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Impacts of State-Level Limits on Greenhouse Gases per Mile In the Presence of National CAFE Standards

Lawrence H. Goulder
Stanford University, Resources for the Future, and NBER

Mark R. Jacobsen
University of California, San Diego, and NBER

Arthur A. van Benthem
Stanford University

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ABSTRACT

As of the present time, 14 U.S. states have formally adopted limits on greenhouse gases (GHGs) per mile of light-duty automobiles. Previous analyses predict that these limits will yield significant reductions in GHGs. However, these studies do not consider critical factors that can imply different results. First, because of the interaction between these state-level limits and the Federal corporate average fuel economy (CAFE) standard, this initiative gives automakers incentives to offset emissions reductions in the adopting states with increased emissions in other states. Second, the initiative induces substitutions of used cars for new cars and leads to reduced scrapping of used cars; this also counteracts the initiative's GHG emissions reduction goals.

This paper develops a multi-period numerical simulation model that accounts for these and other factors in assessing the impact of the new GHG-per-mile standards on U.S. gasoline consumption and GHG emissions. We find that while the state-level initiatives will reduce significantly the emissions associated with new cars in the adopting states, there will be very significant offsetting increases ("leakage") elsewhere, in both new and used car markets. In the most plausible scenarios considered, the leakage is around 80 percent. Correspondingly, the cost per gallon saved under the GHG-per-mile limits is about 50 percent higher than for an equivalent increase in the Federal CAFE standard.

This research examines a particular instance of a general issue of policy significance – namely, problems from overlapping environmental constraints. Similar issues arise with the overlap of state-level renewable fuels standards with the proposed Federal Renewable Fuels Standard, and with the overlap of state-level cap-and-trade policies and a potential Federal cap-and-trade system.

I. Introduction

In response to the prospect of climate change, many U.S. states have adopted or proposed policies to reduce greenhouse gas emissions from the transport sector. One especially noteworthy initiative is the effort to establish limits on greenhouse gases (GHGs) per mile from light-duty automobiles. As of the present time, 14 U.S. states have pledged to adopt these limits. These "Pavley" limits (named after California Assemblywoman Fran Pavley, whose bill establishing such limits was passed in California) require manufacturers to reduce per-mile GHG emissions starting in 2009. Manufacturers would need to reduce emissions by about 30 percent by 2016 and 45 percent by 2020 (California Air Resources Board, 2008).

The limits have been projected to contribute importantly to these states' overall GHG emissions-reduction goals.[1] For example, the California Air Resources Board estimated that the limits will account for over 18 percent of the reductions needed to meet the state's GHG emissions target for 2020. However, the analyses offering these projections have ignored some very important factors. Accounting for these factors can produce a very different picture of the impact of the Pavley effort on GHG emissions.

One overlooked factor is the potential for significant interactions between the state initiatives and existing Federal corporate average fuel economy (CAFE) standards. Since CO_2 emissions and gasoline use are nearly proportional,[2] the Pavley limits effectively raise the fuel economy requirement for manufacturers in the states adopting such limits. Consider an auto manufacturer that, prior to the imposition of the Pavley limits, was just meeting the U.S. CAFE standard. Now it must meet the (tougher) Pavley requirement through its sales of cars registered in the adopting states. In meeting the tougher Pavley requirements, its overall U.S. average fuel economy now exceeds the national requirement: the national constraint no longer binds. This means that the manufacturer is now able to change the composition of its sales outside of the Pavley states; specifically, it can shift its sales toward larger cars with lower fuel-economy. Indeed, if all manufacturers were initially constrained by the national CAFE standard, and there were no offsetting beneficial technological spillovers, the introduction of the Pavley requirements would lead to "emissions leakage" of 100 percent at the margin: the reductions within the Pavley states would be completely offset by emissions increases outside of those states!

The interaction between the new and used car market provides another source for leakage. A more stringent GHG regulation not only leads to substitution of used cars for new cars, but also reduces the rate at which used cars are scrapped. We find that the latter effect, not often discussed in relation to emissions leakage, is responsible for a substantial fraction of the overall leakage we observe.

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[1] For the Pavley limits to go into effect, California must obtain a waiver from the U.S. EPA enabling the state to exceed the Federal Clean Air Act standards. The Obama Administration has pledged to grant the waiver. Once granted, the Pavley limits will go into effect not only in California but also in the 13 other states that support the initiative.

[2] Gasoline combustion in cars is almost complete, yielding a fixed quantity of CO_2 per gallon burned.

While the effects in used car markets tend to exacerbate leakage, technological spillovers have the potential to work in the opposite direction, mitigating leakage. The tighter requirements in the adopting states can be expected to generate technological improvements and better fuel economy in individual models in the adopting states. If manufactures are limited in their ability to differentiate the fuel economy of given models across the two regions, there will be a beneficial technological spillover: models in the non-adopting states will offer better fuel economy. However, if manufacturers can offer different engine technologies for the same car model, depending on whether the model is being sold inside or outside a Pavley state, such technological spillovers are subdued.

This paper develops a numerical simulation model to assess the impact of the new Pavley standards on gasoline consumption and GHG emissions. The model accounts for the various factors indicated above: interactions between the state-level requirements and the Federal CAFE standards, the interplay between new-car and used-car markets, and the potential for technological spillovers. It considers how the Pavley rules affect production, pricing, and fleet-composition decisions of automobile producers engaging in imperfect competition. It also accounts for the demand side of automobile markets, examining the influence of the Pavley rules on consumers' automobile purchase decisions.

We apply the model to assess the impacts of the planned GHGs-per-mile limits, as well as to compare the impacts of the Pavley initiative with those from tighter Federal CAFE standards.

We find that, under a wide range of scenarios, the potential for emissions leakage is very serious. In plausible cases, leakage is nearly one hundred percent in the short run and remains over eighty percent throughout the period 2009-2020. About two thirds of the leakage reflects the interaction between the Pavley effort and the existing CAFE standard, while the remaining third is due to substitutions from new to used cars and reduced used vehicle scrap rates. It should be recognized, however, that the portion of leakage attributable to used cars is not attibutable to the fact that the initiative only encompasses a subset of U.S. states. This used-car-related leakage would arise under any nationwide regulation that only targets new cars.

This paper examines a particular example of a general issue of policy significance – namely, problems from overlapping environmental constraints. The paper shows that emissions leakage, traditionally analyzed in the context of producer relocation[3] and more

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[3] Leakage from producer relocation occurs as follows: a regulation may raise costs of production to manufacturers in a given region, causing these producers to move to another region. In this case, production (and emissions) may decrease in the former region, but these will increase in the latter region in keeping with the newly located production. Felder and Rutherford (1993) and Barker, Junankar, Pollitt and Summerton (2007) have analyzed this form of leakage in connection with international climate change policy. The Pavley regulations, however, do not give automakers any incentive to relocate production facilities. Auto manufacturers cannot escape the tighter limits that pertain to the adopting states by moving to another location. This is the case because the limits are imposed based on the location of an auto's registration (demand), not its production.

recently in the context of incomplete regulation[4], is also an important issue in cases of regulatory overlap. Similar issues would arise with the overlap of state-level cap-and-trade policies and a Federal cap-and-trade system, and with the overlap of states' renewable fuel standards and the proposed Federal Renewable Fuels Standard. The paper aims to clarify the mechanisms that may lead to unintended consequences, and thereby provide information that can promote a better integration of state- and Federal-level environmental policy.

The rest of the paper is organized as follows. Section II describes the planned Pavley limits and the declared profile of CAFE standards up to the year 2020. Section III identifies the various factors that influence the potential for leakage and explains how these factors operate. Section IV presents the structure of the simulation model, while Section V describes the model's data and parameters. Section VI displays and interprets the results from policy simulations. The final section offers conclusions.

II. Projected Limits from Pavley and CAFE

Both the federal CAFE standards and the Pavley standards are expected to change in a number of important ways over the next decade. Here we describe the key components and time-profiles of requirements under both pieces of legislation.

A. Federal CAFE standards

The federal CAFE standards apply at the manufacturer level and place a lower bound on the miles per gallon (MPG) achieved by the fleet of vehicles each firm produces. The limits are set separately for passenger cars (currently a 27.5 MPG average) and light duty trucks (currently a 23.1 MPG average).[5] The average is calculated as the harmonic mean of miles per gallon, weighted by the quantity of each model sold in a particular model year.

In our analysis we project the existing rules forward based on requirements laid out in recent legislation and rulemaking.[6] The standards are expected to increase to 38.6 MPG for cars and 33.0 MPG for light trucks by the year 2020 along the time path shown in Figure 2.1.

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[4] Fowlie (2008) shows that when pollution regulation applies to only a subset of factories, substantial leakage may occur since production at regulated firms can be substituted for unregulated production.

[5] For firms that make passenger cars both in the U.S. and abroad, there is a further requirement that the 27.5 MPG average be met separately for the domestically- and foreign-produced cars. Light trucks are counted together. Some foreign manufacturers do not currently meet the standard and choose to pay a fine. They account for a small fraction of the U.S. automobile market and we abstract from the issue in the remainder of the analysis by assuming they comply with new regulations. To the extent that some firms choose not to comply with the Pavley standard its effectiveness will be further reduced.

[6] Specifically, the rules are based on the Energy Independence and Security Act of 2007 and subsequent rulemaking by the National Highway Transportation Safety Administration.

In addition to the increase in stringency, two other significant changes may occur: (i) the limits for individual producers could become dependent on characteristics of their vehicles, as opposed to the current uniform requirements; and (ii) some form of trading may be permitted across manufacturers and vehicle fleets. These changes would mainly affect the distribution of the burden across producers. (Our analysis mainly focuses on more aggregate impacts.) It is also possible that the changes would improve the efficiency of CAFE by making the constraint bind on a larger fraction of manufacturers.[7] As discussed in Section III below, the interactions between the Pavley and Federal CAFE requirements become more pronounced, and leakage increases, the larger is the share of new car sales associated with producers facing a binding CAFE constraint. Our analysis incorporates the current requirements only; hence it does not include this additional potential source of leakage.

B. The Pavley Standards

Like the CAFE standards, the Pavley GHG-per-mile limits bind at the manufacturer level. Since greenhouse gas emissions from vehicles occur mainly from the combustion of gasoline, the Pavley limits can be very closely approximated by a limit on average gasoline consumption per mile.[8]

The time path of the Pavley standards (after making the transformation to miles per gallon) is also shown on Figure 2.1. Importantly, the Pavley standards do not apply separately to cars and trucks as under CAFE. Instead, a single standard applies for the entire new vehicle fleet of each firm.[9] The efficiency required of each manufacturer under the Pavley rules increases very quickly from 24.4 MPG to 32.4 MPG in the first four years of the policy.[10]

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[7] If compliance becomes tradable, producers that are not directly affected by the current CAFE will now be able to trade their surplus with other firms. Permit trading creates a shadow price for fuel economy for producers that previously had none. This in turn creates the potential for leakage, since the Pavley standard will increase the shadow price in adopting regions and decrease the shadow price for nationwide CAFE. The same argument holds for firms that were previously constrained in only one fleet: If trading is made possible between their car and light truck fleets a positive shadow price (that can be eroded by the introduction of a Pavley-type standard) will appear for both fleets rather than just one.

