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

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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. 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 30 percent in 2016 and 45 percent by 2020. The limits are projected to contribute importantly to these states' overall GHG emissions-reduction goals.

The few existing analyses of the impacts of these limits do not recognize a crucial set of economic factors that can imply very different results from those found previously. An especially important factor is the interaction between the Pavley limits and the Federal corporate average fuel economy (CAFE) standard. In order to meet the Pavley standard, a vehicle manufacturer must improve fuel economy beyond what is required by the CAFE standard. If a manufacturer initially facing a binding CAFE requirement meets the Pavley standard, in doing so it exceeds the Federal CAFE standard and the CAFE constraint no longer binds. As a result, the automaker now is able to change the composition of its sales outside of the Pavley states: it can sell more larger or low fuel-economy vehicles. The reductions in gasoline consumption or GHG emissions in the Pavley-adopting states are thereby offset by increased consumption and emissions in other states. Ceteris paribus, this offset (or "leakage") is 100 percent at the margin.

Other factors influencing the impact of the Pavley initiative include the degree to which car buyers substitute used cars for new cars and the extent to which imposing limits on greenhouse gases per mile leads to technological spillovers. This paper develops a multi-period numerical simulation model that accounts for these and other factors in assessing the impact of the new Pavley standards on U.S. gasoline consumption and GHG emissions.

We find that under the most plausible scenarios considered, the Pavley initiative leads to leakage of over 85 percent. Leakage arises both from increased emissions from new cars in the non-Pavley (non-adopting) states and from changes in the used car market. The cost per gallon saved under the Pavley standard is much 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 leakage potential depends on the degree to which manufacturers are constrained by the U.S. CAFE standard. Other factors can either exacerbate or reduce leakage. An exacerbating factor is the potential of consumers to switch from new cars (which face the tighter GHG-per-mile requirements) to used (and often less fuel-efficient) cars.

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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.

The potential for technological spillovers can 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. 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, 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 on fleet composition, gasoline consumption, and CO_2 emissions in the adopting and non-adopting states. We also compare the impacts of the Pavley initiative with alternative approaches to reduce GHGs emissions from the transport sector.

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. This mainly reflects the interaction between the Pavley effort and the existing CAFE standard. Substitutions from new to used cars also contribute significantly to leakage, particularly in the short run.

This paper examines a particular example of a general issue of policy significance – namely, problems from overlapping environmental constraints. 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 reveal the quantitative importance. It thereby aims to 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 of both pieces of legislation as well as the expected tightening of requirements through time.

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).[3] 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.[4] 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 below. In addition to the increase in stringency two other significant changes may occur:

(i) the limits for individual firms 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 firms and vehicle fleets.

These changes would mainly affect the distribution of the burden across firms. (Our results here consider more aggregate changes.) It is also possible that the changes will improve the efficiency of CAFE by making the constraint bind on a larger fraction of firms.[5] As discussed in Section III below, the interactions between the Pavley requirements and Federal CAFE standards become more pronounced and leakage increases the larger is the share of new car sales associated with firms facing a binding CAFE constraint. We model a case that reflects the current requirements only and hence does not include this additional source of leakage.

B. California's AB 1493 "Pavley" Standards

The Pavley standards place a limit on the average quantity of greenhouse gases that may be emitted per mile and, like the CAFE standards, bind at the manufacturer level. Since

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[3] For those firms that make passenger cars both in the U.S. and abroad there is a further requirement that they meet the 27.5 MPG average separately for the two categories. Light trucks are counted together.

[4] The Energy Independence and Security Act of 2007 and subsequent rulemaking by the National Highway Transportation Safety Administration.

[5] If compliance becomes tradable, firms that are not directly affected by CAFE will now be able to trade their surplus with other firms. This will give them incentive to improve fuel economy at the margin in order to sell more surplus to others.

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.[6]

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.[7] The efficiency required of each manufacturer under the Pavley rule increases very quickly from 24.4 MPG to 32.4 MPG in the first four years of the policy. 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 the profile again increases more steeply, requiring an average fuel economy of 42.5 MPG in the final year shown.

Figure 2.1 displays the stringency of three policies: CAFE for cars, CAFE for light duty trucks, and Pavley for all vehicles combined. In order to compare the CAFE and Pavley standards more easily, we construct 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 CAFE (holding fixed the proportion of cars and light trucks under 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 federally (again holding fixed the proportion of cars and light trucks under CAFE).

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 (and therefore fraction of the automobile market) that can be expected to adopt the Pavley rule is central to our analysis. Leakage will in general be mitigated the larger the number of adopting states. Indeed, the CAFE standards would become redundant if all 50 states were to adopt the more stringent Pavley requirement. As of the present time, 14 states have approved legislation to incorporate the Pavley rule: Arizona,

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[6] 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 1 to 2% depending on model year.

[7] 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.

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 70% 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

Several factors control the impact of the Pavley limits in the adopting states. The Pavley requirements can be expected to encourage automakers to improve the fuel economy (and lower GHG emissions) of the various models they sell. In addition, they will 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. To the extent that these regulations raise the prices of new cars relative to used cars, they can discourage purchases of new cars; some consumers will shift to purchases of used cars, or may decide to refrain from purchasing a car.

B. Impacts on Emissions in Other Markets

However, the Pavley initiative is likely to induce offsetting changes in other markets. The term “leakage” refers to these offsets. Under the Pavley limits, leakage can occur through the following channels:

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

To the extent that the Pavley regulations increase the relative prices of new cars, some consumers will wish to switch purchases toward used cars. Other consumers contemplating purchasing a new car will decide to retain their existing cars longer. After the Pavley rule is put into place used cars tend to be considerably less fuel efficient than new cars. Insofar as consumers are substituting less fuel efficient used cars for new cars, overall fuel economy declines and GHG emissions rise relative to a situation with no such substitutions.[8]

2. 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 over complied with the Federal requirement. This frees up the manufacturer to *reduce* the fuel economy of its fleet outside of the adopting states. At the margin, this leakage is 100 percent: the improvement in fuel economy in the adopting states is entirely offset by a worsening of fuel economy elsewhere.

The numerical model applied in this paper accounts for these two forms of leakage as well as the underlying factors that influence their importance.[9] It incorporates the market for new cars and used cars as well as the interactions between them. In addition, it distinguishes the adopting states from the other U.S. states, and analyzes how impacts in the adopting states can be offset by impacts elsewhere as a result of interactions between the Federal CAFE standard and the Pavley rules.

The force of the first 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 described in Section V incorporates these factors.

The strength of the second channel depends on several important factors. One is the share of new-car production that derives from producers that are constrained by the Federal CAFE standard. Producers that are not initially constrained by the Federal standard have no incentive to sell additional, fuel-inefficient cars in the non-adopting states when the Pavley limits are imposed.

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[8] Leakage deriving from consumer substitution has been analyzed in other contexts. This has been an important consideration in evaluating a potential California cap-and-trade program. Some analyses have explored how higher costs of California-generated electricity as a result of California's efforts might cause consumers (electric utilities) to switch to electricity that is generated out of state (Fowlie, 2008). Analysts have suggested that such leakage can be reduced by including emissions from electricity generated out of state within the cap-and-trade program, but Bushnell, Peterman and Wolfram (2007) show that this might be ineffective as a result of generators' "contract reshuffling".

