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Working Paper 15337
<http://www.nber.org/papers/w15337>

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
September 2009

We are grateful for helpful comments from Steven Albu, Soren Anderson, Kenneth Gillingham, Paul Hughes, James Sallee, Eileen Tutt, Catherine Wolfram, and participants at seminars and workshops at Harvard University, MIT, the University of British Columbia, the University of California at Riverside, Stanford University, the Summer Workshop of the Association of Environmental and Resource Economists, and the NBER Summer Institute. We also thank the Precourt Energy Efficiency Center at Stanford University for financial support. The views expressed herein are those of the author(s) and do not necessarily reflect the views of the National Bureau of Economic Research.

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Unintended Consequences from Nested State & Federal Regulations: The Case of the Pavley
Greenhouse-Gas-per-Mile Limits

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NBER Working Paper No. 15337

September 2009

JEL No. H23,H77,Q52,Q58

ABSTRACT

Fourteen U.S. states recently pledged to adopt limits on greenhouse gases (GHGs) per mile of light-duty automobiles. Previous analyses predicted this action would significantly reduce emissions from new cars in these states, but ignored possible offsetting emissions increases from policy-induced adjustments in new car markets in other (non-adopting) states and in the used car market.

Such offsets (or “leakage”) reflect the fact that the state-level effort interacts with the national corporate average fuel economy (CAFE) standard: the state-level initiative effectively loosens the national standard and gives automakers scope to profitably increase sales of high-emissions automobiles in non-adopting states. In addition, although the state-level effort may well spur the invention of fuel- and emissions-saving technologies, interactions with the federal CAFE standard limit the nationwide emissions reductions from such advances. Using a multi-period numerical simulation model, we find that 70-80 percent of the emissions reductions from new cars in adopting states are offset by emissions leakage.

This research examines a particular instance of a general issue of policy significance – namely, problems from “nested” federal and state environmental regulations. Such nesting implies that similar leakage difficulties are likely to arise under several newly proposed state-level initiatives.

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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 has been the recent effort, undertaken by 14 U.S. states, to establish limits on greenhouse gases (GHGs) per mile from light-duty automobiles. These “Pavley” limits (named after California Assemblywoman Fran Pavley, who sponsored the California bill that launched this multi-state effort) required 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 (2008a)).

Since CO₂ emissions and gasoline use are nearly proportional,¹ the Pavley limits effectively raise the fuel economy requirements for manufacturers in the states adopting such limits. The 14 states claimed that the Pavley restrictions would significantly reduce gasoline consumption and GHG emissions. For example, the California Air Resources Board estimated that the limits would account for over 18 percent of the reductions needed to meet the state’s GHG emissions target for 2020.

The analyses offering these projections ignored some very important factors, however. 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. 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!²

A second important factor is the potential for leakage from the new car to the used car market. A more stringent GHG regulation not only leads to substitution of used cars for new cars: to the extent that the regulation raises the prices of new cars relative to used cars, some households will decide to hold on to their used cars longer (scrap rates will decline). This

¹ For a given mix of gasoline and other fuels (e.g., ethanol) in retail motor fuel, the CO₂ released per gallon is largely determined, since fuel combustion by cars is nearly complete. The fuel mix might change over time, but such changes can be regarded as independent of the Pavley initiative.

² To our knowledge, this study is the first to focus on such leakage from nested regulation in the context of automobile emissions or MPG standards. However, recent work by McGuinness and Ellerman (2008) discusses qualitatively the potential for such leakage in connection with interactions between cap-and-trade climate policies at the state and federal levels.

increases the size of the used car market. Since used cars tend to be less fuel efficient than new cars, this also contributes to leakage.

Technological spillovers represent a third potential interaction. Tighter mileage requirements in the adopting states can stimulate advances in technological know-how. In particular, they can hasten the discovery of low-cost fuel-saving options and thereby lead to improved fuel economy not only in adopting states but in other states as well. This would constitute a negative leakage effect that counters the two forms of leakage just described.

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 each of the forms of leakage 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, overall leakage (the net impact of all three types) is very serious. In plausible cases, overall leakage is nearly 80 percent in the short run and remains over 70 percent throughout the period 2009-2020. Most of the leakage reflects the interaction between the Pavley effort and the existing CAFE standard. Substitutions from new to used cars and reduced used vehicle scrap rates also contribute significantly to the leakage. In nearly all scenarios considered, technological spillovers offset only a small fraction of the leakage. The potential emissions-reduction benefits of technological spillovers are nearly fully eliminated because of interactions with the national fuel-economy constraint. Specifically, technological improvements reduce the shadow value of the federal constraint and induce automobile manufacturers to sell even more fuel-inefficient automobiles in the non-adopting states. This phenomenon has been overlooked by analysts that justify regional policies on the basis of potential technological spillovers.

Thus, this paper shows that emissions leakage, traditionally analyzed in the context of producer relocation³ and more recently in the context of incomplete regulation⁴, is also an important consequence from nested state and federal regulation.

³ Leakage from producer relocation occurs when a regulation, by raising costs of production to manufacturers in a given region, causes producers to move to another region. In this case, policy-induced reductions in emissions in the former region will be offset by increases in the latter region stemming from 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.

In May 2009 the Obama administration reached an agreement with the 14 “Pavley states” according to which the U.S. would tighten the federal fuel economy requirements in such a way as to achieve effective reductions in GHGs per mile consistent with the goals of the Pavley initiative. In return, the 14 states agreed to halt the Pavley effort.⁵

By introducing the tighter mileage requirements nationwide, across-state leakage is largely avoided. However, the issues raised by the Pavley effort remain live and indeed may become increasingly important. Several initiatives currently underway raise the same potential issues – problems arising from “nested” state and federal environmental constraints. Currently the California Air Resources Board is seriously considering going beyond the GHG-per-mile limits implied by the promised federal changes by introducing a state-level “feebate” system. This would tax automobile manufactures with average GHGs per mile exceeding some specified level, and use the tax revenues to rebate manufacturers with average GHGs per mile below that level. The policy has the prospect of triggering the same adjustments by manufacturers, and thus the same type of leakage, as the Pavley effort. In addition, similar issues would arise with the nesting of state-level cap-and-trade policies within a federal cap-and-trade system, and with the nesting of states’ renewable fuel standards within the proposed Federal Renewable Fuels Standard.

As state and federal environmental activities expand, the potential for serious leakage associated with nested state and federal regulation grows as well. By focusing on the Pavley initiative, this paper aims to reveal the mechanisms that lead to unintended consequences from nested regulation 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.

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. Bushnell, Peterman, and Wolfram (2008) show that when a state’s emissions regulations do not control the assignments of supplies by out-of-state emitters, substantial leakage can occur through “contract reshuffling.”

⁵ Discontinuing the effort included dropping some related lawsuits. California had been taking legal action to obtain a waiver from the federal government enabling it to exceed federal fuel economy limits. In the state-federal agreement, the Obama administration pledged to grant the waiver, thus rendering moot the legal issue.