[8] We employ the same conversion factor used in the CARB (2008) analysis of the Pavley standards: each gallon of gasoline is assumed to release 8887 grams of CO_2 when burned. The primary non-combustion-related greenhouse gas is refrigerant that leaks out of automobile air conditioners. We follow the methodology used in a CARB (2008) analysis and employ a small adjustment for this, and for reduced emissions from CH_4 and N_2O that are expected via tailpipe controls. The adjustment ranges from one to two percent depending on model year.

[9] The effective regulation of cars and trucks together under Pavley is the result of allowing trading within a manufacturer: if a manufacturer's cars exceed the standard it can under comply by a comparable amount with its light trucks. The effect is a single standard for all vehicles produced by a given manufacturer.

[10] The rationale for the rapid increase lies in engineering studies that indicate improvement to 32.4 MPG can be achieved relatively easily using existing technologies. After the fourth year, the standard continues to increase in stringency, although more slowly, reaching 35.7 MPG in the eighth year. In the final four years (referred to as "Pavley II", for which no definitive agreement has been reached yet) the profile again increases more steeply, requiring an average fuel economy of 42.5 MPG in the final year shown.

In order to compare the CAFE and Pavley standards more easily, we include in Figure 2.1 a "combined CAFE" measure that averages the car and truck limits weighted by the current composition of the fleet. This weighted average appears as the dashed line in the figure. The Pavley standards start out only 0.5 MPG more stringent than those of CAFE, but the gap widens over time: in the final year shown, the Pavley rule requires a fleet that is 7.5 MPG more efficient than that required by CAFE[11].

While the "combined CAFE" measure gives a rough sense of the stringency of the CAFE standard relative to the standard implied by Pavley, it should be noted that this measure is an average across the entire fleet of new cars projected to be sold in the U.S. For a given manufacturer, the overall requirement implied by CAFE will differ depending on the composition of its own fleet between cars and trucks.

C. Adopting and Non-Adopting States

The number of states (or, more precisely, the fraction of the automobile market) that can be expected to adopt the Pavley rule is central to our analysis. Wider adoption would mitigate leakage. As of the present time, 14 states have approved legislation to incorporate the Pavley rule: Arizona, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New Mexico, New York, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington. These 14 states make up 37 percent of the automobile market. With the addition of pending legislation in Illinois and Delaware that fraction rises to 41.5 percent. We use the latter figure as our central case, and examine possibilities ranging from California alone (11.1% of the market) to a case where 100 percent of the market is included.

III. Factors Determining Overall Impacts on Gasoline Consumption and GHG Emissions

A. Impacts on Emissions from New Cars in the Adopting States

In several ways, the Pavley limits can be expected to reduce emissions from new cars in the adopting states. First, they are likely to encourage automakers to improve the fuel economy (and lower GHG emissions) of the various models they sell. Second, they can be expected to induce automakers to change the composition of their new car sales – in particular, to promote more sales of the relatively fuel-efficient models of passenger cars and light trucks. Third, by leading to higher prices of new cars in these states, they might lower the total sales of new cars in these states, thus reducing aggregate emissions from these cars.

B. Impacts on Emissions in Other Markets

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[11] These comparisons assume no changes in the ratio of passenger cars to trucks.

The initiative is likely to induce changes in other markets as well. Several of the responses imply leakage. Under the Pavley limits, leakage can occur through the following channels:

1. Impacts in the New Car Market in Non-Adopting States: Increased Emissions Reflecting Interactions with the Federal CAFE Standard

As sketched out in the introduction, if a manufacturer is initially constrained by the Federal CAFE standard, then by meeting the tighter Pavley standard it will have overcomplied with the Federal requirement. This frees up the manufacturer to *reduce* the fuel economy of its fleet outside of the adopting states. For an incremental tightening of the fuel-efficiency requirement, this leakage is 100 percent: the improvement in fuel economy in the adopting states is entirely offset by a worsening of fuel economy elsewhere.

2. Impacts in the Used Car Market: Substitutions of Relatively Fuel-Inefficient Used Cars for Relatively Fuel-Efficient New Cars.

The Pavley standard raises the effective price of new cars, particularly of larger and inefficient vehicles, stimulating demands for substitutes. Hence the demand for used cars – and in particular for large used passenger cars and light trucks (SUVs and minivans) – shifts out, and the equilibrium prices and quantities of these used vehicles rises. The increase in quantity reflects both scale and composition effects. The equilibrium quantity of used cars in the market rises (scale) since vehicles are less likely to be scrapped when they become more valuable[12]; higher prices of used vehicles raise retention rates. The quantity rises especially for larger passenger cars and trucks (composition). The scale and composition effects each contribute to leakage: gasoline consumption and GHG emissions in the used car market are above what would be the case had there been no policy-induced increase in new car prices.

The numerical model applied in this paper accounts for these leakage channels. It addresses the interactions between the Pavley rules and the federal CAFE standard that affect new car markets in the adopting and non-adopting states, as well as potential substitutions of used for new cars.

C. Factors Controlling the Strength of the Leakage Channels

The strength of the first (adopting state to non-adopting state) channel depends on several factors:

- The share of new-car production that derives from producers constrained by the Federal CAFE standard. Producers that are not initially constrained by the Federal standard have

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[12] Some scrapped vehicles may in fact be exported to lower income countries, such as Mexico. This analysis abstracts from the emissions implications of the international used car trade. On this issue see Davis and Kahn (2009).

no incentive to sell additional, fuel-inefficient cars in the non-adopting states when the Pavley limits are imposed.

- The elasticity of demand for new cars in the non-adopting states. If this elasticity is large, auto manufacturers will be able to increase sales of fuel-inefficient cars in response to the Pavley initiative without having to reduce auto prices significantly. The greater the elasticity, the greater the amount of leakage in the new car market of the non-adopting states, other things equal.

- The extent to which the tighter requirements in the adopting states lead to technological spillovers applying to cars sold in the non-adopting states. The Pavley limits give automakers an incentive to improve fuel economy of models sold in the adopting states: this helps reduce compliance costs. At the same time, the Pavley limits yield no direct incentive to improve fuel-economy of individual models in the non-adopting states. However, if manufactures are limited in their ability to differentiate fuel economy of given models across the two regions, the Pavley rules would generate a technological spillover: the induced improvements in individual model fuel economy in the Pavley states would also apply to cars sold elsewhere. On the other hand, if manufacturers can offer different engine technologies for the same car model, depending on whether the model is being sold inside or outside a Pavley state, the spillovers are subdued.

The numerical model applied in this study (and described in Sections IV and V) considers this channel and the factors that control its strength. It accounts for the fact that several producers of automobiles sold in the U.S. are not initially constrained by the Federal CAFE standard. And it recognizes that producers need to adjust car prices in order to sell additional vehicles in the non-Pavley states, a phenomenon that can attenuate leakage. The model also considers alternative assumptions about the extent to which producers can differentiate the fuel economy of particular models across the adopting and non-adopting states. In most of our simulations, we assume that producers can in fact differentiate fuel economy. Spillovers can be expected if manufacturers offer only one fuel economy for each model. We believe this is unlikely given that heterogeneity in demand is already large enough that manufacturers have the needed incentive to offer multiple fuel economies for each model.[13] Placing an additional shadow value on fuel economy in the adopting regions will only serve to increase the incentive on manufacturers to offer multiple versions of their cars.

The force of the second (new car to used car) channel depends on the nature of consumer preferences – in particular, the ease with which consumers can substitute used for new cars in utility. It also depends on the extent to which the Pavley regulations would drive up new car prices, which in turn depends on the costs to producers of increasing the fuel economy of given models. The numerical model addresses these factors by incorporating

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[13] Of the 22 hybrids in the market in 2008, only one (the Toyota Prius) does not also offer a less fuel-efficient conventional gasoline version. Even among conventional cars two or more engines with substantially different fuel economies are often offered. For example, the Ford Escape is currently offered in three versions (two gasoline and one hybrid) giving the consumer the choice of 20.5, 25.0, or 32.5 combined city/highway MPG.

utility-maximizing choices among used and new cars, and considering how interactions between new and used car markets jointly determine the prices in those markets.

IV. Model Structure

A. Overview

The economic agents in the model are producers of new cars, suppliers of used cars, and households. The model distinguishes two "regions": the group of states adopting the Pavley limits, and the group that do not. In the adopting region, new car producers need to comply with both the Federal CAFE standard and the Pavley standard.

Vehicles are distinguished by manufacturer, age, size (large and small), type (truck and car), and region (adopting and non-adopting). As indicated in Table 4.1, there are seven manufacturer categories and 18 age categories, along with the two categories of size, type, and region. This yields 1,064 different vehicles (532 for each region).

There are two representative households, one in each region. Each household maximizes a nested CES utility function subject to a budget constraint. The choices made by the representative households are meant to mimic the aggregate behavior of consumers in the adopting and non-adopting regions in terms of demands for the various vehicles.[14] <add footnote indicating why we didn't use multinomial logit.> The utility-based demands for vehicles are functions of purchase prices and expected operating costs, where operating costs (as well as purchase prices) depend on fuel economy. Aggregate income (to be spent on vehicle ownership and other goods) is exogenous.

The specification on the production side accounts for the oligopolistic nature of the new car market. The seven producers engage in Bertrand competition, setting prices of each manufactured automobile to maximize profits subject to the CAFE and Pavley constraints and accounting for the influence of their prices on consumer demand. Producers also determine the level of fuel-economy of individual models, taking into account the cost of fuel-economy improvements and the impact of improved fuel-economy on consumer demand.

In the used car market, the supply of used cars in a given period consists of the used cars and new cars from the previous period net of scrapping at the end of the previous period. The scrap probability for each vehicle type and vintage is endogenous, depending on the price of the car: it is assumed that one is more likely to make repairs (rather than scrap the car) the greater is the value of the vehicle when it is in working condition.