[9] Another important leakage channel is producer relocation. 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.

A second factor is 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.

A third factor is 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 each of these factors. It accounts for the fact that several producers of automobiles sold in the U.S. are not initially constrained by the Federal CAFE standard. In addition, 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.[10] 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.

Finally, we expect that imports of new cars from non-adopting regions will not represent a source of leakage under the Pavley rule: current law specifies that vehicles with fewer than 7,500 miles on them may not be imported unless they were manufactured to California specifications.[11] We assume that this provision continues to be enforced, such that new vehicles in our model cannot move into the adopting region from outside.

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[10] 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.

[11] The California DMV does make one-time exceptions on the import of new vehicles for people who are moving their primary residence into the state or are stationed on out-of-state military bases. We assume these exceptions do not create significant leakage in the new vehicle fleet.

The rules for the import of used vehicles (defined as those with more than 7,500 miles) are less stringent and we expect a significant amount of leakage to occur through trade in used vehicles. Imported used vehicles must still pass California's annual emissions testing requirement for local air pollutants (known as "smog check"). This annual requirement is not as strict as the requirement for newly manufactured cars: used vehicles that meet only the minimum federal standards can be expected to pass as long as their emissions control equipment is in working order.[12]

IV. Model Structure

A. Overview

The model is designed to capture the key economic channels determining the potential impact of the Pavley initiative on U.S. gasoline consumption and automobile-generated GHG emissions. 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. 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.

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[12] Summary of import and smog check rules: http://www.arb.ca.gov/msprog/NonCAVeh/NonCAVeh.pdf.

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 is modeled explicitly, and decreases in the purchase price of a car.

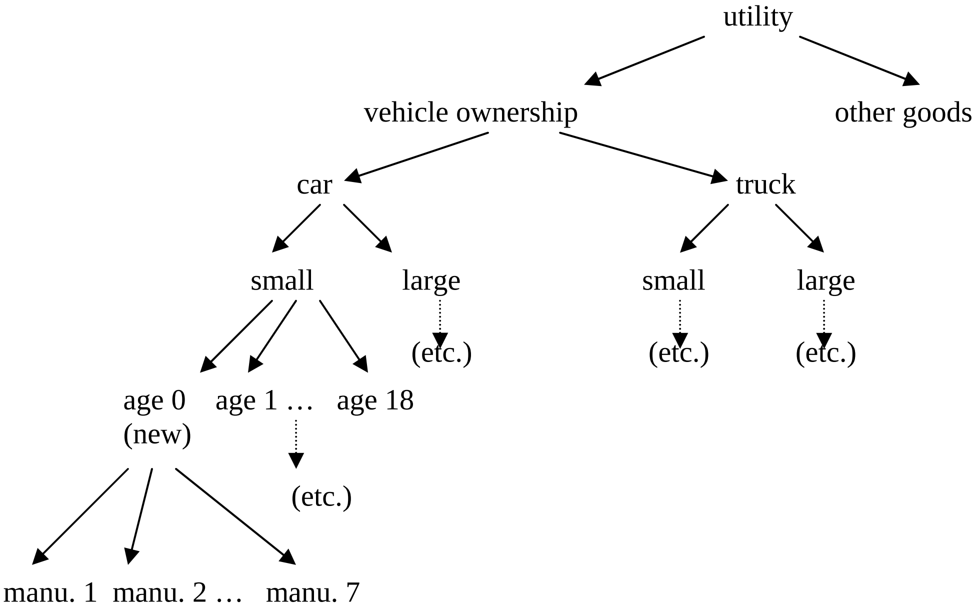
The model solves forward supply-demand equilibrium in the new and used car markets. These equilibria are calculated at one-year intervals.

B. Household Behavior and Automobile Demand

Two representative consumers represent households in each of the two regions. They each derive utility from vehicles and other goods, modeled as a composite consumption good. We model the representative consumers' demand for vehicles using a CES utility function with a nested structure.

We employ the following notation: At the highest level, the consumer chooses between vehicles (*v*) and other goods (*x*). Vehicles have the following dimensions: vehicle type (*t*: car or truck), size (*s*: small or large), age (*a*: 0 years (new cars), …, 18 years), and manufacturer (*m*: Ford, Chrysler, GM, Honda, Toyota, Other Asian, and European). Hence, $v_{t,s,a,m}$ refers to the amount of vehicles of type *t*, size *s*, age *a* and manufacturer *m*[13].

We use the following nested structure for the preference function and assume CES subutility functions at each level for each region:



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[13] The subscript *r* for region is omitted for notational simplicity.

The nested structure of the model with the CES utility function gives rise to composite goods at the various nesting levels. For instance, $v_{t,s,a}$ refers to the composite of all cars of type *t*, size *s* and age *a*. The CES utility function has associated elasticity of substitution parameters $\rho_{t,s,a}$ for the lowest nest, $\rho_{t,a}$ for the nest one level up, etc. In addition, there are distribution parameters $\alpha_{t,s,a,m}$ for the lowest nest, $\alpha_{t,s,a}$ for the nest one level up, etc. Finally, total income is given by *M*.

We now turn to the problem of finding the demand for the various vehicles at each nesting level. Given prices, elasticity of substitution and distribution parameters, the representative consumer first chooses $v_{t,s,a,m}$ given $v_{t,s,a}$ (nest 1), and then progresses to higher nests in the tree, finally choosing between vehicles *v* and the composite consumption good *x* (nest 5). At the highest nest, the representative consumer solves the following optimization problem:

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

subject to

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

and non-negativity constraints. At lower levels, the representative consumer chooses a mix of “sub-vehicles” given the amount of the composite vehicle one level up. The CES structure allows a closed form solution for demand ratios $v_{t,s,a,m}/v_{t,s,a},\ldots, v_t/v$. The optimal solution v^* from the consumer problem pins down all vehicle demands. The appendix describes this solution method in more detail, and explains 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 model here reduces the number of vehicle types to four while adding the Pavley rule as a third potentially binding regulatory constraint.

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 sold in the adopting region only.

Each manufacturer *m* maximizes profits by choosing 8 prices $p_{t,s,r}$ (4 in each region) and 8 fuel economies $e_{t,s,r}$

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

subject to the CAFE standards for cars and trucks:

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

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

and the Pavley standard for all new vehicles 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 $\check{p}$ and $\check{e}$ (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[14]. Marginal cost for each model is a function of its chosen fuel economy. The model includes the limitation that producers cannot introduce new vehicle classes or alter attributes that determine class.

Solving the firms' profit maximization problems requires a demand function and a cost function. Demand is given by the representative consumers' utility maximization problems (Section B above). The cost function is calibrated using engineering estimates of

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

the relationship between production cost and fuel economy from the National Research Council (2002). Details are provided in Section V.

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 more details.

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 current scrappage. Thus:

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

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 the two versions need to be linked such 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 cars (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 cars 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 cars 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

A solution to the model is a set of rental prices for each new and used car in each region, such that there is equilibrium in both the new and the used car market, the representative consumers maximize utility given prices and income, and the new car producers maximize profits subject to federal and state fuel economy requirements. The first order conditions for profit maximization are functions of all car prices, for which the models needs to solve simultaneously.