II. Limits Imposed by the Pavley and CAFE Regulations

Here we describe the key requirements and their time profiles under the Pavley and federal CAFE rules. In presenting the federal CAFE standards, we project the existing rules forward based on requirements laid out in prior legislation and subsequent rulemaking.⁶ As part of Section VI's policy analysis, we will examine the implications of the tighter CAFE standards implied by the recent pledges of the Obama administration.

A. The 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).⁷ 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.⁸

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. In addition to the increase in stringency, two other significant changes may occur: (1) the limits for individual producers could become dependent on characteristics of their vehicles, as opposed to the current uniform requirements; and (2) 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.⁹ As discussed in Section III below, the

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.

⁷ 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.

⁸ Following the California Air Resources Board, we assume that each constrained manufacturer will continue to exploit a loophole in the CAFE regulation stemming from its treatment of credits for flex-fuel vehicles. When fully exploited this loophole reduces the effective standard for passenger cars to 26.3 MPG.

⁹ If the federal CAFE policy were altered to allow trading of fuel economy credits, producers that are not directly affected by the current CAFE would 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 further 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.

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.¹⁰

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.¹¹ 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.¹²

To facilitate comparisons of the CAFE and Pavley standards, 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.¹³

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

¹⁰ We employ the same conversion factor used in the CARB (2008a) analysis of the Pavley standards: each gallon of gasoline is assumed to release 8887 grams of CO₂ 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 (2008b) analysis and employ a small adjustment for this, and for reduced emissions from CH₄ and N₂O that are expected via tailpipe controls. The adjustment ranges from one to two percent depending on model year.

¹¹ The effective single MPG requirement for cars and trucks under the Pavley rules is the result of a provision allowing a manufacturer to trade across vehicle classes. If a manufacturer’s passenger 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.

¹² 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.

¹³ These comparisons assume no changes in the ratio of passenger cars to trucks.

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) adopting the Pavley rule is central to our analysis. Wider adoption reduces the significance of the non-adopting region and thus mitigates leakage. Fourteen states 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. Illinois and Delaware also planned to adopt the Pavley rules; this would have raised the fraction 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 standards give manufacturers incentives to reduce emissions from new cars in the adopting states. First, they encourage automakers to improve the fuel economy (and lower GHG emissions) of the various models they sell. They can improve fuel economy of a given model either by making “static” substitutions of car features involving known technologies (e.g., substituting smaller engines for larger ones) or through “dynamic” technological progress (which improves the fuel economy associated with a given set of car features). Second, they give automakers incentives 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 promote lower total sales of new cars in these states, thus reducing aggregate emissions from these cars.

B. Impacts on Emissions in Other Markets

But the Pavley effort affects other markets as well: namely, the new car market in non-adopting states, and the used car market. The responses in other markets, and their implications for gasoline consumption and GHG emissions, include the following:

1. Impacts in the New Car Market in Non-Adopting States:

a. 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. 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.

b. Reduced Emissions Reflecting Technological Spillovers

The tighter mileage requirements in the Pavley states give firms incentives to expand research into fuel-saving technologies. This can accelerate the discovery of lower-cost ways to improve fuel economy. Such knowledge is likely to reduce the costs of improving fuel economy, and thus it works toward enhancements in fuel economy in the non-adopting states as well as the adopting states. Such technological spillovers could promote the goals of the Pavley effort and counteract other, adverse forms of leakage.

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

The Pavley standards raise 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 valuable¹⁴; 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 each of these leakage channels. It addresses the two forms of leakage in the new car market – one from interactions between the Pavley rules and the federal CAFE standard, and the other from technological spillovers. It also accounts for leakage from the new car market to the used car market.

C. Factors Controlling the Strength of the Leakage Channels

¹⁴ 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).

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 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 relative emphasis on static (substituting car components) versus dynamic (investing in research) approaches to improving the fuel economy of given models. Only the dynamic approaches yield spillovers to the non-adopting states. Thus, spillovers are enhanced to the extent that automakers emphasize dynamic approaches.

The numerical model applied in this study (and described in sections IV and V) considers this first channel and the factors that control its strength. Specifically, 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 distinguishes between the static and dynamic channels for improving fuel economy of given models, and derives the relative emphasis on these two channels from profit-maximizing behavior.

The force of the second (new car to used car) channel depends on:

- The nature of consumer preferences – including the ease with which consumers can substitute used for new cars in utility.
- 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 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 does 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.¹⁵ 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 static and dynamic fuel-economy improvements and the impact of improved fuel-economy on consumer demand.

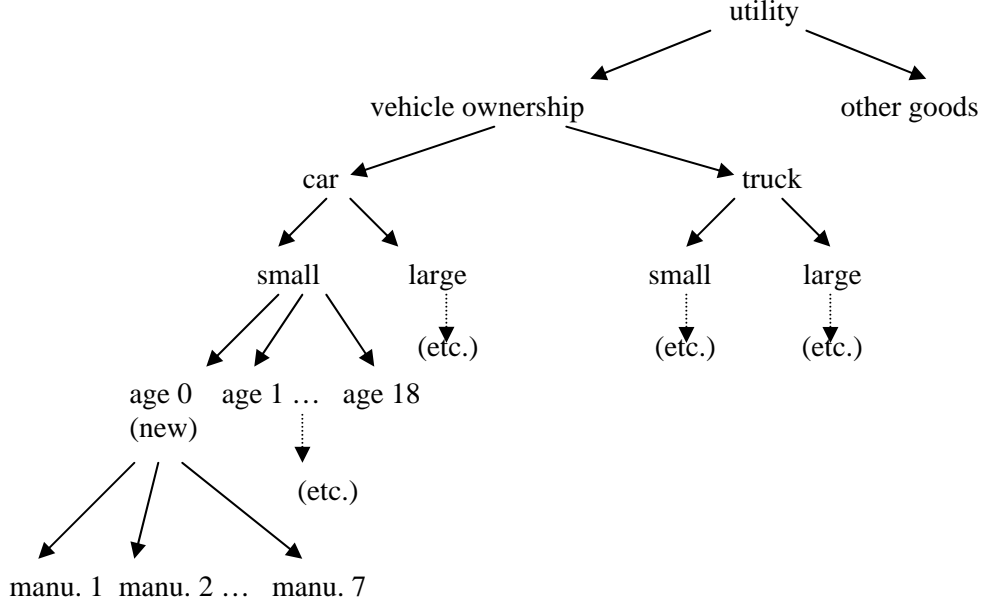
In the used car market, the supply of used cars in a given period consists of the used cars and new cars from the previous period net of scrapping at the end of the previous period. The scrap probability for each vehicle type and vintage is endogenous, depending on the price of the car: it is assumed 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. We model a national used car market, consistent with various state-level regulations allowing the importing of out-of-state vehicles once they have been driven several thousand miles. In a sensitivity analysis we examine the alternative, where the importing of used vehicles is restricted.

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

¹⁵ 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.