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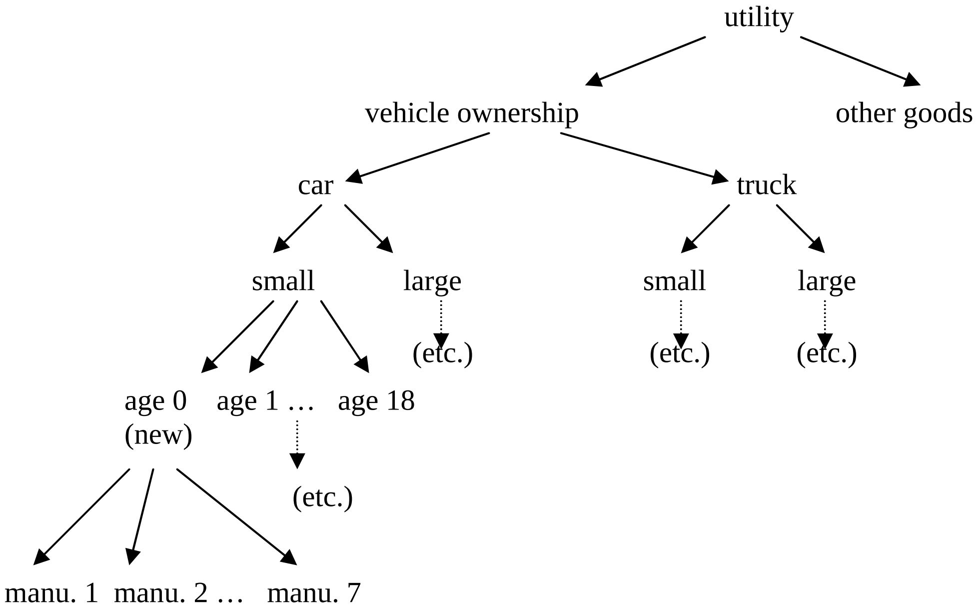
[14] It would also be possible to model the choice in a discrete way, using a multinomial logit model. CES was adopted here in order to provide more flexibility in modeling cross-price elasticities, without the restrictions embedded in the logit demand framework.

The model solves for supply-demand equilibrium in the new and used car markets. These equilibria are calculated at one-year intervals.

B. Household Behavior and Automobile Demand

The representative consumer in each of the two regions derives utility from the various vehicles and a composite consumption good. We model each consumer's demand for vehicles and other goods using a CES utility function with the following nested structure:



At each level, the consumer chooses the shares of vehicle characteristics that achieve the relevant composite at the lowest unit cost. For example, at the lowest nest, the consumer chooses (for a small or large car or truck of a given age) the mix of manufacturers that yields the composite for that aged vehicle at the lowest cost. At the highest nest, the consumer chooses not only the mix between vehicle ownership *(v)* and other goods *(x)* but also the levels that satisfy its budget constraint. Thus, at the highest nest, the consumer in each region solves the following problem:

$$\max_{v,x} U(v,x) = \left(\alpha_v v^{\rho_u} + \alpha_x x^{\rho_u}\right)^{\frac{1}{\rho_u}} \tag{4.1}$$

subject to

$$p_v v + p_x x \le M \tag{4.2}$$

and non-negativity constraints, where M is total income, p_v is the implicit rental price of the vehicle ownership composite, p_x is the price of other goods, M is total income, ρ_u is the elasticity of substitution between vehicles and other goods, and α_v and α_x are distribution parameters. The appendix describes the optimal solution to the consumer problem in detail and indicates how the distribution parameters are calibrated to the data.

C. Supply of New Cars

The seven manufacturers sell four classes of cars in each of the two regions. Car classes (combinations of types t = 1,2 and sizes s = 1,2) represent small cars, large cars, small trucks and large trucks, respectively, sold in regions r = 1,2. Producers set prices $p_{t,s,r}$ and fuel economy $e_{t,s,r}$ for the two regions, given competitors' prices and fuel economies and subject to fleet fuel economy constraints. Demand is less than perfectly elastic, allowing firms' profits. The basic structure of the new and used car supply models follows Bento *et al.* (2008). The effect of the CAFE constraints on manufacturers with differing baseline production builds on results in Jacobsen (2007).

The CAFE standard is a constraint on each manufacturer's nationwide fleet fuel economy for two types of vehicles, passenger cars and light trucks. These categories correspond to the labels "cars" and "trucks" used in this paper. In contrast with the Federal CAFE standard, the Pavley standard is a constraint on each manufacturer's fleet-wide average for all new vehicles – cars and trucks together.

Each manufacturer m maximizes profits by choosing eight prices $p_{t,s,r}$ (four in each region) and eight fuel economies $e_{t,s,r}$

$$\max_{\{p_{ts1},p_{ts2},e_{ts1},e_{ts2}\}}\left(\sum_{t,s=1,2}\Big(\big(p_{t,s,1}-c_{t,s}(e_{t,s,1})\big)\cdot q_{t,s,1}(\boldsymbol{p},\boldsymbol{e})+\big(p_{t,s,2}-c_{t,s}(e_{t,s,2})\big)\cdot q_{t,s,2}(\boldsymbol{p},\boldsymbol{e})\Big)\right) \tag{4.3}$$

subject to the CAFE standards for cars and trucks:

$$\frac{\sum_{s,r=1,2} q_{1,s,r}}{\sum_{s,r=1,2}\left(\frac{q_{1,s,r}}{e_{1,s,r}}\right)} \geq \bar{e}_C \tag{4.4}$$

$$\frac{\sum_{s,r=1,2} q_{2,s,r}}{\sum_{s,r=1,2}\left(\frac{q_{2,s,r}}{e_{2,s,r}}\right)} \geq \bar{e}_T \tag{4.5}$$

and the Pavley standard for all new vehicles sold in the adopting region:

$$\frac{\sum_{t,s=1,2} q_{t,s,1}}{\sum_{t,s=1,2}\left(\frac{q_{t,s,1}}{e_{t,s,1}}\right)} \geq \overline{e}_P \tag{4.6}$$

where $p_{t,s,r}$ and $c_{t,s}$ refer to the purchase price and marginal cost, respectively, of a particular car, and $q_{t,s,r}$ is the demand as a function of all prices and fuel economies ***p***and ***e*** (arguments in the constraints omitted for notational simplicity). All other variables are specific to producer *m*. $\overline{e}_C$ and $\overline{e}_T$ refer to the CAFE requirements for cars and trucks; $\overline{e}_P$ refers to the Pavley requirement[15].

In the model, producers are specified as knowing the demand functions of consumers. Marginal cost for each model is a function of its chosen fuel economy. Producers can alter vehicle prices and fuel economy, but they cannot introduce new vehicle classes or alter attributes that determine class. The constrained optimization problem needs to be solved simultaneously for all firms, since the residual demand curve faced by any particular firm depends on its competitors' choices. For each firm, there are between 16 and 19 first-order conditions, depending on which constraints bind (8 on prices, 8 on fuel economy and as many as three fuel economy constraints). Section E provides details on the solution method.

D. Used Car and Scrap Market

1. The Used (or "Retained") Car Market

The supply of used cars equals the total stock in the previous year minus the ones that are scrapped. By "used cars" we mean vehicles (passenger cars and light trucks) that are not new and remain in operation (are not scrapped). The stock of used cars in a given period is the previous period's stock plus the previous period's new car stock minus scrapped vehicles. Thus:

$$q_{t,s,a+1,m,r}(\tau+1) = \left(1-\theta_{t,s,a+1,m,r}(\tau+1)\right) q_{t,s,a,m,r}(\tau) \quad a = 0,1,\ldots,18 \tag{4.7}$$

where τ indexes time, *a* indicates age and *a* = 0 refers to new cars and $\theta_{t,s,a,m,r}$ is the probability that the car will be scrapped at the end of the period, to be specified in the next section. All 18-year-old cars are scrapped at the end of the period.

Each used car indexed by *t,s,a,m* has the same model, age and manufacturer, but its fuel economy depends on the region in which it was initially sold. We assume a national used car market where the representative consumer is indifferent between buying a particular type and vintage of used car produced in either of the regions. To achieve this, the prices of

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[15] Note that while the producer problem is static within each time period, the CAFE and Pavley requirements change through time.

the two versions need to be linked so that the sum of the rental price $r_{t,s,a,m,r}$ and operating fuel cost $f_{t,s,a,m,r}$ are equated across the two regions.

The used car purchase price $p_{t,s,a,m,r}$ is the sum of scrap-adjusted, discounted future rental prices. This assumes that used car owners are myopic in the sense that they expect the rental price of their used car next year to be the same as that of a one-year-older used car this year. Used car purchase prices can be solved for recursively according to

$$\begin{aligned} p_{t,s,18,m,r} &= r_{t,s,18,m,r} \\ p_{t,s,a,m,r} &= r_{t,s,a,m,r} + \frac{(1-\theta_{t,s,a,m,r})\, p_{t,s,a+1,m,r}}{1+dr} \end{aligned} \tag{4.8}$$

where *dr* is the annual discount rate.

The demand for used vehicles (conditional on a solution for the new car producer problem) is given by the solution of the consumers' utility maximization problem. All used car rental prices need to be solved simultaneously, since demands are interdependent.

2. The Scrap Market

A car will be scrapped when its resale value falls below a certain point. We calibrate this process as follows: since vehicles of model *t,s,a,m,r* actually represent an aggregate category of similar cars with different quality, condition and value, we assume a fraction of these vehicles will fall under the scrapping threshold value in each period. The fraction falling under the threshold will be inversely related to the resale value of that type of vehicle, and we model the relationship as:

$$\theta_{t,s,a,m,r} = b_{t,s,a,m,r}\,(p_{t,s,a,m,r})^{\eta} \tag{4.9}$$

where $b_{t,s,a,m,r}$ is a scale parameter determined in the calibration to actual scrap rates and η is the price elasticity of the scrap rate.

E. Solution Method

The solution to the model is a set of rental prices for all vehicles that equates supply and demand in the new and used car markets. Solving the model also requires determining which constraints actually bind for given producers. The model obtains the solution using a three-level iterative procedure. At the "innermost" level, the model solves for the set of used car prices that clear the used vehicle market, conditional on a posited set of new car prices and on assumptions as to which of the regulatory constraints actually bind for each manufacturer. At the "middle" level, the model solves for the equilibrium new car prices, conditional on assumptions as to which regulatory constraints bind. At the "outermost" level, it determines which regulatory constraints actually bind for each manufacturer in each region. Through this procedure, we obtain a solution in which demands equal supplies for both new and used vehicles, and in which all producers meet the regulatory constraints that bind (and more than meet the constraints that do not)[16]. This procedure is repeated every year, yielding a sequence of equilibria over the simulation period (2009-2020).

V. Data and Parameters

The simulation model employs automobile market data from a variety of sources.

A. Aggregate Data

A set of aggregate statistics describes the size of the car market, GDP, interest rates and gasoline prices and usage. Table 5.1 lists the aggregate values used and their sources. We have taken estimates for 2009 where available to generate a realistic scale. Vehicle sales and income are then divided into two regions, identical except for size. 41.5 percent of the income and vehicles are assigned to the group of adopting states (Arizona, California, Connecticut, Delaware, Illinois, Maine, Maryland, Massachusetts, New Jersey, New Mexico, New York, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington) on the basis of November 2008 vehicle registrations available from the Department of Transportation (DOT).