The model solves for the equilibrium vector using an iterative procedure involving three parts. The first, outermost, procedure determines the set of regulatory constraints that binds in each region. In equilibrium it must be the case that none of the manufacturers violates a constraint and all of the shadow costs of regulations which do bind are weakly positive. The second procedure involves solving for a set of prices and fuel economies for new cars such that all of the producers are maximizing profits. The third, innermost, nest of the procedure solves for equilibrium in the used market: used car prices must be such that demand equals the stock of used cars net of vehicles scrapped. The solution algorithm iterates over these three procedures until the sets of used car prices, new car prices, and binding constraints stop changing and are therefore mutually consistent[15].

This procedure is repeated every year, which results in a sequence of equilibria with possibly different prices, quantities and binding constraints.

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[15] 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.

V. Data and Parameters

The simulation model employs automobile market data from a variety of sources. The parameters used in the central case fall into three general categories. First, a set of aggregate statistics describes the size of the car market, GDP, interest rates and gasoline prices and usage. These aggregates determine the overall scale of effects from the policy but do not substantially affect results that are expressed in relative terms, such as the amount of leakage. Second, a more detailed data set describes the automobiles in the economy including the composition of the fleet, fuel economies and prices. Third is a set of vehicle demand elasticities and cost functions that combine to form the market equilibrium. The values used in this last category are important to our results and the principal subject of our sensitivity analysis; the central case values are described here.

A. Aggregate Data

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 (AZ, CA, CT, DE, IL, ME, MD, MA, NJ, NM, NY, OR, PA, RI, VT, WA) on the basis of November 2008 vehicle registrations available from the Department of Transportation (DOT).

B. Vehicle Fleet

The composition and characteristics of the vehicle fleet make up the core of our model. The data is 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.[16] The baseline fuel economies and composition of the new vehicle fleet are listed in the first two columns of Table 6.1.

C. Demand Elasticities

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.

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

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.[17] 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.[18]

D. Automobile Supply Parameters

Our central case parameters controlling used and new vehicle supply are again drawn from the literature, with a range of alternative values considered in the sensitivity analysis. The model parameters describe used vehicle supply and the costs of engineering improvements to fuel economy. We model used vehicle supply as the number of cars in a particular vintage less vehicles scrapped or exported.

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 1 percent increase in the value of a particular used model decreases the number of vehicles scrapped (or otherwise removed from the market) by 3 percent ($\eta = 3$). 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 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

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

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

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.[19] 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.[20]

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 perform some simulations in a simplified setting where the baseline exhibits balanced growth and where the stringency of the Pavley limits remains constant through time. In addition, we perform simulations in a more realistic setting, one 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 10 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 Pavley rules is also simple in this environment. Here we assume, counter to fact, that the stringency of the regulations is constant through time. In

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[19] 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. The sensitivity analysis explores alternative shadow values.

[20] 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.

particular, 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 Pavley initiative, and corresponds to a fuel economy requirement of 24.4 miles per gallon[21]. 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 does not exhibit balanced growth. In particular, the composition of the automobile fleet changes over time due mainly to the expected increase in 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 Cases

Constant 24.4 MPG Standard (Imposed in an Economy with a Simplified Baseline)

First consider the impacts of a constant 24.4 MPG Pavley requirement. This requirement leads to a reduction of about 10 percent in gasoline consumption associated with new cars sold in the adopting states. Within these states, several factors contribute to this

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

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 in the non-adopting states offsets about two thirds of the reduction associated with new cars in the adopting states.

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 (or refrain from purchasing a new car by holding an existing car longer). Furthermore, the decrease in number of large new vehicles causes a compositional shift in the used car market: large 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.

Together, these adjustments imply leakage of 96 percent in the first year.

Figure 6.1(a) indicates 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.[22] 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 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 does not account for leakage. It 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 does account for these effects, and thus it shows the full impact of the Pavley regulations. 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

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[22] 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.

somewhat. It is about 75 percent by year 12 (or 2020), the last year stipulated under the Pavley legislation.

The slightly lower long-run leakage percentage reflects the net impact of two opposing effects in the used car market. As mentioned, increased sales of more efficient new cars in the adopting states yield over time an improvement in the average fuel economy in the used car market. However, higher sales of less efficient new cars in the other states works toward reduced fuel economy in the used car market. We find that the former effect is slightly stronger; hence average fuel economy of the used car market improves, with the effect compounding over time. This contributes to lower overall gasoline consumption and reduces somewhat the leakage percentage over time. This effect appears in the dashed gray line in Figure 6.1(a), which shows the portion 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 panel of Table 6.3 displays this decomposition. 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. 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.

Constant 30.0 MPG Standard (Imposed in an Economy with a Simplified Baseline)

Table 6.2 also displays the effects from the imposition of a constant 30.0 MPG Pavley standard in the simplified economic environment. This standard causes a much larger reduction in gasoline consumption from changes in the new car market in the adopting states.

As in the case of the 24.4 MPG standard, this reduction is accompanied by increased gasoline consumption by new cars in the other states. Compared with the 24.4 MPG case, this offset is larger in absolute terms, but smaller relative to the reduction associated with adopting state new car sales. 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.

At the same time, the leakage effect from substitutions to used cars is larger than under the 24.4 MPG standard in absolute and relative terms. The larger relative contribution is in keeping with the fact that leakage to the non-adopting state new car market is less pronounced. Total leakage is of similar magnitude (93 percent).

Figure 6.1(b) shows how leakage changes over time in this case. The dynamic pattern is similar to that of Figure 6.1(a), though more pronounced.

The second panel of Table 6.3 shows the decomposition of this policy's gasoline consumption into the various fleet-related changes. The effects in the new car market are similar to the 24.4 MPG case but on a larger scale. In keeping with the leakage measures in table 6.2, the increases in gasoline use due to used car fleet size and composition become more pronounced and make up a larger fraction of the overall leakage.

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

Table 6.2 displays the impact of the Pavley initiative in the first year, where the Pavley requirement translates to 24.4 MPG. The first-year 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 (98 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. Despite the ever-larger reduction in gasoline consumption associated with new cars in the adopting states (black dashed line) this reduction is continually offset almost entirely by increased consumption of gasoline stemming from changes in the new car market in other states, as well as from substitutions from new cars to used cars. Leakage is nearly 100 percent initially, and remains near 100 percent through the first 8 years of the policy. When the leakage to used cars begins to flatten (gray dashed line) the overall leakage drops slightly, but still remains near 90% at the 2020 conclusion of the simulation.

The third panel of Table 6.3 shows the contributions to reduced 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. 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. This is more difficult, because 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[23].

Figure 6.2 displays the amount and composition of leakage in year 1 for three cases: California alone (about 11 percent of the car market), our central case (41.5 percent of the market covered by Pavley) and a hypothetical case where 70 percent of the market is included in the Pavley region. The percentage of gasoline savings that leak away (height of the bars) declines as the size of the adopting region increases. The numbers underneath show absolute leakage in gallons, increasing with the size of the adopting region. Finally, the light and dark shades of gray display the fraction of leakage attributable to used and new cars respectively.