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:

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

subject to

$$p_v v + p_x x \leq M \quad (4.2)$$

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.¹⁶

Producers can change the fuel economy of individual models two ways: through technological *substitution* (altering the mix of currently available car components or features such as engine or transmission types) and through technological *change* (discovering new, fuel-saving power processes or components). We refer to these as the “static” and “dynamic” channels for improving fuel economy.¹⁷

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), eight fuel economies $e_{t,s,r}$, and four choices for investment in dynamic technology improvement, $z_{t,s}$.

$$\begin{aligned} \max_{\{p_{t,s,1}, p_{t,s,2}, e_{t,s,1}, e_{t,s,2}, z_{t,s}\}} \sum_{t,s=1,2} [& (p_{t,s,1} - c_{t,s}(e_{t,s,1} - z_{t,s})) \cdot q_{t,s,1}(\mathbf{p}, \mathbf{e}) \\ & + (p_{t,s,2} - c_{t,s}(e_{t,s,2} - z_{t,s})) \cdot q_{t,s,2}(\mathbf{p}, \mathbf{e}) - h_{t,s}(z_{t,s})] \end{aligned} \quad (4.3)$$

subject to the CAFE standards for cars and trucks:

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

¹⁶ The model assumes that producers can separately control the characteristics and prices of new cars sold in the adopting and non-adopting states. This is consistent with current regulations in California barring the import of new and lightly used (less than 7,500 miles) vehicles not certified for the state's pollution standards. To the extent that consumers or producers circumvented these regulations with “gray market” imports, additional leakage would result.

¹⁷ The basic structure of the new and used car supply models is similar to that in Bento *et al.* (2009), although that model involved a much simpler treatment of fuel economy and technological change. The effect of the CAFE constraints on manufacturers with differing baseline production builds on results in Jacobsen (2007).

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

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

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

where $p_{t,s,r}$ and $c_{t,s}$ refer to the purchase price and marginal production cost, respectively, of a particular car. \bar{e}_C and \bar{e}_T refer to the CAFE requirements for cars and trucks; \bar{e}_P refers to the Pavley requirement¹⁸.

For a given car or truck, marginal production cost is a function of both the fuel economy $e_{t,s,r}$ ($r = 1,2$) chosen for that vehicle and $z_{t,s}$, the expenditure on research toward invention of new fuel-saving technologies. By prompting technological change, an increase in $z_{t,s}$ lowers costs; this is captured through the function $h_{t,s}(z_{t,s})$ in equation (4.3).¹⁹ This cost saving is enjoyed in both regions: z and h are not region-specific. Thus, to the extent that new regulations in the Pavley states prompt an increase in $z_{t,s}$, there are spillover benefits in the non-adopting states as well, realized through a reduction in the technological-change-related cost component, $h_{t,s}$.

The cost functions c and $h(z_{t,s})$ are quadratic and calibrated as described in Section V. The lower are the costs in $h(z_{t,s})$ relative to c , the greater is the potential spillover across regions. The only variables not specific to a particular producer m are \mathbf{p} and \mathbf{e} , which denote all prices and fuel economies in the market and determine demand $q_{t,s,r}$ for each model. (For notational simplicity, the subscript identifying the manufacturer (m) has been suppressed.)

Producers are specified as knowing the demand functions of consumers. They can alter vehicle prices and fuel economy but 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 20 and 23 first-order conditions, depending on which constraints bind (8 on prices, 12 for fuel economy, and up to three fuel economy constraints). Section E provides details on the solution method.

¹⁸ Note that while the producer problem is static within each time period, the CAFE and Pavley requirements change through time.

¹⁹ The costs in $h_{t,s}(z_{t,s})$ are paid on an annual basis in keeping with the static nature of the maximization problem.

D. Used Car and Scrap Markets

1. The Used (or “Retained”) Car Market

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:

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

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 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. As part of the sensitivity analysis below, we assume a region-specific used car market.

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

$$p_{t,s,18,m,r} = r_{t,s,18,m,r} \quad (4.8)$$

$$p_{t,s,a,m,r} = r_{t,s,a,m,r} + \frac{(1 - \theta_{t,s,a,m,r})p_{t,s,a+1,m,r}}{1 + \delta}$$

where δ 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. This fraction is inversely related to the resale value of that type of vehicle. We model the relationship as:

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

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)²⁰. 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.²¹ 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

²⁰ 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.

²¹ Usage measured as vehicle miles traveled is assumed constant. Relaxing this assumption in the presence of fuel economy standards is likely to increase leakage via a “rebound” effect. Small and Van Dender (2007) estimate the magnitude of this effect.

and income are then divided into two regions, which in our central case are identical except for size.²² 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 the 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.²³

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. 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.²⁴ 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 0.75.²⁵

²² Fleet composition and average fuel economy are actually quite similar in the two regions (with fuel economy differing by only one tenth of a mile per gallon). We allow for differences in preferences and fleet composition in the sensitivity analysis.

²³ Data available at <http://www.fueleconomy.gov>.

²⁴ 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.

²⁵ The corresponding value used for ρ_u is -0.33.

D. Used Vehicle Scrap Parameters

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 one percent ($\eta = -1$). This reflects the lower (less elastic) range of response to “bounties” for scrapped vehicles described in Alberini *et al.* (1998) and in Hahn (1995). We chose a lower part of the range for our central case to provide a conservative estimate of leakage in the used market. We also consider a value of -3 in a sensitivity analysis, closer to the center of the range of available estimates. 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

$$\theta_a = \frac{1}{19-a} \quad a = 0, 1, \dots, 18 \quad (5.1)$$

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.

E. Fuel Economy Cost Functions

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 function quadratic in fuel economy. We further divide that function into the “dynamic” and “static” components. Dynamic innovations include, for example, improved aerodynamics and certain improvements in engine design. Once “purchased,” these technologies may be applied freely across all vehicles a firm makes in a particular category. Static technologies, in contrast, are represented in our model as movements along a fixed cost curve; they add to marginal cost. Many of these technologies are already available as optional features, and include better tires, oils, and advanced electronic transmissions.²⁶

Because the fraction of technology in the dynamic category is central to our consideration of spillovers we simulate a large range of possibilities, varying it between 10 and 95 percent in sensitivity analysis. For our central case we examine the list of efficiency

²⁶ Although we classify many developments in engine technology as dynamic (to give considerable weight to the potential for spillovers), Klier and Linn (2008) emphasize that in the short and medium run firms may be restricted to a fixed engine platform and thus may face static tradeoffs between horsepower, weight, and fuel-economy.

enhancing technologies in NRC (2002) and categorize each as primarily static, dynamic, or mixed. The categorization is intentionally generous in terms of dynamic technology and spillovers in order to err on the conservative side in our measure of total leakage. Weighted by contribution to fuel savings, we classify the technologies as about 40 percent dynamic for the central case.²⁷ In equation (4.3) this implies that the quadratic parameters of c and h are calibrated such that a cost-minimizing firm achieves an improvement of 1 mile per gallon by setting $z_{t,s}$ to 0.4, with the remaining 0.6 resulting from movement along the cost curve $c_{t,s}(e_{t,s})$. The quadratic cost functions and associated first order conditions used in calibration are included in Part II of the appendix.