B. Vehicle Fleet

A more detailed data set describes the automobiles in the economy, including the composition of the fleet, fuel economies and prices. The composition and characteristics of the vehicle fleet make up the core of our model. The data are assembled from several sources: new car fleet composition and prices are taken from *Automotive News* for model year 2006 and aggregated according to manufacturer and vehicle type. The distinction between passenger cars and light duty trucks follows the EPA classification for the purposes of fuel economy rating. The distinction between “small” and “large” vehicle sizes is made based on an average of normalized volume, weight, and engine size, with 2006 model-level characteristics data coming from Ward’s automotive. Fuel economies are the 2006 certified values from the EPA.[17]

C. Demand Elasticities

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[16] The oligopolistic structure of the new car market involves both multiple products and multiple producers. Under these conditions, theory leaves open the possibility of non-uniqueness. In our simulations, however, the model has always converged to one solution.

[17] Data available at http://www.fueleconomy.gov.

The nested CES demand system described in the previous section includes 84 elasticity parameters at 5 levels of nesting. We have selected central case utility parameters that reflect vehicle demand elasticities from the literature. In particular, Kleit (2004) presents a set of new car demand elasticities taken from an internal demand model used by GM. Aggregated up to our four vehicle types, the own price elasticities average -2.4 and range between -1.7 and -3.3. Cross-price elasticities are higher among sizes of cars or trucks (averaging 0.76) than across vehicle types (where they average 0.18). We calibrate the elasticity parameters in the lower four nests of the utility function to match the average own-price elasticity of -2.4 and approximate the substitution patterns seen in the GM data.[18] The highest-level utility parameter determines the substitution between vehicles and other goods. Our central case value for this parameter implies an aggregate elasticity of demand for cars (including gasoline cost) of 0.75.[19]

D. Scrap and Fuel Economy Parameters

In a given period, the supply of used vehicles of a given vintage is the number of cars of that vintage from the previous period less vehicles scrapped or exported at the end of that period.

To calibrate the scrap probability function (4.9), we need to determine the constants $b_{t,s,a,m,r}$ and the scrap elasticity η. In the central case, a one percent increase in the value of a particular used model decreases the number of vehicles scrapped (or otherwise removed from the market) by three percent (η = -3). This reflects the response to an experimental "bounty" for scrapped vehicles described in Alberini *et al.* (1998). The $b_{t,s,a,m,r}$ are obtained by fitting the baseline scrap rates to the roughly linear trend in the number of cars of each vintage in the consumer fleet (as observed in the 2001 National Household Transportation Survey). Taking the percentage of vehicles scrapped to be equal for each vintage, the baseline scrap rate is calibrated to

$$\theta_a = \frac{1}{19-a} \qquad a = 0,1,\ldots,18 \tag{5.1}$$

Given used car purchase prices and the scrap elasticity η, this determines the constants $b_{t,s,a,m,r}$. Baseline used car quantities and scrap rates are given in Table 5.2.

The cost to manufacturers of improving fuel economy (via technological changes to particular models) is of central importance to understanding the effects of increasingly stringent regulation. In its study of CAFE standards, the National Research Council (NRC, 2002) estimates the costs of fuel economy using engineering data. Their results can be approximated very closely with a cost function that is quadratic in fuel economy, which we employ to model costs. The slope of the cost function around the profit-maximizing point

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[18] The calibrated values are: $\rho_{t,s,a}$ = 0.65 for all manufacturer nests, $\rho_{t,s}$ = 0.575 for all age nests, ρ_t = 0.55 for both size nests, and ρ_v = 0.575 for the car/truck nest.

[19] The corresponding value used for ρ_u is -0.33.

depends on two factors: the demand for fuel economy from consumers and the shadow value of fuel economy due to pre-existing CAFE standards. For the first of these we assume forward-looking consumers, such that willingness to pay for a marginal improvement in fuel economy reflects the discounted stream of savings on gasoline. The shadow value due to CAFE is taken from Jacobsen (2007) and combined with consumer willingness to pay to determine the baseline slope of the quadratic cost function.[20] To model the curvature of the cost function as producers move away from the baseline, we incorporate the parameters estimated from fitting a quadratic to the results of the NRC study.[21]

VI. Policy Simulations and Results

A. Two Economic Environments

We analyze the impacts of the Pavley initiative in two economic environments. To bring out most clearly the key channels at work, we begin with some simulations in a simplified setting where the baseline exhibits unchanging fleet composition through time and where the stringency of the Pavley limits remains constant through time. We then perform simulations in a more realistic setting, in which the composition of the automobile fleet changes in the baseline and where both the Pavley and CAFE limits become more stringent over time.

1. The Simplified Environment

For the simplified baseline, we calibrate the simulation model so that the economic path under business as usual is in a steady state. In particular, the composition of the U.S. automobile fleet remains unchanged through time: the shares of cars of each age, manufacturer, and model remain constant. For this baseline we assume no income growth.

Our steady state assumptions assume that (absent regulation) fuel economy remains constant through time. This has been approximately true over the past ten years, as efficiency improvements have generally gone to horsepower and weight rather than fuel economy. The differences in vintages along quality dimensions (like horsepower, weight, electronic equipment, etc.) are assumed to reflect a constant rate of improvement. Furthermore, the relative value of cars and the outside good in utility is also assumed to stay constant. Combined, these assumptions lead to equilibrium quantities in the used market that remain constant through time. Table 6.1 summarizes the statistics of the simplified baseline.

The representation of the existing CAFE standard and the Pavley rules is also simple in this environment. Here we assume, counter to fact, that the stringency of both regulations

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[20] The value of an extra mile per gallon to the consumer ranges from $150 to $530 across models, while the pre-existing CAFE standards add between $50 and $600 in shadow value in the central case.

[21] The coefficients on improvement in fuel economy squared vary between $18 and $41 and are taken from a least squares fit of the NRC data performed by vehicle class.

is constant through time. The CAFE standard is held fixed at 27.5 and 23.1 MPG for passenger cars and light trucks, respectively. For the Pavley requirements, we consider two constant limits on CO_2 emissions: 360 and 299 grams of CO_2 per mile. The former represents the requirement in the first year of the initiative and corresponds to a fuel economy requirement of 24.4 miles per gallon[22]. The second represents the requirement approximately four years into the program's implementation, and corresponds to a requirement of 30.0 MPG. To simplify comparisons with the Federal CAFE standard, in the discussion below we will usually express the Pavley requirements in terms of their fuel economy equivalents.

2. The More Realistic Environment

The more realistic baseline incorporates the following assumptions, which differ from those of Phase I:

-- per-capita income growth of two percent annually
-- two percent annual improvements in fuel economy for all car models
-- continual tightening of the Federal CAFE standards, as described in Section III

The income growth equals the average GDP growth rate for the United States in the period 2001 – 2008. The exogenous technological trend allowing improvements in fuel economy is based on expert opinion gathered by the authors. Different assumptions are considered in a sensitivity analysis.

In contrast with the simplified baseline, this baseline involves changes in fleet composition, which is primarily a reflection of the increasing stringency of federal CAFE standards. Smaller vehicles and the foreign firms that specialize in them become a larger share of the fleet while large vehicles and domestic firms decline significantly.

The representation of the Pavley effort is now more realistic as well, incorporating the steady tightening of its requirements. We impose the requirements depicted in Section III: in the first year (2009), the Pavley law requires manufacturers to limit carbon dioxide emissions to 360 grams per mile in the adopting states, which translates to 24.4 MPG. The emissions limits are reduced gradually, and the limit is 203 grams per mile in 2020, translating to 42.5 MPG.

B. Impacts of the Pavley Initiative – Central Simulations

1. Constant 24.4 and 30.0 MPG Standards (Imposed in an Economy with a Simplified Baseline)

First consider the impacts of two constant Pavley requirements: 24.4 and 30.0 MPG. These requirements leads to reductions of about 10 and 37 percent in gasoline consumption

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[22] See Section II for a discussion of the relation between fuel economy and CO_2 per mile in the context of the Pavley requirements.

associated with new cars sold in the adopting states, respectively. Within these states, several factors contribute to this reduction: the number of new cars sold falls, smaller cars account for a larger share of new car sales, and the fuel economy of individual models increases. (We focus on the relative contribution of these factors below.)

However, as indicated in Table 6.2, the impacts in the adopting states' new car market are offset by two other changes. First, gasoline consumption increases in the non-adopting states, a reflection of the fact that in meeting the tighter standards in the adopting states, manufacturers are now less constrained in terms of the overall fuel economy they must achieve in the other states. They respond to this relaxation of the CAFE constraint by shifting sales toward larger cars (which tend to be less fuel efficient) and by offering smaller fuel economy improvements in individual models of the new cars sold in these states, relative to the improvements they make in the baseline in order to comply with CAFE.

As indicated in the table, the increase in gasoline consumption for the 24.4 MPG target in the non-adopting states offsets about two thirds of the reduction associated with new cars in the adopting states. The 30.0 MPG standard is sufficiently tight that, for some manufacturers, the existing Federal CAFE standard no longer binds. This mitigates the leakage effect among new cars. Compared with the 24.4 MPG case, the offset is larger in absolute terms, but smaller relative to the reduction associated with adopting state new car sales.

The used car market also contributes to leakage. The Pavley initiative raises costs of production, which implies higher prices for new cars sold in the Pavley states. This induces consumers to shift toward used cars. There is also a compositional effect in the used market as the decline in supply of large new vehicles raises the value of large used vehicles. This means large used vehicles are less likely to be scrapped and more likely to be imported from other states. The effects in the used market offset about 29 percent of the reduction linked to the adopting states' new cars for the 24.4 MPG target, and 55% for the 30.0 MPG target. The larger relative contribution is in keeping with the fact that leakage to the non-adopting state new car market is less pronounced.

Together, these adjustments imply leakage of 96 and 93 percent in the first year under the 24.4 and 30.0 MPG requirements, respectively.

Figure 6.1(a) and 6.1(b) indicate how leakage changes over time. The black dashed line indicates the reduction in gasoline consumption attributable only to the changes in sales of new cars in the adopting states. Thus, this line ignores potential leakage. However, it does account for how changes in new car sales in the adopting regions translate, as new cars age, to changes in the used car market.[23] Over time, increased sales of more efficient new cars imply (other things equal) improvements in average fuel economy of used cars, relative to the fuel economy in the corresponding year in the baseline. The downward slope of the

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[23] This calculation is made holding scrap rates at their baseline levels and then projecting the penetration of the more efficient new cars into the used market. We therefore measure leakage via the used market as the net effect after changes to the scrap rate have been included.

dashed line reflects the fact that these effects cumulate as successive vintages of more fuel-efficient new cars move into the used car market.

However, the black dashed line ignores the impact of the Pavley rules on sales in the non-adopting states, as well as the impacts in the used car market associated with regulation-induced substitutions from (more expensive) new cars to used cars. The solid line accounts for these effects. This line shows much smaller reductions in gasoline consumption. Leakage in any year corresponds to the difference between the two lines. In the first year, leakage is nearly 100 percent, as was discussed above. Over time, leakage declines somewhat. In Figure 6.1(a), it is about 74 percent by or 2020, the last year stipulated under the Pavley legislation. The dynamic pattern in Figure 6.1(b) is similar, but leakage by 2020 is about 64%.