Two effects are present as the adopting region increases in size: i) The potential for leakage to used cars declines (the stock of used cars available for import from the other region is limited); ii) The potential for leakage to new cars declines (the capacity of other states to absorb large cars is limited). When comparing the California only and central cases effect (i) dominates and the fraction of leakage from used cars falls. As the region grows very large (to 70% of the market) effect (ii) dominates and the proportion of leakage attributable to used cars begins to grow again. In the limit, if 100% of the market were to adopt Pavley, leakage to new cars would disappear entirely.

Figure 6.3 shows the difference between the central case and the broad participation case through time. Broader participation mitigates leakage, although leakage by 2020 is still substantial.

2. 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 6.4(c) shows the results for the simplified environment and a constant Pavley requirement of 24.4 MPG[24]. The results differ sharply from those of the central case. In

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[23] 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.

[24] A similar simulation for the more realistic case will be provided in the next draft.

particular the leakage to new cars in the outside regions is entirely reversed and becomes a spillover of 70% (indicated as negative leakage in the figure). Leakage to the used car market is more pronounced than in the central case. 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.

3. Further Sensitivity Analysis

[This is currently work in progress. Figure 6.4(b) shows the effects of a tighter Pavley regulation in which the 2009 target is raised to 30.0 MPG, with a linear increase to 50.0 MPG by 2020. Other sensitivity analyses we plan to do include demand elasticities, the scrap elasticity, low-cost fuel-economy improvements and alternative exogenous trends, and a case in which the whole country adopts the Pavley regions.]

4. Welfare Cost per Gallon and Comparison with an Increment to CAFE

While we can only consider welfare effects in a very aggregate sense, the relative size of the distortionary costs underscores our findings on leakage. Table 6.4 displays the welfare cost, gasoline saved, and average cost per gallon of the central policies explored above. The cost is measured as the equivalent variation relative to the baseline case without the Pavley rule. The costs and gasoline savings in each of the 12 simulated years are combined and discounted to the present.

The first row of Table 6.4 indicates the welfare costs associated with our central case simulation. For example, a reduction of 3.3 billion gallons in the adopting region costs that region $34 billion, for a cost per gallon of about $10. The welfare cost per gallon is very high, reflecting the stringency of pre-existing CAFE policy assumed in the baseline:[25] a large distortion in the new car market has already been created by the existing policy. When the policy costs are considered for the country as a whole the effects of leakage enter. We observe more than 90% leakage over the simulated period corresponding to an extremely high cost per gallon nationally of about $60. Notice that as leakage approaches 100% the cost per gallon will tend to infinity.

The second row of Table 6.4 provides a basis for comparison: the policy shown is an increment to the CAFE policy (above the already stringent baseline path of requirements) that achieves the same gasoline reductions in the adopting region. The cost per gallon is now much lower at about $6 per gallon, and is the same across regions and the nation since the policy applies uniformly.

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[25] Our estimates in a version of the model that holds CAFE constant in the baseline are much lower, at less than $1 per gallon in the adopting region and between $2 and $3 for the nation as a whole.

The final row of the table considers sensitivity of costs if more states were to decide to adopt the Pavley requirements. This would be expected to lower costs per gallon (the scope for leakage to other states is less). Indeed we find that costs decline by a factor of about four reflecting the reduced scope for leakage. Costs per gallon within the adopting region remain approximately the same. Even when a large group of states adopts the rule we find that costs remain more than twice that of a comparable increment to the CAFE standard.

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 initiative: the Pavley limits on GHGs per mile from new cars sold in the adopting states.

Our analysis indicates that in assessing the impact of the Pavley initiative on GHG emissions or gasoline consumption, it is critical to look beyond the market for new cars in the states where these limits are implemented. Changes in the new car market in non-adopting states, as well as changes in the used car market, fundamentally alter one's assessment of the overall impacts on GHG emissions or gasoline consumption.

We find that there are substantial offsetting impacts in the states that do not impose the Pavley limits – impacts (or leakage) deriving from interactions between the Pavley limits and the Federal CAFE standard. The Pavley limits are likely to cause a reduction in the fuel economy of cars sold in non-adopting states that offsets about half of 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 between 30 and 60 percent of the reduced emissions or gasoline consumption from adopting state new cars.

Overall, leakage amounts to over 90 percent in the most plausible scenarios. Consequently, the cost per gallon saved under the Pavley standard is much higher than what would result from 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. 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 by firms within the states that adopt the more stringent policies, and do not directly impose costs on producers or households in other states. In coming years we may well witness continued debates along these lines – between those preferring preemption and those favoring the add-ons that, while preventing leakage, would effectively make the Federal rules adjust to the stringency of state efforts.

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Appendix: CES Demand System

Solving the Representative Consumer Problem

This appendix solves the consumer problem with the nested CES utility structure. Let the representative consumer maximize

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

subject to

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

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.

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[26].
- Step 1: determine $v_{t,s,a}$ given $p_{t,s,a}$ and using the relationship

$$\sum_{m=1}^{7} p_{t,s,a,m} v_{t,s,a,m} = p_{t,s,a} v_{t,s,a} \tag{A.11}$$

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

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

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

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[26] 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 All Years, Simple Baseline		***Year 12, Realistic Baseline***	
	Class	*Fleet Composition (%)*	*Fuel Economy (mpg)*	*Fleet Composition (%)*	*Fuel Economy (mpg)*
Ford					
	Small car	2.7	28.7	2.5	40.4
	Large car	3.3	23.3	0.5	32.4
	Small truck/SUV	2.8	24.4	2.7	31.8
	Large truck/SUV	8.2	17.6	1.2	23.4
	avg.		*20.8*		*32.4*
Chrysler					
	Small car	1.8	25.5	0.0	42.3
	Large car	2.5	24.4	0.1	37.8
	Small truck/SUV	4.9	21.5	3.3	30.5
	Large truck/SUV	4.4	17.7	0.9	25.7
	avg.		*20.9*		*29.5*
General Motors					
	Small car	5.2	28.9	0.1	43.3
	Large car	9.0	25.7	0.1	37.1
	Small truck/SUV	4.3	22.3	2.1	30.9
	Large truck/SUV	7.1	18.0	0.8	25.5
	avg.		*22.9*		*29.8*
Honda					
	Small car	4.7	33.0	13.6	41.3
	Large car	0.6	25.0	2.1	31.2
	Small truck/SUV	2.3	23.8	4.5	32.4
	Large truck/SUV	1.8	22.7	3.6	30.8
	avg.		*27.5*		*36.5*
Toyota					
	Small car	7.4	33.4	20.2	41.4
	Large car	1.3	26.2	4.0	32.5
	Small truck/SUV	5.1	25.6	12.5	33.2
	Large truck/SUV	1.2	18.1	1.8	24.2
	avg.		*28.0*		*36.2*
Other Asian					
	Small car	8.3	28.8	10.3	40.2
	Large car	1.4	23.2	0.6	32.0
	Small truck/SUV	3.4	22.3	2.8	32.3
	Large truck/SUV	2.1	19.6	0.6	29.0
	avg.		*25.0*		*37.4*
European					
	Small car	2.2	32.5	6.6	42.6
	Large car	1.5	25.4	2.5	33.3
	Small truck/SUV	0.2	20.6	0.1	33.9
	Large truck/SUV	0.6	17.9	0.1	30.3
	avg.		*26.6*		*39.5*

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

	New Cars		***Used Cars***	***Total***
	Adopting States	*Other States*		
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 Pavley MPG Standards, Realistic Baseline				
Change	-164.5	104.5	56.9	-3.0
	-10.61%	*4.50%*	*0.16%*	*-0.01%*
Leakage		*63.55%*	*34.60%*	*98.16%*

* 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	-164.5	104.5	56.9	**-3.0**
Change due to:				
change in fleet composition	-28.6	10.6	2.5	**-15.6**
change in individual models' fuel economy	-77.3	63.9	0.0	**-13.4**
change in total fleet size	-58.6	30.0	54.5	**25.9**

* Gasoline consumption in millions of gallons.