The slope of the aggregate cost function, or the optimal combination of the c and h functions, 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 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.²⁸ To model the curvature of the aggregate 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.²⁹

VI. Policy Simulations and Results

Here we first focus on the impacts of the Pavley initiative in the presence of the federal CAFE standard. Subsequently we examine the extent to which adopting Pavley-like regulations at the federal level overcomes leakage problems arising from a sub-national effort.

A. 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

²⁷ *Static*: tires, low friction oil and parts, transmissions. *Mixed (50-50)*: hybrid engines, other engine component improvements. *Dynamic*: aerodynamics, electrical system efficiency, electric power steering. Among NRC's "Path 2" technologies, 37 percent were classified as dynamic. Among "Path 3" technologies, 43 percent were so classified.

²⁸ 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.

²⁹ 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.

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.³⁰ 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 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 CO₂ emissions: 360 and 299 grams of CO₂ 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 gallon³¹. 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 the simplified baseline:

- per-capita income growth of two percent annually
- autonomous improvements in fuel economy at a rate of 1.8 percent per year³²

³⁰ This has been approximately true over the past ten years, as efficiency improvements have generally gone to horsepower and weight rather than fuel economy.

³¹ See Section II for a discussion of the relation between fuel economy and CO₂ per mile in the context of the Pavley requirements.

³² These improvements supplement the endogenous fuel economy improvements chosen by automobile producers.

- 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 rate of autonomous improvements in fuel economy is based on Knittel (2009). 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 two requirements lead to reductions of about 9 and 29 percent in gasoline consumption from 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.

However, as indicated in Table 6.2, the gasoline savings in the adopting states' new car market are offset by increasing gasoline consumption in the non-adopting states. This reflects 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 to meet the national standard. They respond to this relaxation of the CAFE constraint by shifting sales in non-adopting states toward larger cars (which tend to be less fuel efficient) and by introducing fewer static fuel economy improvements in individual models of the new cars sold in these states. The 24.4 and 30.0 MPG requirements also stimulate technological progress to improve fuel economy. This amounts to about three tenths of an MPG in the 30.0 MPG case. Importantly, however, these technological improvements contribute to a further relaxing of the federal CAFE constraint, which causes manufacturers to shift further toward large cars in the non-adopting states.

As indicated in the table, the increase in gasoline consumption for the 24.4 MPG target in the non-adopting states offsets about 71 percent of the reduction associated with new cars in the adopting states. The 30.0 MPG standard is sufficiently tight and creates

enough technological spillovers 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. About 40 percent of the reduction in gasoline consumption from adopting states' new cars is offset in this case.

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.³³ This induces consumers to shift toward used cars. There is also a compositional effect within 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 nine percent of the reduction linked to the adopting states' new cars for the 24.4 MPG target, and 16 percent for the 30.0 MPG target. The larger relative contribution in the latter case squares with the fact that leakage to the non-adopting state new car market is less pronounced.

Together, these adjustments imply leakage of about 80 and 55 percent in the first year under the 24.4 and 30.0 MPG requirements, respectively.

Figures 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.³⁴ 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.

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 figures 6.1(a) and 6.1(b), the absolute amount of leakage increases through time, while the leakage remains fairly constant as a percentage of the reduction in gasoline consumption in the adopting states.

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

³³ After imposing the Pavley restrictions, the price of new cars in the new equilibrium (on average) increases about 1.5 percent relative to used cars.

³⁴ 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.

panel, changes in fleet composition account for slightly more of the overall reduction in consumption than do changes in fuel economy. In the second panel, fuel economy improvements account for a much larger share of the reduction. This reflects the fact that the fleet-composition margin becomes saturated at a less stringent level of the Pavley standard than does the fuel-economy margin.

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

The third panel of Table 6.2 displays the impact of the 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 close to those observed earlier. Increased gasoline consumption from new cars in the non-adopting states contributes the lion's share of the leakage effect. The overall leakage percentage is again about 80 percent.

Figure 6.1(c) displays the results over time. The solid black, dashed black, and dashed gray lines have the same function as in figures 6.1(a) and 6.1(b). In this more realistic simulation, the relative contributions of leakage to the non-adopting state new car market and the used car market are fairly similar to those observed in the simpler cases. This simulation imposes an MPG requirement in year 2020 of 42.5. Total leakage in 2020 is somewhat lower than in the first year, but remains above 70 percent.

Importantly, these high rates of leakage persist despite the presence of technological spillovers. The Pavley standard induces the most additional technological change in compact cars. By 2020, the additional technological change corresponds to an additional 1.2 MPG in these cars (in both regions). However, this improvement in underlying technology reduces pressure on the federal CAFE constraint. Thus it enables firms to sell more large vehicles while still complying with CAFE. We find that in our central case (and even in cases involving more substantial spillovers, as discussed below in our sensitivity analysis) CAFE standards remain binding through 2020, and thus the leakage continues.³⁵

The third panel of Table 6.3 provides a further decomposition, showing the first-year changes in gasoline consumption attributable to changes in fleet composition, improved fuel economy of individual models, and changes in fleet size. The results are very similar to the simpler 24.4 MPG case in the first panel. As indicated by the far-right column, the overall contributions of changes in fuel economy and fleet composition to reductions in consumption are similar in magnitude and somewhat larger than the contribution of reductions in fleet size. Leakage to the non-adopting state new car market derives in large part from reductions in fuel economy (relative to the baseline increases spurred by the increasingly stringent

³⁵ The model assumes that all of the technological advances are devoted to fuel economy improvements. This could bias the results toward an underestimation of leakage. As suggested by Knittel (2009), if some technological change were focused elsewhere – for example, toward increased horsepower – leakage could be greater.

CAFE requirements). Leakage to the used car market comes mainly from lower scrap rates and associated increases in the stock of used cars.

C. Alternative Scenarios

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

1. Increased Technological Change from Research on Fuel-Economy

As discussed earlier, our analysis distinguishes between static and dynamic improvements in fuel economy, corresponding to (a) improvements due to substitution among existing technological options and (b) those arising from the invention of hitherto unknown technologies. The relative importance of these two channels for fuel economy improvements is controlled by the parameter θ_I , which defines the fraction of fuel economy improvement at the margin that stems from new advances in technology. This parameter is defined explicitly in Appendix B. Our central case value of θ_I is 0.4, based on considerations described in Section V.

Figure 6.2 displays leakage for four scenarios that differ according to the value of θ_I . Leakage to new cars declines only slightly as θ_I varies between 10 and 75 percent (panels (a) through (c) in the figure). This result may at first defy one's intuition – but recall from above that in order for leakage to diminish it must be the case that the CAFE standard stops binding.³⁶ Since CAFE is quite stringent in the later years of the simulation, it takes very large technological spillovers to cause this to happen: only when θ_I exceeds 90 percent (far above the plausible range in the engineering studies discussed in section V) does CAFE begin to stop binding for the majority of firms. Leakage to new cars then drops off sharply and, as shown in panel (d) of figure 6.2, it nearly disappears as the fraction exceeds 95 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

³⁶ As discussed in subsection VI.B above, as long as the CAFE standard continues to bind, increased technological spillovers only push the leakage further into the fleet composition and static technology channels.

prices more than cases involving a narrower Pavley effort, since the new car market represented by the non-adopting states is smaller³⁷.