The declining long-run leakage percentage reflects a supply effect in the used car market. The less efficient new cars sold in the non-adopting region become less efficient used cars compared to their counterparts of the same size, type and manufacturer in the adopting region. This reduced efficiency translates in a lower purchase price of these used cars, and hence increased scrap rates. Over time, the less efficient used cars are scrapped faster than the more efficient ones, leading to a reduction in leakage. This effect appears in the dashed gray line in Figure 6.1(a) and 6.1(b), which show the relative contribution of leakage attributable to used cars declining over time.

The Pavley impacts on gasoline consumption can be decomposed into those due to changes in fleet composition, changes in fuel economy of individual models, and changes in total fleet size. The first two panels of Table 6.3 display this decomposition. In the first panel, roughly half of the gasoline savings among new cars is attributable to improvements in technology, with the other half from new car fleet composition and size. In the second panel, technology improvements account for about 70 percent. The change in gasoline use among used cars is positive, reflecting reduced scrap rates particularly among larger used vehicles. The Pavley initiative causes the prices of used cars to fall relative to those of new cars. Households choose to hold their used cars longer, raising gasoline consumption from the used car fleet.

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2. Dynamic Pavley Limits (Imposed in an Economy with a Realistic Baseline)

The third panel of Table 6.2 displays the impact of the dynamically (i.e., realistically) specified Pavley initiative relative to the realistic baseline. In the first year, where the Pavley requirement translates to 24.4 MPG, the effects are quite similar to those in the case above where the 24.4 MPG requirement was held constant through time (and the baseline path was simpler). The levels of leakage and the relative contributions from the used car market and the non-adopting states’ new car market are similar to those observed earlier. Increased gasoline consumption from new cars in the non-adopting states contributes about two thirds of the leakage effect. The overall leakage percentage is again quite high (96 percent), just slightly higher than in the case with the simpler baseline and constant policy.

Figure 6.1(c) displays the results over time. As with Figures 6.1(a) and 6.1(b), this figure compares the actual impact on gasoline consumption (solid line) with the impact one would estimate if one ignored leakage, that is, only considering the reductions in gasoline consumption associated with changes in the adopting states' new car market. The black dashed line shows the impact from ignoring all sources of leakage, while the gray dashed line shows the impact when ignoring only the leakage to new cars in other states. In contrast to the results from the simpler cases in panels (a) and (b) of the figure, leakage under the more realistic baseline remains high for a longer period. In the final year of the simulation 80% of the gasoline savings in the adopting states is offset by changes in other states and in the used car market. Over the time period shown, approximately three quarters of the leakage is attributable to increased gasoline use by new cars in the other states with one quarter coming from changes in the scale and composition of the used car fleet.

The third panel of Table 6.3 provides a further decomposition, showing the changes in gasoline consumption attributable to changes in fleet composition, improved fuel economy of individual models, and changes in fleet size. The results are comparable to the simpler 24.4 MPG case in the first panel, where fuel savings among new cars is split about evenly between technology and fleet changes. Leakage to the used car market comes mainly through fleet size with a smaller portion coming from compositional effects in used cars.

C. Alternative Scenarios

Here we consider the impact of the Pavley regulations under some alternative scenarios. In general these scenarios will involve dynamic specifications of the Pavley limits, imposed on a realistic baseline.

1. No Potential to Differentiate Fuel Economy

Here we consider the case where manufacturers are unable to differentiate the fuel economy of given models across the two regions. We perform this simulation mainly to expose the significance of this assumption. As indicated in Section III, there is strong evidence that manufacturers can in fact differentiate fuel economy across regions.

Figure 6.2(b) shows this experiment's results, which can be compared with those of the central case (Figure 6.2(a)). The results differ sharply. In particular the leakage to new cars in the outside regions is entirely reversed and becomes a spillover of 70% in the first year (indicated as negative leakage in the figure). Leakage to the used car market is more pronounced than in the central case, particularly in the later years of the simulation. The reason is that new vehicles in other states are now restricted to the same smaller and lighter technologies, and higher prices, as in the adopting regions. This increases the relative attractiveness of used models (now in both the adopting and other states simultaneously), causing overall scrap rates to fall and gasoline consumption by used cars to rise. Overall leakage by 2020 (61.6 percent) is considerably smaller than in the central case (79.0 percent).

2. Broader and Narrower Initiatives

We now consider how the Pavley impacts differ depending on the breadth of the initiative. Greater breadth increases absolute leakage but reduces the leakage percentage. If more states sign on to the initiative, it becomes more difficult for manufacturers to shift sales in the non-adopting states toward less fuel efficient cars. With a broader initiative, more fuel inefficient cars must be "unloaded" in the non-adopting states relative to the overall size of the new car market in those states. To increase sales of such cars, manufacturers must reduce prices more than cases involving a narrower Pavley effort, since the new car market represented by the non-adopting states is smaller[24].

Figure 6.3 displays the cumulative amount and composition of leakage in year 12 for four cases: California alone (about 11 percent of the car market), our central case (41.5 percent of the market covered by Pavley), and two hypothetical cases where 70 percent and 100 percent of the market is included in the Pavley region. The bars indicate the leakage percentages for each of these cases, subdivided into that which is due to changes in the used car market (light gray) and new car market (dark gray). The numbers underneath the bars show the total reduction in gasoline consumption, as well as absolute leakage.

As shown in the figure, the leakage percentage declines as the size of the adopting region increases. The implications for new-car-market and used-car-market leakage are quite different, however. In the new car market, the capacity of other states to absorb large vehicles is more limited, the larger is the adopting region. Hence as more states adopt the Pavley limits, the fraction of gasoline savings offset by new cars in the other states falls. Effects in the used car market go in the opposite direction: when few states adopt the Pavley rule there is a large pool of outside states that can absorb small used cars coming from the adopting states (large cars enter the adopting states and small cars exit, leading to a relatively small change in the used market as a whole). In contrast, when many states adopt there are only few states to absorb small used cars, creating pressure for changes in the used market as a whole. Note that even with a nationwide Pavley rule, leakage to used cars is significant (59 percent). Figure 6.4 shows the difference between the narrow and broad adoption cases through time.

Table 6.4 displays the welfare cost, gasoline saved, and average cost per gallon under alternative assumptions as to the breadth of the initiative. The cost is measured as the equivalent variation relative to the baseline case without the Pavley rule. The costs in each of the 12 simulated years are combined and discounted to the present. Gasoline savings are total gallons saved over the 12 years, and future gallons are not discounted.

Leakage raises the cost per gallon saved. Under the actual, 14-state initiative (the central case), the costs are approximately $6.13 per gallon. In the narrower, California-only case, it is $8.60. Broader participation reduces leakage significantly and, correspondingly, reduces substantially the costs per gallon saved. While we can only consider welfare effects in a very aggregate sense, the relative size of the distortionary costs underscores our findings on leakage.

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[24] Put differently, profit maximization in the other states limits the number of large vehicles that they will absorb. When enough states sign on to Pavley this limit is reached and further leakage is limited.

3. Comparison with Equivalent Increments to the Federal CAFE Standard

The final two rows of Table 6.4 show the impacts under increments to the federal CAFE standard (beyond the requirements in the baseline path). The two CAFE increments are set to achieve the same nationwide gasoline savings as in the central (actual adoption) Pavley case and the 100-percent adoption Pavley case, respectively. The central-case-equivalent CAFE increment has a major advantage over the actual Pavley limits because it avoids leakage in the new car market. (Leakage still occurs in the used car market.) Costs fall from \$6.13/gallon in the central case to \$4.26/gallon in the equivalent CAFE case. The increment to CAFE that corresponds to nationwide implementation of the Pavley standard (bottom row) is less cost-effective than the Pavley counterpart. This is the case for two reasons. First, in some years CAFE binds for a smaller number of fleets than Pavley, reducing efficiency (because of differences in the time path of the standard, and because CAFE sometimes binds in only one of a manufacturers two fleets). Second, in contrast with the Pavley rules, CAFE does not offer incentives to improve fuel economy (or reduce GHG emissions) by switching from trucks and SUVs to passenger cars.

D. Further Sensitivity Analysis

Table 6.5 lists results from further sensitivity analysis. It gives an overview of the gasoline savings under the Pavley standard in year 12 for new and used cars, as well as total leakage in the year 2020. These numbers can be compared with the 2020 values of the lines in figures 6.1, 6.2 and 6.4.

More stringent Pavley standard: This is a case in which the Pavley target is 30 MPG in 2009 and increases linearly to 50 MPG by 2020. This reduces leakage to 71.4 percent, and increases gasoline savings to 4,902 million gallons. Leakage is reduced because the more stringent Pavley standard causes CAFE to stop binding sooner and for more firms.

Separate used car markets: In the central case, we assumed a nationwide used car market. In this experiment we assume instead that used cars now cannot move between the adopting and non-adopting states. There are numerous interactions in the used car market, but two main competing effects emerge in this experiment. The first is that when the used car market is closed the adopting region can no longer import large used cars from the non-adopting region. This tends to reduce leakage. The second, competing, effect is that the small and efficient cars produced in the adopting region can no longer be resold to the non-adopting region when they become used. Instead, these smaller efficient cars fall in value and become scrapped quite quickly since manufacturers keep supplying more of them to the new market in order to meet the Pavley standard. The two effects offset almost exactly, with the second effect that acts to increase leakage to the used market dominating by a small margin.

Lower autonomous fuel economy improvements: Instead of a two percent annual growth rate for the exogenous component of fuel economy, we now assume a one percent growth rate. This applies to both the baseline and the policy case. It has little impact on leakage and gasoline consumption.

Lower cost of fuel-economy improvements: Here we reduce by 50 percent the curvature parameter of the cost function (see footnote 16). This causes more of the adopting region gasoline savings to come from technology changes and less from mixes in the fleet. Leakage correspondingly increases on the technology margin and decreases on the vehicle mix margin, with little overall impact on leakage and gasoline consumption.

Lower scrap elasticity: Here the scrap elasticity η in (4.9) is set to -1 instead of -3. This reduces the tendency of consumers to hold their used cars longer in response to the Pavley initiative. Hence there is less leakage to the used car market in both the scale and composition dimensions. Overall leakage is 69.9 percent, as compared with 79.0 percent in the central case.

Altered elasticities of substitution across car vintages: Here we reduce this elasticity from 2.35 to 0.75. This reduces the extent to which the Pavley initiative causes substitutions from new to used cars, and associated leakage. In fact, leakage to used cars disappears (it is negative but close to zero). Correspondingly, overall leakage falls to 59.1 percent.

Higher gasoline price: In the central case the gasoline price is $1.83 per gallon. Here we assume a gasoline price of $3.00 per gallon. Higher gas prices make switching to less efficient used cars somewhat less attractive and increases the value of efficient new cars to consumers, thereby (slightly) reducing leakage.