Table 6.4: Cost and Cost per Gallon Under Different Adopting Regions Sizes[1].

	Cost			*Gallons*			*Cost per Gallon*		
	Adopting States	**Other States**	**Total**	**Adopting States**	**Other States**	**Total**	**Adopting States**	**Other States**	**Total**
Central Case (41.5 Percent of National Market Adopts)	33.6	26.3	59.9	-3.3	2.4	-0.9	10.35	-	68.04
Federal CAFE Increment[2]	19.6	29.4	49.0	-3.3	-4.9	-8.2	5.95	5.95	5.95
70 Percent of National Market Adopts	57.2	5.7	62.9	-5.9	1.7	-4.1	9.73	-	15.24

[1] Costs and gasoline consumption expressed in billions of discounted dollars and gallons over 12 years.

[2] CAFE is increased uniformly by 2.85 mpg to match central case reductions in adopting states, for example making the year 12 car target 42.5 mpg instead of 39.6 mpg.

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

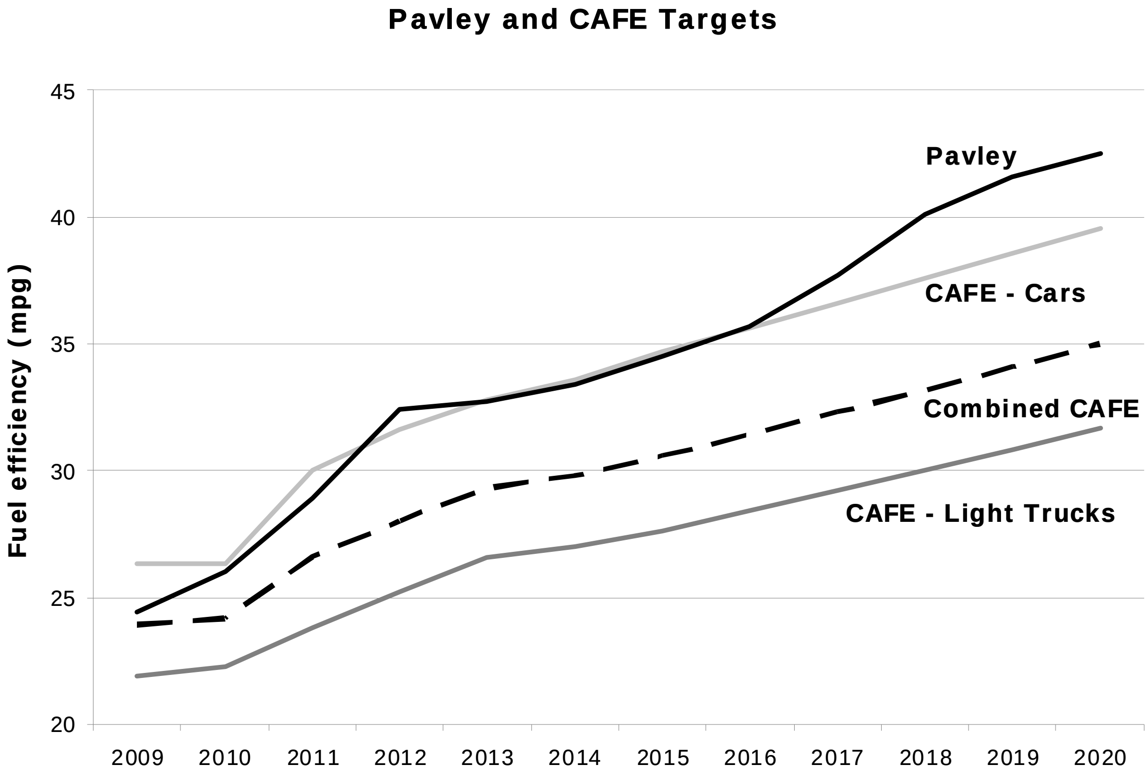
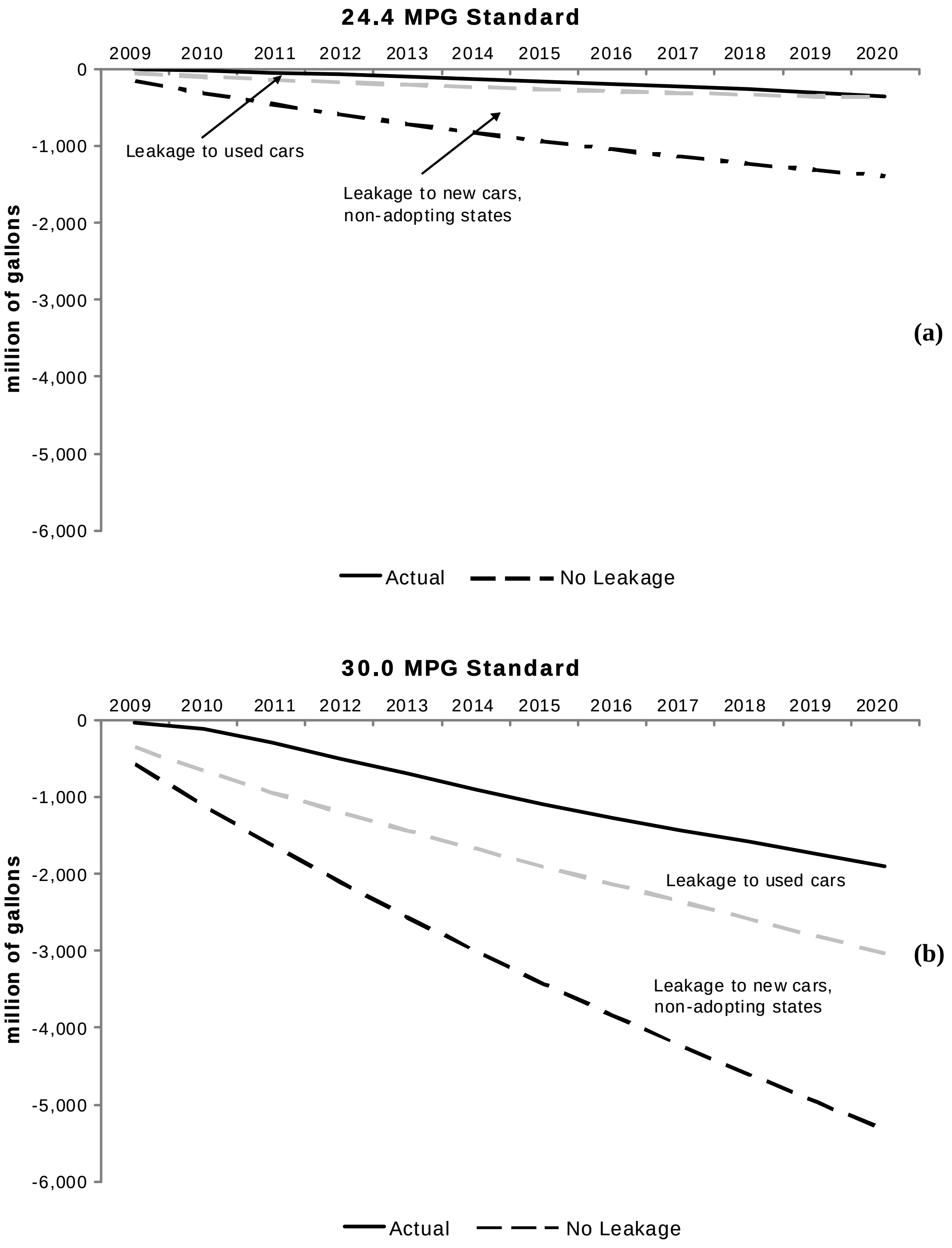


