of cost savings. This result is due to the steeply declining standards examined in this study which make borrowing a relatively unattractive alternative for firms.

Several limitations associated with the study should be noted. First, abatement cost functions are estimated using 1990 data and these functions are assumed to be the relevant cost functions during the entire 20-year period under study. To the extent that new technologies are developed in this time period, these costs are likely to be overestimates. Cronshaw and Kruse address the technological change issue by interpreting the discount factor, β, as incorporating both time preference and technological progress. Adopting this approach suggests that high discount rates might be fruitfully used to examine the implications of technological change in a study of this sort.

Second, our empirical work is limited to three vehicle classes and three manufacturer groups. Our data, therefore, may not permit the full realization of the gains that could be expected from a general permit system where trades are based on individual vehicles and there are many manufacturers. The extent to which our functions yield underestimates depends on the degree to which the abatement costs for individual vehicles and manufacturers differ from the aggregated functions used here.

A third limitation concerns the model simplification that limits vehicle sales mix changes to 20%. Sensitivity analysis, however, indicated that variations in the limit had little effect on the size of the cost savings estimates.

This work has studied the implications of an emission banking system for attaining emission standards through time. Such empirical work on the likely benefits of emission banking is timely given that regulators increasingly are adopting incentive-based emission control systems. Although this study suggests that cost savings are relatively small, the estimated emission reductions associated with banking may be substantial. Banking may be a useful tool for an environmental authority interested in speeding the reduction of effluents, or in decreasing the delays in obtaining standards. Thus, a case can be made for the inclusion of forward banking in an incentive-based system for reductions in automobile emissions.

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