Logistic scrap function: The logistic scrap function below provides a closer fit to the data on vehicle scrap rates collected in Hahn (1995) than the more convenient constant elasticity form used in our central analysis:

$$\theta_{t,s,a,m,r} = 1 - \frac{1}{1+\eta \exp\left(-b_{t,s,a,m,r}\, p_{t,s,a,m,r}\right)} \tag{6.1}$$

Fitting the above function to Hahn's data by least squares provides an estimate of 49.0 for η. The b parameters are calibrated to match baseline scrap rates. The results are largely unaffected: leakage by 2020 increases slightly to 81.4 percent.

VII. Conclusions

In the U.S., the states have led the way in formulating and implementing climate change policy. This paper has focused on one important state-level initiative: the Pavley limits on GHGs per mile from new cars sold in the adopting states. This constitutes a particular instance of a general issue of policy significance – namely, problems from overlapping environmental constraints.

In the case of the Pavley initiative, we find that there are substantial offsetting impacts in the states that do not impose the Pavley limits – offsets (or leakage) deriving from interactions between the Pavley limits and the Federal CAFE standard. The adjustments in new car markets in non-adopting states offset about 55 percent of the reduction in emissions or gasoline consumption from new cars in the adopting states.

We also find significant leakage occurring through changes in the used car market. This results from households substituting used cars for new cars – that is, postponing purchases of new cars and retaining for a longer period used cars that tend to be less fuel-efficient than new cars. The adjustments in the used car market offset about 25 percent of the reductions from new cars in the adopting states.

Overall leakage amounts to around 80 percent in the most plausible scenarios. New cars in the non-adopting states account for about two thirds of this leakage. Consequently, the cost per gallon saved under the Pavley standard is about 50 percent higher than what would result from an equivalent increase in the Federal CAFE standard.

Similar issues arise with the overlap of state-level renewable fuels standards with the proposed Federal Renewable Fuels Standard, and with the overlap of state-level cap-and-trade policies and a potential Federal cap-and-trade system. In each of these cases, the co-existence of the Federal and state efforts can make state-level efforts ineffective. For example, a state that introduces a more stringent cap-and-trade system than the Federal system will not thereby cause further reductions in GHG emissions (absent supplementary provisions). Whatever reductions are achieved in the more aggressive state will reduce pressure on the Federal cap and thereby allow facilities in other states to increase their emissions.

Some analysts might argue that the solution to this problem is Federal pre-emption – the elimination of “redundant” state-level environmental programs once a structurally equivalent Federal program is implemented. States that wish to achieve levels of environmental protection exceeding those assured by the Federal statutes will not be content with this solution. The alternative would seem to be the introduction of provisions in the Federal rules that effectively cause the Federal regulations to become tougher once states implement more stringent environmental policies. Proponents of this approach might argue that this is appropriate if these provisions only necessitate additional adjustments within the states that adopt the more stringent policies. In coming years we may well witness continued debates along these lines – between those preferring pre-emption and those favoring the add-ons that, while preventing or reducing leakage, would effectively make the Federal rules adjust to the stringency of state efforts.

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Appendix: The CES Demand System

A. Solving the Representative Consumer Problem

The model employs a nested CES utility structure. In each region, the representative consumer's optimization problem is:

$$\max_{v,x} U\left(v,x\right)=\left(\alpha_v v^{\rho_u}+\alpha_x x^{\rho_u}\right)^{\frac{1}{\rho_u}} \tag{A.1}$$

subject to

$$p_v v+p_x x\leq M \tag{A.2}$$

This yields the following expressions for the demand for (composite) vehicles and other goods

$$\begin{aligned} v\left(p_v,p_x,M\right)&=\left(\frac{\alpha_v}{p_v}\right)^{\frac{1}{1-\rho_u}}\frac{M}{\alpha_v^{\frac{1}{1-\rho_u}}p_v^{\frac{\rho_u}{\rho_u-1}}+\alpha_x^{\frac{1}{1-\rho_u}}p_x^{\frac{\rho_u}{\rho_u-1}}} \\ x\left(p_v,p_x,M\right)&=\left(\frac{\alpha_x}{p_x}\right)^{\frac{1}{1-\rho_u}}\frac{M}{\alpha_v^{\frac{1}{1-\rho_u}}p_v^{\frac{\rho_u}{\rho_u-1}}+\alpha_x^{\frac{1}{1-\rho_u}}p_x^{\frac{\rho_u}{\rho_u-1}}} \end{aligned} \tag{A.3}$$

Define the composite overall (or "ideal") price index as

$$p^*=\left(\alpha_v^{\frac{1}{1-\rho_u}}p_v^{\frac{\rho_u}{\rho_u-1}}+\alpha_x^{\frac{1}{1-\rho_u}}p_x^{\frac{\rho_u}{\rho_u-1}}\right)^{\frac{\rho_u-1}{\rho_u}} \tag{A.4}$$

That means the consumer buys an amount *M*/*p** of the composite good. Hence, the ratio of the demand for composite vehicles to total demand for the composite good equals

$$\begin{aligned} \frac{v(p_v,p_x,M)}{M/p^*}&=\left(\frac{\alpha_v}{p_v}\right)^{\frac{1}{1-\rho_u}}\frac{M}{\alpha_v^{\frac{1}{1-\rho_u}}p_v^{\frac{\rho_u}{\rho_u-1}}+\alpha_x^{\frac{1}{1-\rho_u}}p_x^{\frac{\rho_u}{\rho_u-1}}}\cdot\frac{p^*}{M} \\ &=\left(\frac{\alpha_v}{p_v}\right)^{\frac{1}{1-\rho_u}}\left(\alpha_v^{\frac{1}{1-\rho_u}}p_v^{\frac{\rho_u}{\rho_u-1}}+\alpha_x^{\frac{1}{1-\rho_u}}p_x^{\frac{\rho_u}{\rho_u-1}}\right)^{-\frac{1}{\rho_u}} \end{aligned}$$

$$= \left(\frac{\alpha_v p^*}{p_v} \right)^{\frac{1}{1-\rho_u}} \tag{A.5}$$

Similarly, the ratio of the demand for other goods to total demand for the composite good equals

$$\frac{x(p_v, p_x, M)}{M/p^*} = \left(\frac{\alpha_x p^*}{p_x} \right)^{\frac{1}{1-\rho_u}} \tag{A.6}$$

These ratios are functions of the price of the composite vehicle p_v, the price of other goods p_x and the overall composite price index p^*. At each level, it is optimal to buy the given amount of the composite good at minimum cost. Thus, the consumer solves the following optimization problem

$$\min_{c_i} \sum_{i=1}^{n} p_i c_i \tag{A.7}$$

subject to

$$C = \left(\sum_{i=1}^{n} \alpha_i c_i^{\rho} \right)^{\frac{1}{\rho}} \tag{A.8}$$

for $i = 1,\dots,n$ and non-negativity constraints and where C is the (given) amount of the composite good demanded.

Solving this problem for the various nests yields the following solution for nest 1 (and analogous solutions for nests 2, 3 and 4):

$$\frac{v_{t,s,a,m}}{v_{t,s,a}} = \left(\frac{\alpha_{t,s,a,m} p_{t,s,a}}{p_{t,s,a,m}} \right)^{\frac{1}{1-\rho_{t,s,a}}} \qquad m = 1,\dots,7 \tag{A.9}$$

where

$$p_{t,s,a} = \left(\sum_{m=1}^{7} \alpha_{t,s,a,m}{}^{\frac{1}{1-\rho_{t,s,a}}} p_{t,s,a,m}{}^{\frac{\rho_{t,s,a}}{\rho_{t,s,a}-1}} \right)^{\frac{\rho_{t,s,a}-1}{\rho_{t,s,a}}} \tag{A.10}$$

The solution to the problem in nest 5 is described above.

Given prices $p_{t,s,a,m}$ (and normalizing $p_x = 1$), elasticity of substitution parameters $\rho_{t,s,a}$, $\rho_{t,s}$, ρ_t, ρ_v and ρ_u, distribution parameters $\alpha_{t,s,a,m}$, $\alpha_{t,s,a}$, $\alpha_{t,s}$, α_t and (α_v, α_x) and total income M, we can now use the equations derived above to solve for the demands at all nesting levels. First, solve for the demand ratios and $p_{t,s,a}$ at nesting level 1, then for nest 2, etc. Using the p_v, p_x obtained for nest 5 above and total income M, one can now solve for the level of nest 5 demand v and x. Finally, the solutions for the levels of demand at lower nesting levels can be calculated using the earlier obtained demand ratios.

B. Calibration of the CES Parameters

The distribution parameters will be calibrated to the actual fleet composition data described in Section V. Starting from the lowest nest and using observed vehicle demands $v_{t,s,a,m}$, the calibration proceeds in three steps.

- Step 0: set $p_{t,s,a} = 1$ for all t, s, a[25].
- Step 1: determine $v_{t,s,a}$ given $p_{t,s,a}$ and using the relationship

$$\sum_{m=1}^{7} p_{t,s,a,m} v_{t,s,a,m} = p_{t,s,a} v_{t,s,a} \qquad \text{(A.11)}$$

- Step 2: calculate $\alpha_{t,s,a,m}$ by rearranging

$$\frac{v_{t,s,a,m}}{v_{t,s,a}} = \left(\frac{\alpha_{t,s,a,m} p_{t,s,a}}{p_{t,s,a,m}} \right)^{\frac{1}{1-\rho_{t,s,a}}} \qquad m = 1,\ldots,7 \qquad \text{(A.12)}$$

This gives the distribution parameters as a function of prices, quantities and the elasticity of substitution parameters.

---

[25] The total expenditure on the composite good $v_{t,s,a}$ is uniquely determined by the demands and prices of the specific goods, but the choice of units for $v_{t,s,a}$ is arbitrary. Hence we can define units such that $p_{t,s,a} = 1$.

Table 4.1: Vehicle Categories.

Manufacturer	***Age***	***Size***	***Type***	***Region***
Ford	new	small	car	adopting states
Chrysler	1 year old	large	truck/SUV	other states
General Motors	2 years old			
Honda	.			
Toyota	.			
Other Asian	.			
European	18 years old			

Table 5.1: Parameter Values.

Parameter	***Value***	***Source***
New car sales	12 million	Industry estimates for 2009 (central value from Ford, upper end of range from GM)
GDP	$14.2 trillion	Energy Information Administration (EIA) estimate for 2009, expressed in 2008 dollars
GDP growth rate	2.0%	Average GDP growth rate for the United States, 2001 - 2008 (WDI, World Bank)
Gasoline price	$1.83	Average daily price of regular unleaded November 2008-January 2009 (EIA)
Average miles traveled per car	10,524	January 2009 seasonally adjusted annual rate (DOT)
Interest rate	3.0%	The real daily rate on long term T-bills ranged from 1.6 to 3.4 percent in 2008

Table 5.2: Baseline Age Composition and Scrap Rates.