Figure 6.1: Impacts on Gasoline Consumption over Time; (a) 24.4 MPG Pavley Target, Simplified Baseline, (b) 30.0 MPG Pavley Target, Simplified Baseline, (c) Realistic Pavley Target, Realistic Baseline.



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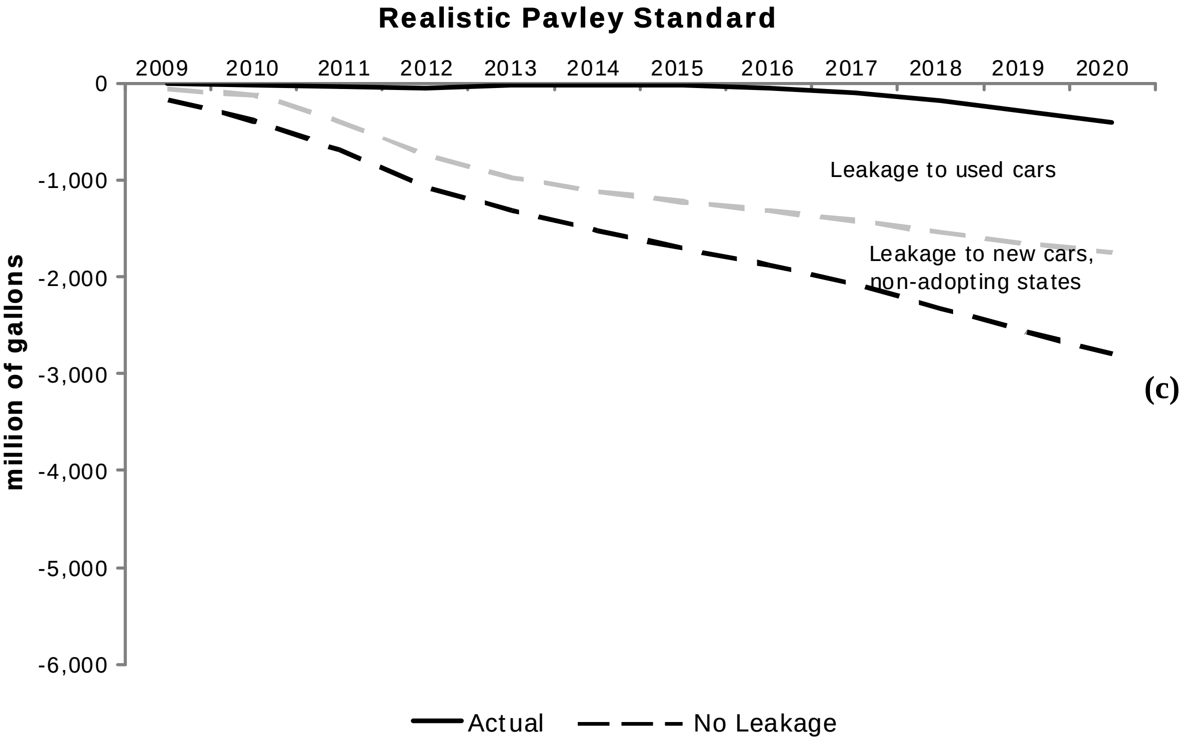


Figure 6.2: Contributions to Leakage Under Different Adopting Region Sizes in Year 1.

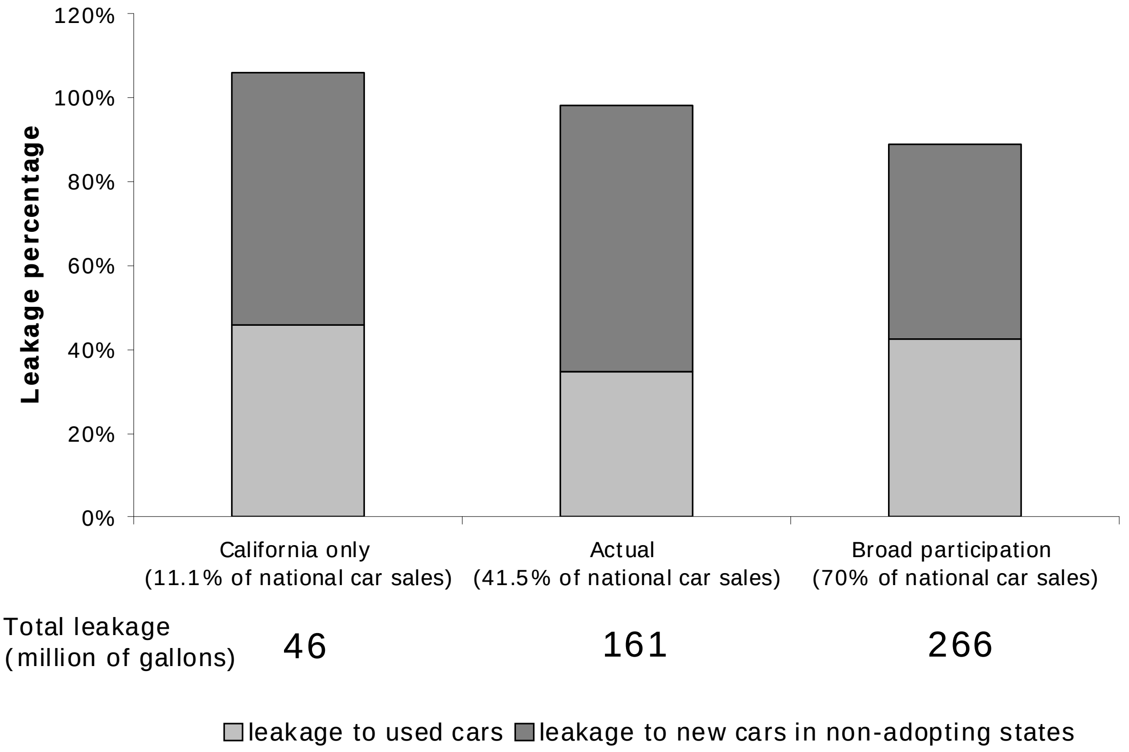
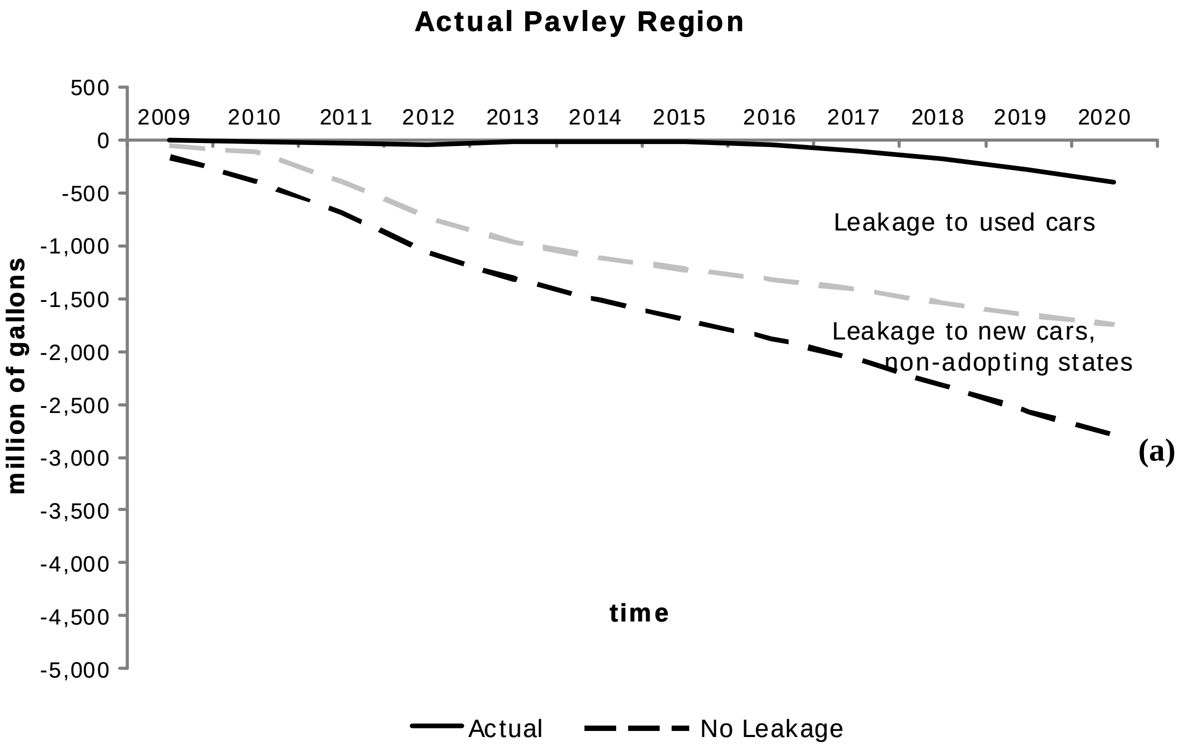