Figure 6.3 displays the cumulative amount and composition of leakage as of year 2020 for four possible sizes of the adopting region: 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. The capacity of other states to absorb large vehicles in the new car market becomes 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 remains significant, ranging between 24 and 39 percent, depending on the elasticity of the scrap vehicle market (described in section IV above). Figures 6.4(a) through (6.4(d)) display the differences 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.

Broader participation reduces leakage significantly and, correspondingly, reduces substantially the costs per gallon saved. The costs per gallon saved range from \$2.99 under the broadest (nationwide) case, to \$9.67 in the narrowest (California only) case.

3. Comparison with Equivalent Increments to the Federal CAFE Standard

Here we consider the impacts of potential increments to the federal CAFE standard as an alternative to the state-level Pavley initiative. The possible changes at the federal level are relevant to current policy initiatives, given the recent pledges of the Obama administration referred to in the introduction. Various potential increments to the federal CAFE standard

³⁷ 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.

(beyond the requirements in the baseline path) are displayed in the bottom three rows of Table 6.4.

The rows labeled “Equivalent to Actual Pavley” and “Equivalent to Pavley with 100 Percent Adoption” present results from experiments in which the CAFE standards are raised enough to achieve the same nationwide gasoline savings as in the 14-state adoption (i.e., actual) and all-state adoption Pavley cases, respectively. Under the “Equivalent to Actual Pavley” policy, the costs per gallon (\$4.52) are considerably lower than under the actual Pavley initiative (\$7.77). The lower costs reflect the federal policy’s avoided cross-state leakage in the new car market. (Leakage still occurs in the used car market, however.)

In contrast, the “Equivalent to Pavley with 100 Percent Adoption” policy (second row from bottom), which was constructed to achieve the same reductions as a national-level Pavley program, is less cost-effective than a national-level Pavley program would be. This is the case for two reasons. First, the Pavley standard is more broadly based, affecting a manufacturer’s car and truck fleets simultaneously, while for some manufacturers the CAFE standard could bind for just one. Thus, the Pavley standard engages more channels for achieving the overall target for improved fuel economy. Second, the Pavley standard rewards a manufacturer for achieving improved fuel-economy by switching from an average truck to an average car; the CAFE standard does not.

The last row of Table 6.4 shows results from a simulation in the miles-per-gallon requirements of the federal CAFE standard are incremented by the same amount as is implied by the Pavley regulations.³⁸ This adjustment to CAFE yields considerably larger reductions in gasoline consumption and emissions than the actual Pavley initiative: the policy would reduce cumulative consumption of gasoline by 9.8 billion gallons, compared with 4.0 billion gallons under Pavley. However, the cost per avoided gallon is lower, reflecting the reduced leakage under a nationwide policy.

D. Further Sensitivity Analysis

Table 6.5 lists results from further sensitivity analysis. It reports cumulative gasoline savings by 2020 for new and used cars, as well as total leakage in the year 2020. These numbers can be compared with leakage in 2020 indicated by 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 52.7 percent, and increases gasoline savings to 4,943 million gallons in the adopting region. Leakage is reduced because the more stringent Pavley standard causes CAFE to stop binding sooner and for more firms.

³⁸ We increment the car and truck MPG requirements by the same amounts, so as to yield the same average MPG increment as that implied by Pavley. This change (represented in the last row of the table) is consistent with the new federal targets identified in President Obama’s May 2009 remarks. However, there appears to be a reasonable chance that the new CAFE standards will eventually include trading among fleets. In this event the federal program would be most similar to the case considered in line 4 of the table.

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. Two main competing effects underlie the results from this experiment. The first is that when the used car market split, the adopting region can no longer import large used cars from the non-adopting region. This tends to reduce leakage. The second and opposing 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 almost exactly offset each other; the second effect seems to dominate by a small margin.

Lower autonomous fuel economy improvements: Instead of a 1.8 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 or changes in gasoline consumption.

Lower cost of fuel-economy improvements: Here we reduce by 25 percent the curvature parameter of the fuel-economy-improvement cost function. 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 static technology margin and decreases on the vehicle mix margin, with little overall impact on leakage and gasoline consumption.

Higher scrap elasticity: Here the scrap elasticity η in (4.9) is set to -3 instead of -1. This increases the tendency of consumers to hold their used cars longer in response to the Pavley initiative. Hence there is more leakage to the used car market in both the scale and composition dimensions. Overall leakage is 75.2 percent, as compared with 70.1 percent in the central case.

Lower 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 65.7 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.

CAFE initially just binding: Here we consider a case where, in the first year of the baseline, the shadow value of the CAFE constraint is exactly zero³⁹. In this case, firms would have no incentive to reduce fuel economy if the standard were removed. This scenario involves less leakage because the CAFE constraint does not bind in the first year that the Pavley limits are imposed. However, there remains considerable leakage after the first few years. The reason is that CAFE ramps up considerably over time: this constraint begins to bind by year two and very strongly by 2020. Because the CAFE constraint binds through most of the simulation interval, there is considerable leakage to the new car market in the non-adopting states. Cumulative leakage over the whole simulation period is 68.9 percent, only slightly lower than leakage in the central case (70.1 percent).

Heterogeneous demand: In a final sensitivity case we calibrate demand to approximate baseline differences in the composition of the automobile fleets between the two regions. Lower overall demand for new vehicles in the non-adopting region reduces the scope for leakage, slightly lowering the overall measure (to 66.3 percent).

VII. Conclusions

This paper reveals some significant unintended consequences from the Pavley initiative to limit GHGs per mile from new cars sold in 14 U.S. states – substantial offsetting impacts (or leakage) in the states that do not impose the Pavley limits. Much of this leakage derives from interactions between the Pavley limits and the federal CAFE standard. We estimate that over the period 2009-2020, adjustments in new car markets in non-adopting states would offset about 65 percent of the reduction in emissions or gasoline consumption from new cars in the adopting states.

We also estimate leakage occurring through changes in the used car market. This stems 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 five percent of the central case reductions from new cars in the adopting states. Under nationwide adoption of the Pavley standard, leakage to the used car market offsets 24 to 39 percent of the reductions from new cars in the adopting states.

The Pavley initiative stimulates additional investments in research toward new, fuel-saving technologies. The resulting discoveries produce beneficial spillovers, as they lend toward improvements in fuel economy not only in the adopting states but in other states as well. However, interactions with the federal CAFE standard neutralize most of the emissions benefits from technology spillovers. So long as the CAFE constraint continues to bind, auto

³⁹ We use a value of zero to demonstrate the robustness of our result at the lower bound. Anderson and Sallee (2009) apply the observable marginal cost of using a loophole in CAFE standards for flex-fuel vehicles (see footnote 8) to estimate the shadow costs of the CAFE standard. Their central estimate is \$8 - \$18 per mile per gallon, much lower than that used in our central case and suggesting that CAFE standards may bind to only a small degree.

manufacturers have incentives to offset the fuel-economy improvements attributable to new knowledge by making fewer fuel-saving changes to car components and by promoting offsetting changes in fleet composition. Only at extreme values for the relative contribution of technological progress (where the portion that can spill over is set larger than 95 percent) does the CAFE standard cease to bind; only in this case do technological spillovers yield significant reductions in nationwide gasoline consumption or GHG emissions. Many advocates of the Pavley initiative have invoked beneficial technological spillovers as a way of justifying such efforts. This analysis indicates that the benefits from such spillovers are quite limited in the presence of a federal constraint.