Age	*Fraction of Total Fleet*	*Scrap Rate (End of Year)*
new car	10.0%	5.3%
1 year	9.5%	5.6%
2 years	8.9%	5.9%
3 years	8.4%	6.3%
4 years	7.9%	6.7%
5 years	7.4%	7.1%
6 years	6.8%	7.7%
7 years	6.3%	8.3%
8 years	5.8%	9.1%
9 years	5.3%	10.0%
10 years	4.7%	11.1%
11 years	4.2%	12.5%
12 years	3.7%	14.3%
13 years	3.2%	16.7%
14 years	2.6%	20.0%
15 years	2.1%	25.0%
16 years	1.6%	33.3%
17 years	1.1%	50.0%
18 years	0.5%	100.0%

Table 6.1: Baseline Statistics.

		Year 1, Realistic Baseline Every Year, Simplified Baseline		***Year 12, Realistic Baseline***	
	Class	*Fleet Composition (%)*	*Fuel Economy (mpg)*	*Fleet Composition (%)*	*Fuel Economy (mpg)*
Ford					
	Small car	2.7	28.7	3.1	43.1
	Large car	3.3	23.3	2.3	34.2
	Small truck/SUV	2.8	24.4	3.4	33.8
	Large truck/SUV	8.2	17.6	5.2	26.2
	avg.		*20.8*		*31.9*
Chrysler					
	Small car	1.8	25.5	0.9	41.6
	Large car	2.5	24.4	1.7	36.6
	Small truck/SUV	4.9	21.5	5.0	31.4
	Large truck/SUV	4.4	17.7	3.6	26.9
	avg.		*20.9*		*31.0*
General Motors					
	Small car	5.2	28.9	2.9	44.6
	Large car	9.0	25.7	4.2	37.5
	Small truck/SUV	4.3	22.3	4.0	32.2
	Large truck/SUV	7.1	18.0	4.9	27.2
	avg.		*22.9*		*33.2*
Honda					
	Small car	4.7	33.0	7.3	40.8
	Large car	0.6	25.0	0.8	30.9
	Small truck/SUV	2.3	23.8	3.0	32.5
	Large truck/SUV	1.8	22.7	2.5	30.8
	avg.		*27.5*		*36.0*
Toyota					
	Small car	7.4	33.4	11.6	41.2
	Large car	1.3	26.2	1.9	32.1
	Small truck/SUV	5.1	25.6	7.7	33.1
	Large truck/SUV	1.2	18.1	1.3	25.4
	avg.		*28.0*		*36.0*
Other Asian					
	Small car	8.3	28.8	9.5	40.8
	Large car	1.4	23.2	1.3	32.3
	Small truck/SUV	3.4	22.3	3.9	32.9
	Large truck/SUV	2.1	19.6	2.0	29.7
	avg.		*25.0*		*36.4*
European					
	Small car	2.2	32.5	3.5	43.6
	Large car	1.5	25.4	1.9	33.9
	Small truck/SUV	0.2	20.6	0.2	34.3
	Large truck/SUV	0.6	17.9	0.6	30.9
	avg.		*26.6*		*38.3*

Table 6.2: Impacts of Pavley Requirements on Gasoline Consumption[*] in Year 1.

	New Cars		***Used Cars***	***Total***
	Adopting States	*Other States*		
Simplified Baseline	1,557	2,336	35,042	38,936
Constant 24.4 MPG Standard, Simplified Baseline				
Change	-160.9	107.9	47.0	-6.0
	-10.33%	*4.62%*	*0.13%*	*-0.02%*
Leakage		*67.02%*	*29.23%*	*96.26%*
Constant 30.0 MPG Standard, Simplified Baseline				
Change	-571.0	215.9	315.7	-39.4
	-36.67%	*9.24%*	*0.90%*	*-0.10%*
Leakage		*37.80%*	*55.29%*	*93.09%*
Realistic Baseline	1,550	2,325	35,050	38,924
Realistic Pavley MPG Standards, Realistic Baseline				
Change	-161.6	108.0	47.7	-5.9
	-10.43%	*4.65%*	*0.14%*	*-0.02%*
Leakage		*66.85%*	*29.52%*	*96.37%*

[*] Gasoline consumption in millions of gallons.

Table 6.3: Sources of Changes in Gasoline Consumption* in Year 1.

	New Cars		*Used Cars*	*Total*
	Adopting States	*Other States*		
Constant 24.4 MPG Standard, Simplified Baseline				
Overall gasoline use change	-160.9	107.9	47.0	**-6.0**
Change due to:				
change in fleet composition	-27.8	10.8	2.2	**-14.8**
change in individual models' fuel economy	-77.2	63.6	0.0	**-13.6**
change in total fleet size	-56.0	33.5	44.8	**22.4**
Constant 30.0 MPG Standard, Simplified Baseline				
Overall gasoline use change	-571.0	215.9	315.7	**-39.4**
Change due to:				
change in fleet composition	-75.6	16.2	6.8	**-52.6**
change in individual models' fuel economy	-243.7	107.8	0.0	**-135.9**
change in total fleet size	-251.8	91.9	308.9	**149.0**
Realistic Pavley MPG Standards, Realistic Baseline				
Overall gasoline use change	-161.6	108.0	47.7	**-5.9**
Change due to:				
change in fleet composition	-29.2	11.0	2.3	**-15.9**
change in individual models' fuel economy	-77.1	63.8	0.0	**-13.3**
change in total fleet size	-55.3	33.3	45.4	**23.3**

* Gasoline consumption in millions of gallons.

Table 6.4: Cost and Cost per Gallon under Different Pavley Region Sizes and under Equivalent Increments to the Federal CAFE Standard[1].

	Cost			*Gallons Saved*			*Cost per Gallon Saved*
Pavley Regulation: Percent of National Market:	**Adopting States**	**Other States**	**Total**	**Adopting States**	**Other States**	**Total**	**(All States)**
11.1 Percent (California Only)	8.5	-4.8	3.7	0.6	-0.2	0.4	8.60
41.5 Percent (Actual Pavley)	34.8	-21.9	12.9	2.4	-0.3	2.1	6.13
70 Percent	60.8	-39.2	21.6	5.1	-0.4	4.7	4.60
100 Percent	55.8		55.8	18.3		18.3	3.06
Equivalent Federal CAFE Standard:							
Equivalent to Actual Pavley[2]	3.6	5.4	8.9	0.7	1.4	2.1	4.26
Equivalent to Pavley with 100 Percent Adoption[2]	37.1	55.6	92.6	7.3	10.9	18.2	5.08

[1] Costs in billions of discounted dollars; gallons in billions of gallons saved over the period 2009-2020.

[2] The equivalent CAFE standard is the sum of the baseline CAFE standard plus a linear additional growth term. The annual linear addition is selected to match the cumulative gasoline reductions under Pavley, and equals 0.10 and 1.13 mpg/annum for the actual and 100% Pavley standard, respectively.

Table 6.5: Further Sensitivity Analysis
(Cumulative Changes from the Baseline by 2020, in Millions of Gallons)

	Accumulated Gasoline Savings by 2020				*Leakage*
	New Cars		*Used Cars*	*Total*	
	Adopting States	Other States			
Central Case	-3,239	1,948	611	-680	79.0%
More Stringent Pavley Standard	-6,866	3,217	1,685	-1,964	71.4%
Separate Used Car Markets	-2,742	1,465	818	-458	83.3%
Lower Autonomous Fuel-Economy Improvement	-3,175	2,046	540	-589	81.4%
Lower Cost of Fuel-Economy Improvements	-3,109	2,025	433	-650	79.1%
Lower Scrap Elasticity	-3,036	1,918	206	-912	69.9%
Lower Elasticity of Substitution Between Vintages	-2,515	1,534	-46	-1,027	59.1%
Higher Gasoline Price	-2,937	1,648	555	-734	75.0%
Logistic Scrap Function	-3,411	1,988	789	-634	81.4%

Figure 2.1: Pavley and CAFE Targets for the Period 2009 – 2020.

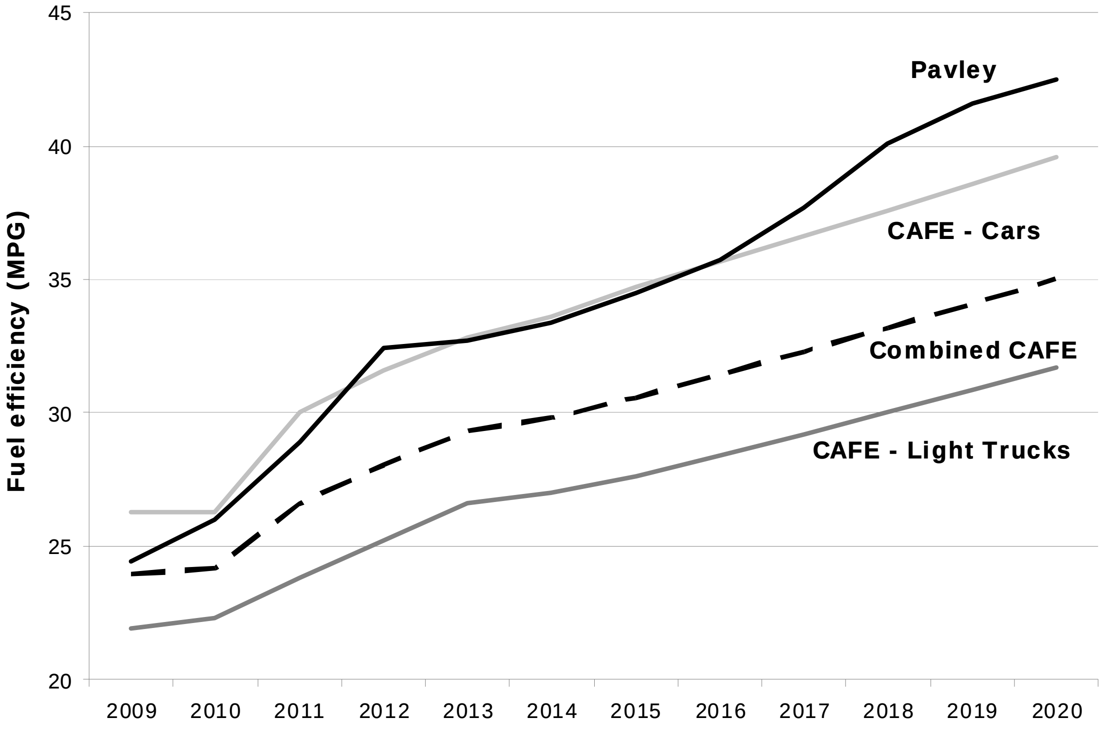

Figure 6.1: Impacts on Gasoline Consumption over Time: (a) 24.4 MPG Pavley Target, Simplified Baseline, (b) 30.0 MPG Pavley Target, Simplified Baseline, (c) Realistic Pavley Target, Realistic Baseline.