Figure 6.3: Implications of Policy Scope for Gasoline Consumption: (a) Actual Pavley Region (41.5% of National Car Sales) and (b) Broad Participation (70% of National Car Sales).



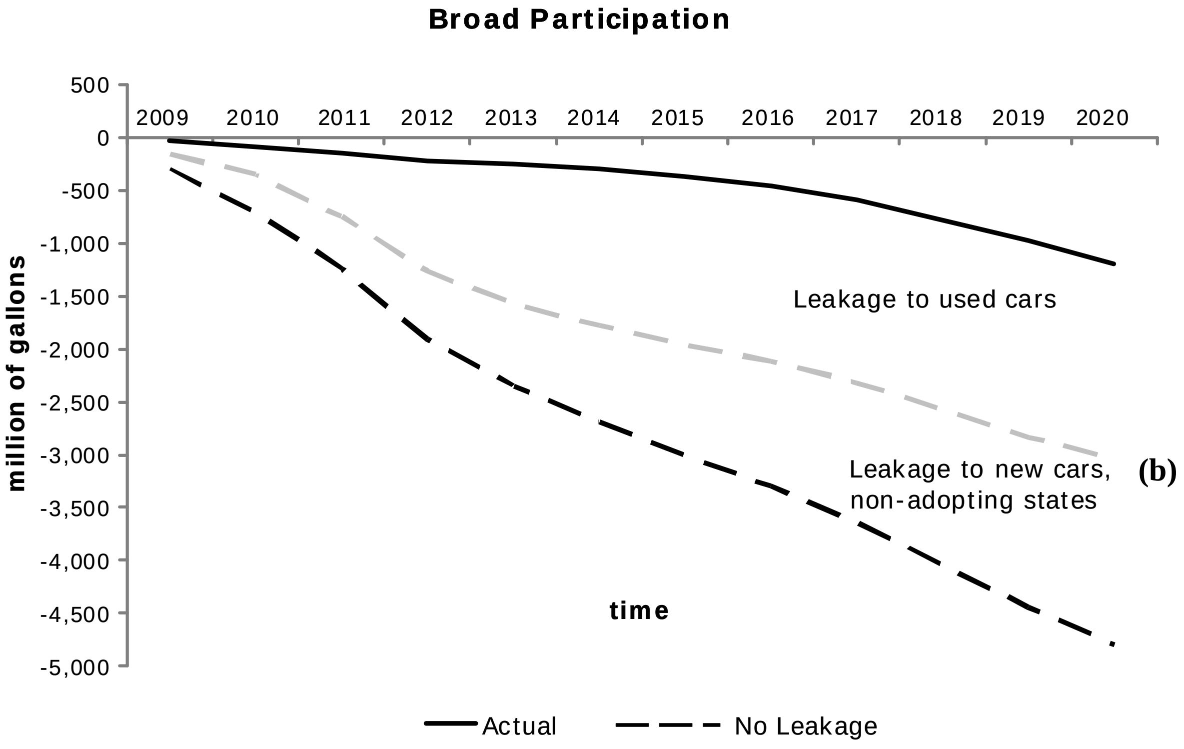
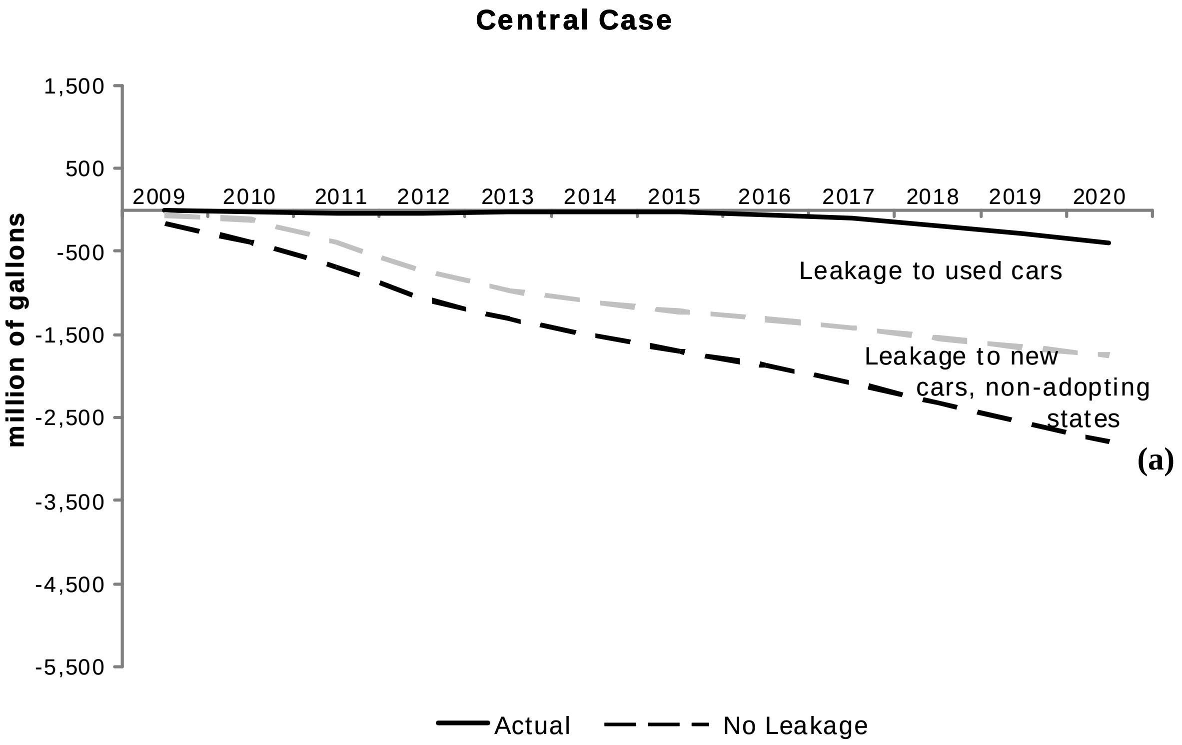
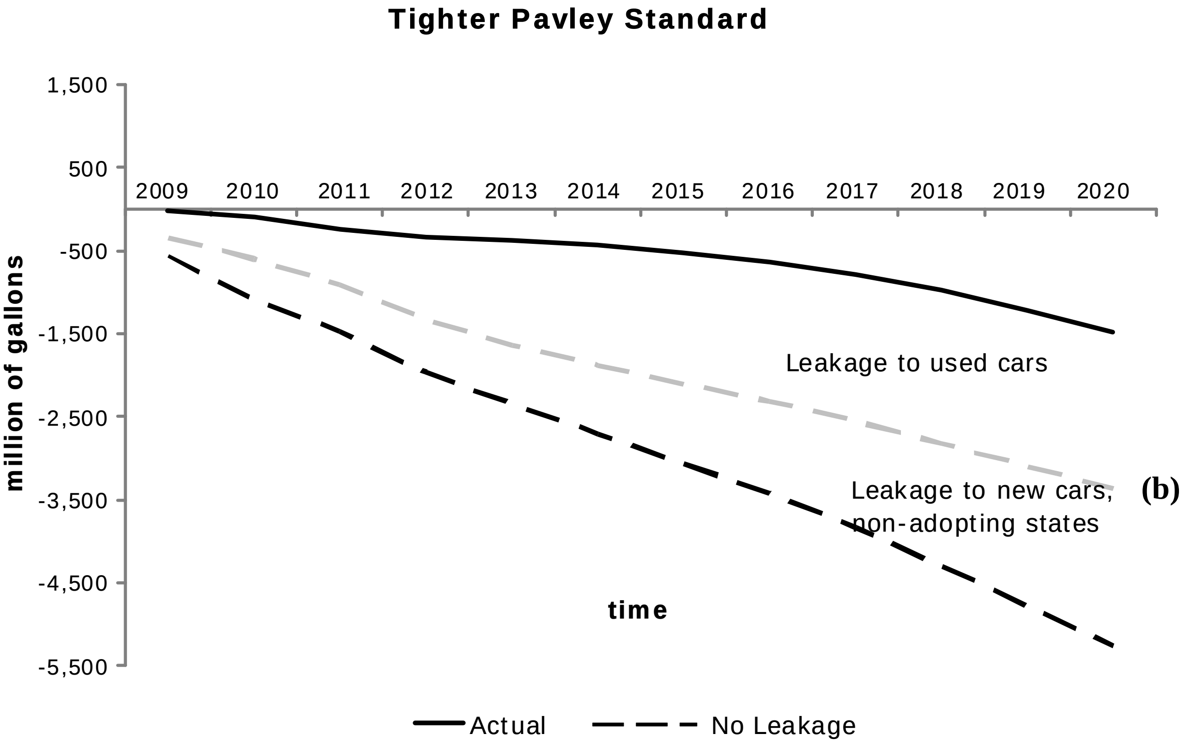