The recent agreement between the 14 “Pavley states” and the Obama administration – to replace the Pavley initiative with increments to the federal CAFE standard that achieve comparable reductions in GHGs – largely eliminates the across-state leakage problem for the new car market (though leakage to the used car market remains). Thus, one case of nested state-federal regulation has been avoided. However, several other initiatives currently underway raise the same potential issues. The same issues arise with the potential implementation in California of a “feebate” program to tax or reward automobile manufacturers depending on whether the cars they sell in the state exceed or fall short of prescribed limits on GHGs per mile. They also 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 all 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.

This paper has revealed some important disadvantages of state regulations nested within federal constraints. Are such state-level efforts misguided? Proponents of such efforts argue that they make sense, despite the potential for serious leakage, on the grounds that they serve as a test-bed for innovative environmental policies and that, by providing useful information, they hasten the arrival of (more cost-effective) federal legislation. Thus, many of the initial supporters of the Pavley effort insist that it was a wise policy move even while acknowledging the leakage problem. On the other hand, critics maintain that the Pavley effort and other state-level initiatives are costly measures that yield little environmental benefit and distract attention from appropriate action at the federal level. In coming years we may well witness ever more frequent debates along these lines as the phenomenon of nested state and federal environmental regulation becomes increasingly prevalent.

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Appendix

I. 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:

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

subject to

$$p_v v + p_x x \leq M \quad (\text{A.2})$$

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

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

Define the composite overall (or “ideal”) price index as

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

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

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

$$\begin{aligned}
&= \left(\frac{\alpha_v}{p_v} \right)^{\frac{1}{1-\rho_u}} \left(\alpha_v^{\frac{1}{1-\rho_u}} p_v^{\frac{\rho_u}{\rho_u-1}} + \alpha_x^{\frac{1}{1-\rho_u}} p_x^{\frac{\rho_u}{\rho_u-1}} \right)^{\frac{1}{\rho_u}} \\
&= \left(\frac{\alpha_v p^*}{p_v} \right)^{\frac{1}{1-\rho_u}}
\end{aligned} \tag{A.5}$$

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):

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

where

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

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 ⁴⁰.
- Step 1: determine $v_{t,s,a}$ given $p_{t,s,a}$ and using the relationship

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

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

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

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

⁴⁰ 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 $p_{t,s,a} = 1$.

II. Fuel Economy Cost Functions

The functional forms used for static costs, $c_{t,s}$, and dynamic costs, $h_{t,s}$, are:

$$c_{t,s}(e_{t,s,r} - z_{t,s}) = k_{t,s} + a_{t,s} \cdot (e_{t,s,r} - z_{t,s} - \tilde{e}_{t,s}) + b_{t,s} \cdot (e_{t,s,r} - z_{t,s} - \tilde{e}_{t,s})^2 \quad (\text{A.13})$$

$$h_{t,s}(z_{t,s}) = a_{t,s}^z \cdot z_{t,s} + b_{t,s}^z \cdot (z_{t,s})^2 \quad (\text{A.14})$$

where $\tilde{e}_{t,s}$ is baseline fuel economy and $k_{t,s}$ is baseline marginal cost. $z_{t,s}$ is normalized to zero in the baseline, which leaves four parameters ($a_{t,s}$, $b_{t,s}$, $a_{t,s}^z$, and $b_{t,s}^z$) to be calibrated.

Solving the first order condition of the unit cost minimization problem for $z_{t,s}$ yields:

$$z_{t,s} = \frac{a_{t,s}q_{t,s} - a_{t,s}^z + 2b_{t,s} \cdot (e_{t,s,r} - \tilde{e}_{t,s}) \cdot q_{t,s}}{2(b_{t,s}^z + b_{t,s}q_{t,s})} \quad (\text{A.15})$$

The definition of $\tilde{e}_{t,s}$ implies $e_{t,s,r} - \tilde{e}_{t,s} = z_{t,s} = 0$ in the baseline, so for a marginal change in fuel economy we have:

$$a_{t,s}^z = a_{t,s} \cdot q_{t,s} \quad (\text{A.16})$$

This reduces the system to three parameters and three data points, which can be solved simultaneously. The three pieces of data used are:

$$\text{Dynamic fraction of fuel economy improvement} = \frac{z_{t,s}}{e_{t,s,r} - \tilde{e}_{t,s}} \equiv \theta_1 \quad (\text{A.17})$$

$$\text{First derivative of the aggregate cost function} = \frac{a_{t,s}^z b_{t,s} + a_{t,s} b_{t,s}^z}{b_{t,s}^z + b_{t,s}q_{t,s}} \equiv \theta_2 \quad (\text{A.18})$$

$$\text{Second derivative of the aggregate cost function} = 2 \frac{b_{t,s} b_{t,s}^z}{b_{t,s}^z + b_{t,s}q_{t,s}} \equiv \theta_3 \quad (\text{A.19})$$

Where the expressions for θ_2 and θ_3 can be derived by substituting (A.15) into aggregate costs (defined as $c_{t,s}(e_{t,s,r} - z_{t,s}) + h_{t,s}(z_{t,s}) / q_{t,s}$) and differentiating. The data sources are described in more detail in the main text, but briefly the central case value of θ_1 is 0.40, θ_2 is calculated directly from the first order conditions of (4.3) in the text, and θ_3 is the curvature of quadratic functions fit to the NRC (2002) data.

Substituting (A.16) into (A.15) and dividing gives the following expression for θ_1 at the margin:

$$\theta_1 = \frac{b_{t,s} q_{t,s}}{b_{t,s}^z + b_{t,s} q_{t,s}} \quad (\text{A.20})$$

The first order parameters are available directly by substituting (A.16) into (A.18):

$$\begin{aligned} a_{t,s} &= \theta_2 \\ a_{t,s}^z &= q_{t,s} \theta_2 \end{aligned} \quad (\text{A.21})$$

The solution to (A.19) and (A.20) provides expressions for the remaining two parameters in terms of the data:

$$\begin{aligned} b_{t,s} &= \frac{\theta_3}{2(1 - \theta_1)} \\ b_{t,s}^z &= q_{t,s} \frac{\theta_3}{2\theta_1} \end{aligned} \quad (\text{A.22})$$

Table 4.1: Vehicle Categories.

<i>Manufacturer</i>	<i>Age</i>	<i>Size</i>	<i>Type</i>	<i>Region</i>
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.

<i>Parameter</i>	<i>Value</i>	<i>Source</i>
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.

<i>Age</i>	<i>Fraction of Total Fleet</i>	<i>Scrap Rate (End of Year)</i>
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.