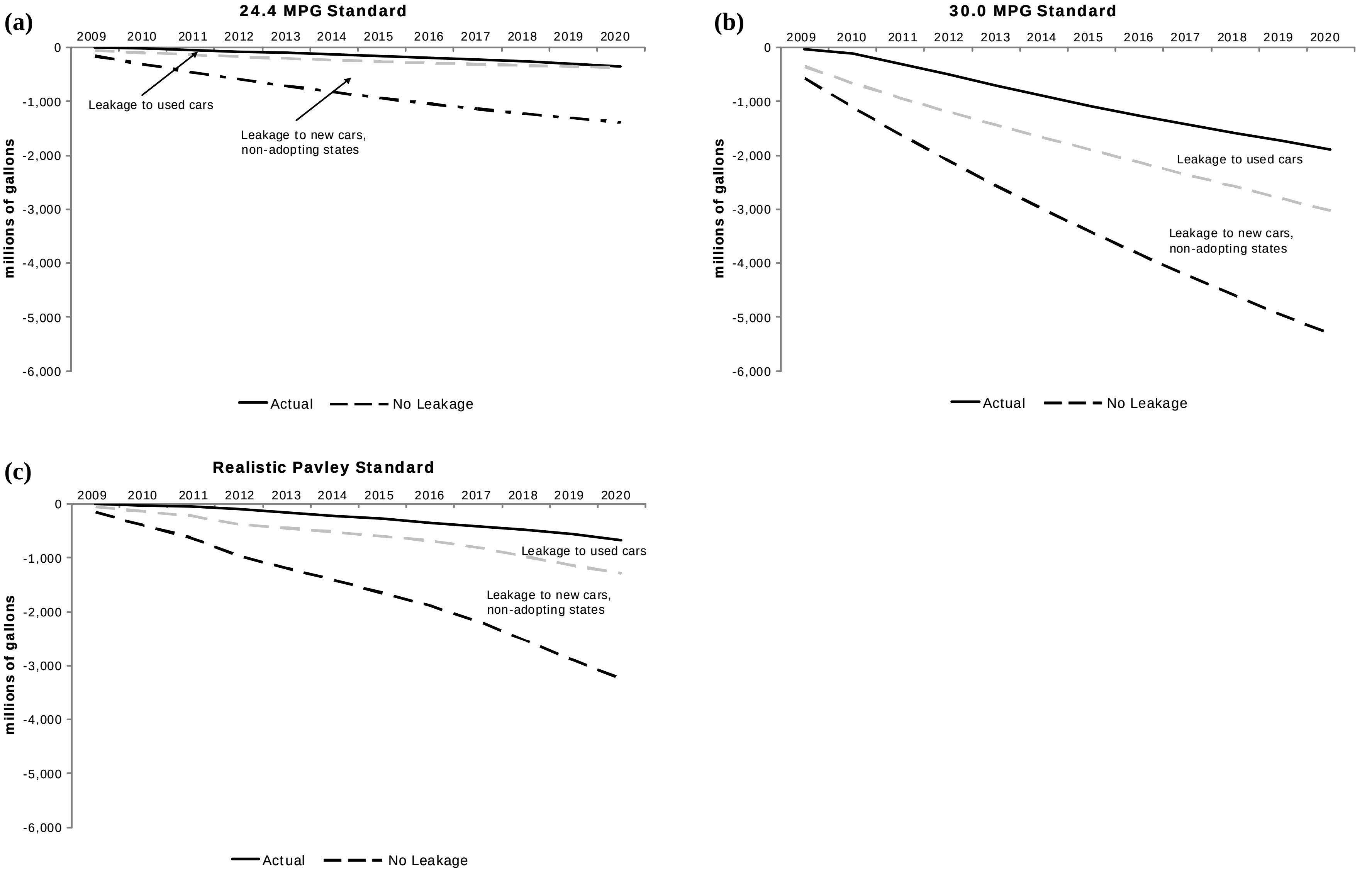

Figure 6.2: Implications of No Fuel-Economy Differentiation: (a) Central Case, (b) No Fuel-Economy Differentiation.

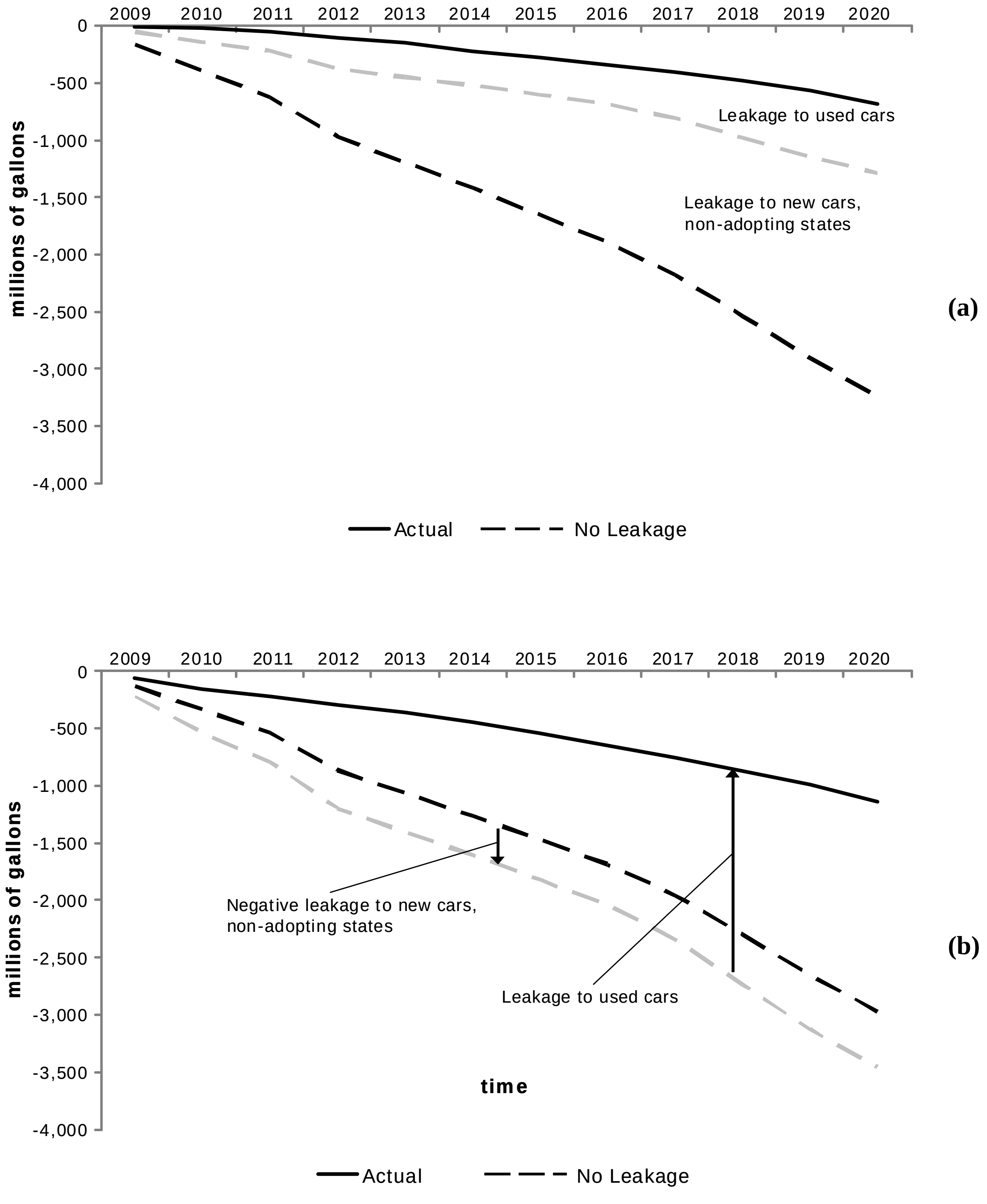

Figure 6.3: Cumulative Contributions to Leakage under Different Adopting Region Sizes in Year 12.

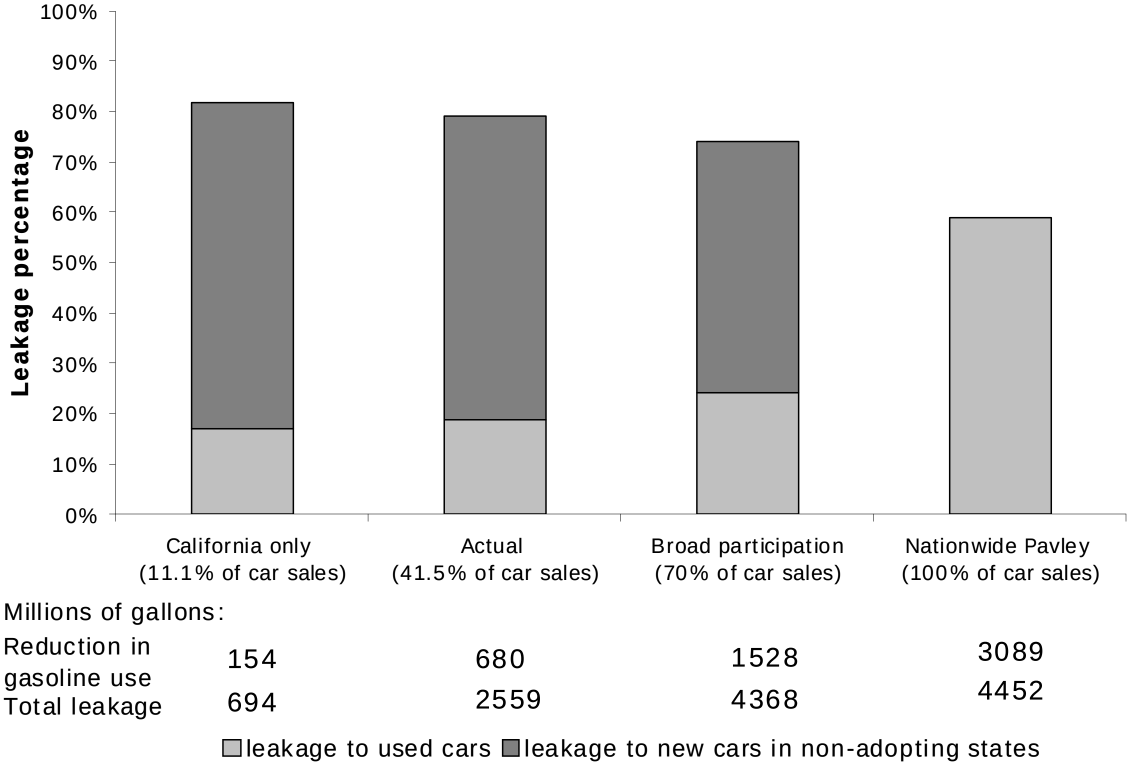

Figure 6.4: Implications of Policy Scope for Gasoline Consumption: (a) 11.1% of National Car Sales (California Only), (b) 41.5% of National Car Sales (Actual Pavley Case), (c) 70% of National Car Sales, (d) 90% of National Car Sales.