Figure 6.4: Implications of a Tighter Pavley Standard and No Fuel-Economy Differentation: (a) Central Case (Targets Increasing to 42.5 MPG by 2020), (b) Tighter Pavley Standard (Targets Increasing to 50.0 MPG by 2020), (c) No Fuel-Economy Differentiation.





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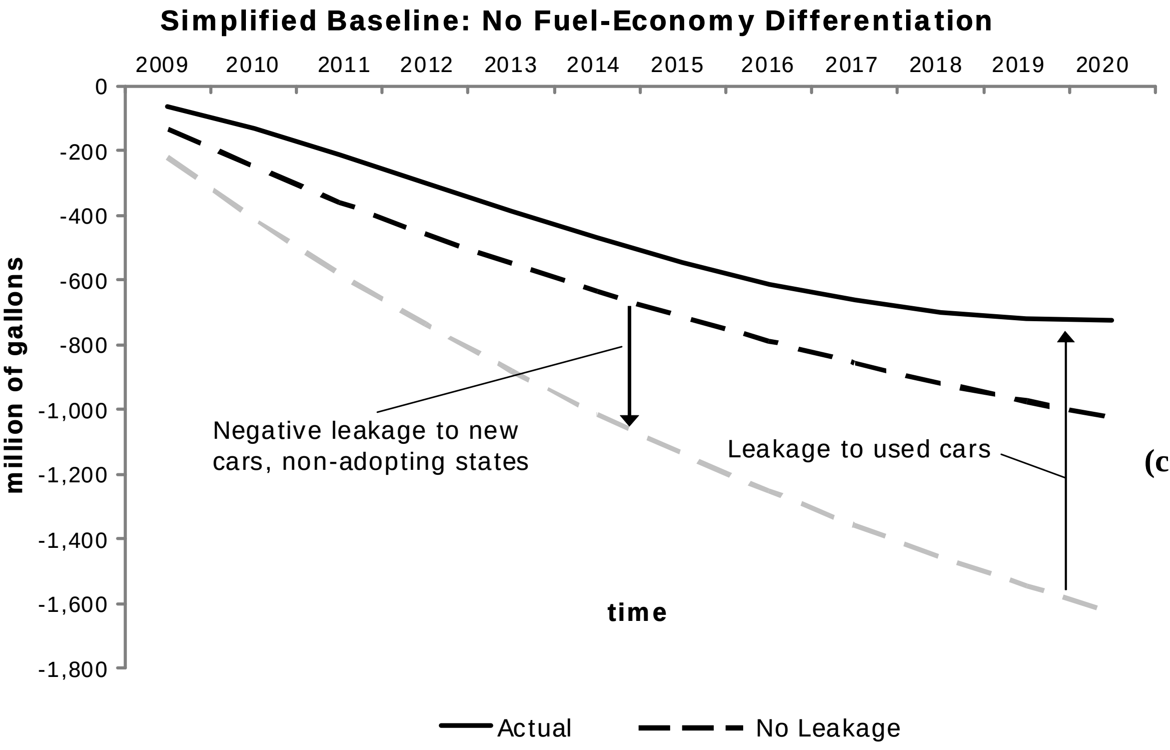

(c)