		<i>Year 1, Realistic Baseline Every Year, Simplified Baseline</i>		<i>Year 12, Realistic Baseline</i>	
	<i>Class</i>	<i>Fleet Composition (%)</i>	<i>Fuel Economy (mpg)</i>	<i>Fleet Composition (%)</i>	<i>Fuel Economy (mpg)</i>
<i>Ford</i>	Small car	2.7	28.7	2.8	44.2
	Large car	3.3	23.3	3.1	34.8
	Small truck/SUV	2.8	24.4	3.1	36.3
	Large truck/SUV	8.2	17.6	7.9	26.5
	avg.		20.8		31.5
<i>Chrysler</i>	Small car	1.8	25.5	1.8	40.4
	Large car	2.5	24.4	2.3	36.6
	Small truck/SUV	4.9	21.5	5.1	32.0
	Large truck/SUV	4.4	17.7	4.3	26.6
	avg.		20.9		31.6
<i>General Motors</i>	Small car	5.2	28.9	5.6	44.7
	Large car	9.0	25.7	7.9	37.4
	Small truck/SUV	4.3	22.3	4.6	33.3
	Large truck/SUV	7.1	18.0	6.9	27.0
	avg.		22.9		34.2
<i>Honda</i>	Small car	4.7	33.0	4.8	41.0
	Large car	0.6	25.0	0.6	30.9
	Small truck/SUV	2.3	23.8	2.3	32.4
	Large truck/SUV	1.8	22.7	1.8	30.8
	avg.		27.5		35.7
<i>Toyota</i>	Small car	7.4	33.4	7.6	41.2
	Large car	1.3	26.2	1.3	32.3
	Small truck/SUV	5.1	25.6	5.2	33.9
	Large truck/SUV	1.2	18.1	1.1	24.6
	avg.		28.0		35.9
<i>Other Asian</i>	Small car	8.3	28.8	8.4	41.0
	Large car	1.4	23.2	1.4	32.5
	Small truck/SUV	3.4	22.3	3.5	33.2
	Large truck/SUV	2.1	19.6	2.0	29.5
	avg.		25.0		36.3
<i>European</i>	Small car	2.2	32.5	2.2	44.1
	Large car	1.5	25.4	1.5	34.3
	Small truck/SUV	0.2	20.6	0.2	34.8
	Large truck/SUV	0.6	17.9	0.6	30.8
	avg.		26.6		38.0

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

	New Cars		Used Cars	Total
	<i>Adopting States</i>	<i>Other States</i>		
<i>Simplified Baseline</i>	1,490	2,235	33,526	37,251
<i>Constant 24.4 MPG Standard, Simplified Baseline</i>				
Change	-127.0 -8.52%	90.4 4.04%	10.9 0.03%	-25.7 -0.07%
Leakage		71.17%	8.61%	79.78%
<i>Constant 30.0 MPG Standard, Simplified Baseline</i>				
Change	-433.0 -29.06%	172.4 7.71%	67.7 0.20%	-192.9 -0.52%
Leakage		39.82%	15.64%	55.46%
<i>Realistic Baseline</i>	1,484	2,227	33,526	37,237
<i>Realistic Pavley MPG Standards, Realistic Baseline</i>				
Change	-126.9 -8.55%	90.5 4.07%	10.9 0.03%	-25.5 -0.07%
Leakage		71.31%	8.60%	79.91%
<i>Note: Gasoline consumption in millions of gallons.</i>				

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

	<i>New Cars</i>		<i>Used Cars</i>	<i>Total</i>
	<i>Adopting States</i>	<i>Other States</i>		
<i>Constant 24.4 MPG Standard, Simplified Baseline</i>				
Overall gasoline use change	-127.0	90.4	10.9	-25.7
Change due to:				
change in fleet composition	-13.5	1.8	0.5	-11.2
change in individual models' fuel economy	-86.0	76.5	0.0	-9.4
change in total fleet size	-27.4	12.0	10.4	-5.0
<i>Constant 30.0 MPG Standard, Simplified Baseline</i>				
Overall gasoline use change	-433.0	172.4	67.7	-192.9
Change due to:				
change in fleet composition	-41.2	-1.2	1.9	-40.5
change in individual models' fuel economy	-260.3	140.6	0.0	-119.7
change in total fleet size	-131.5	33.0	65.8	-32.7
<i>Realistic Pavley MPG Standards, Realistic Baseline</i>				
Overall gasoline use change	-126.9	90.5	10.9	-25.5
Change due to:				
change in fleet composition	-13.7	1.9	0.5	-11.3
change in individual models' fuel economy	-85.9	76.7	0.0	-9.2
change in total fleet size	-27.3	12.0	10.4	-5.0
<i>Note: Gasoline consumption in millions of gallons.</i>				

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

	Adopting States	Cost Other States	Total	Gallons Saved			Cost per Gallon Saved (All States)
	Adopting States	Other States	Total	Adopting States	Other States	Total	
Pavley Regulation:							
Percent of National Market:							
11.1 Percent (California Only)	4.8	3.4	8.2	-2.6	1.8	-0.8	9.67
41.5 Percent (Actual Pavley)	27.8	3.5	31.3	-9.6	5.5	-4.0	7.77
70 Percent	61.5	-4.9	56.6	-17.4	5.8	-11.7	4.86
100 Percent	81.9		81.9	-27.4		-27.4	2.99
Equivalent Federal CAFE Standard:							
Equivalent to Actual Pavley ^b	7.2	10.8	18.1	-1.6	-2.4	-4.0	4.52
Equivalent to Pavley with 100 Percent Adoption ^b	56.8	85.3	142.1	-11.0	-16.5	-27.4	5.18
CAFE Increments = Pavley Increments	47.1	70.6	117.6	-7.9	-11.9	-19.8	5.95

^aCosts in billions of discounted dollars; gallons in billions of gallons saved over the period 2009-2020.

^bThe equivalent CAFE standard increases in proportion to the increases in the Pavley standard.

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

	Accumulated Gasoline Savings by 2020				Cumulative Leakage in 2020
	New Cars		Used Cars	Total	
	Adopting States	Other States			
Central Case	-2,577	1,671	136	-770	70.1%
More Stringent Pavley Standard	-4,943	2,311	294	-2,338	52.7%
Separate Used Car Markets	-2,379	1,491	272	-616	74.1%
Lower Autonomous Fuel-Economy Improvement	-2,574	1,726	152	-695	73.0%
Lower Cost of Fuel-Economy Improvements	-2,566	1,641	168	-756	70.5%
Higher Scrap Elasticity	-2,704	1,676	358	-670	75.2%
Lower Elasticity of Substitution Between Vintages	-2,232	1,561	-94	-766	65.7%
Higher Gasoline Price	-2,311	1,371	138	-802	65.3%
CAFE Initially Just Binding	-2,451	1,592	98	-762	68.9%

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

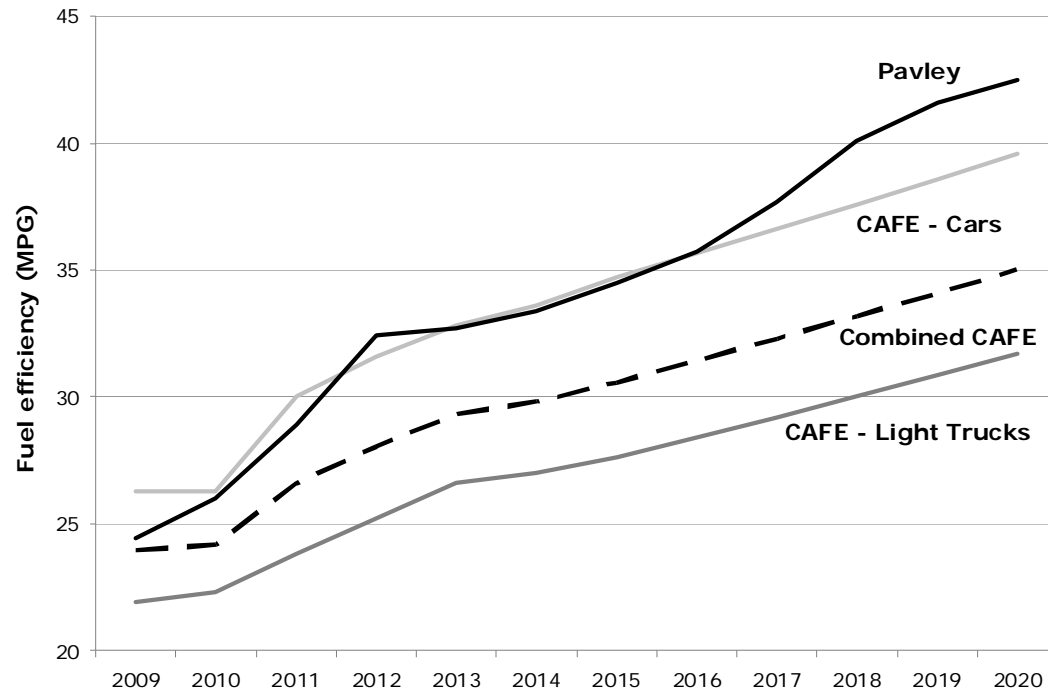


Figure 6.1: Impacts on Gasoline Consumption over Time: (a) 24.4 MPG Pavley Target, Simplified Baseline, (b) 30.0 MPG Pavley Target, Simplified Baseline, (c) Realistic Pavley Target, Realistic Baseline.

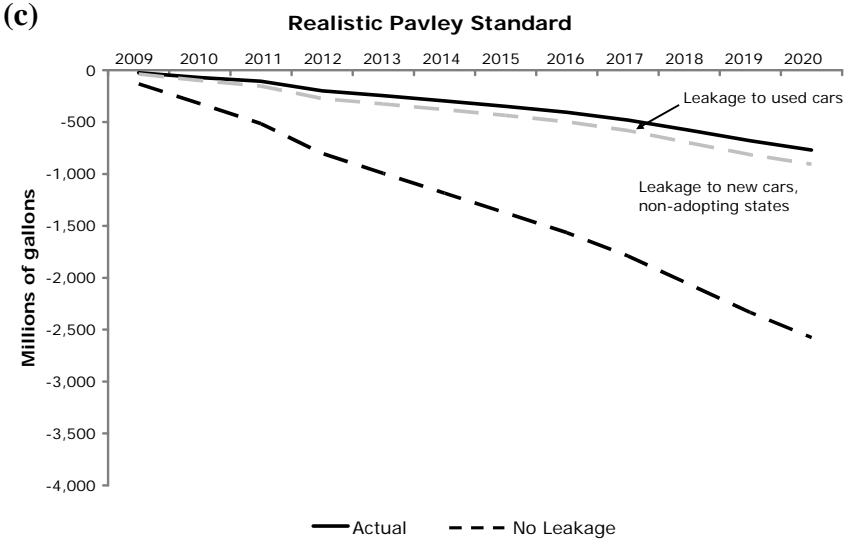
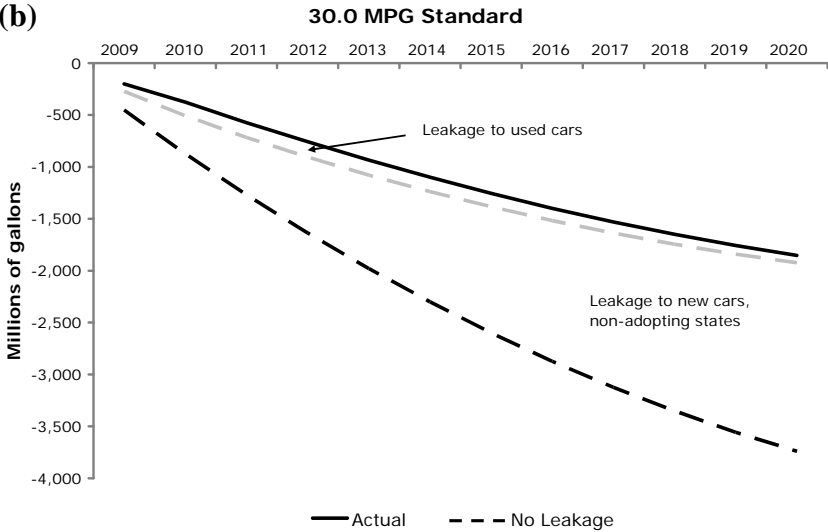
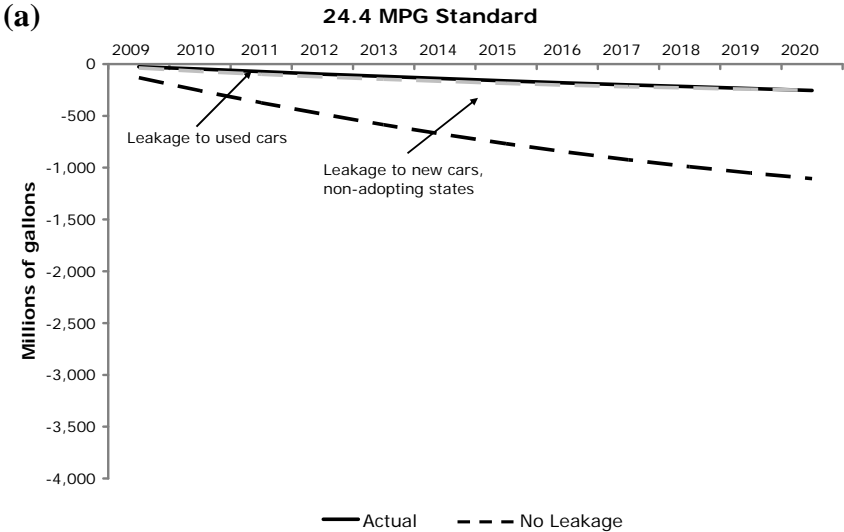


Figure 6.2: Implications of Alternative Technology Spillover Assumptions: (a) $\theta_I = 0.1$, (b) $\theta_I = 0.4$ (Central Case), (c) $\theta_I = 0.75$, (d) $\theta_I = 0.95$.

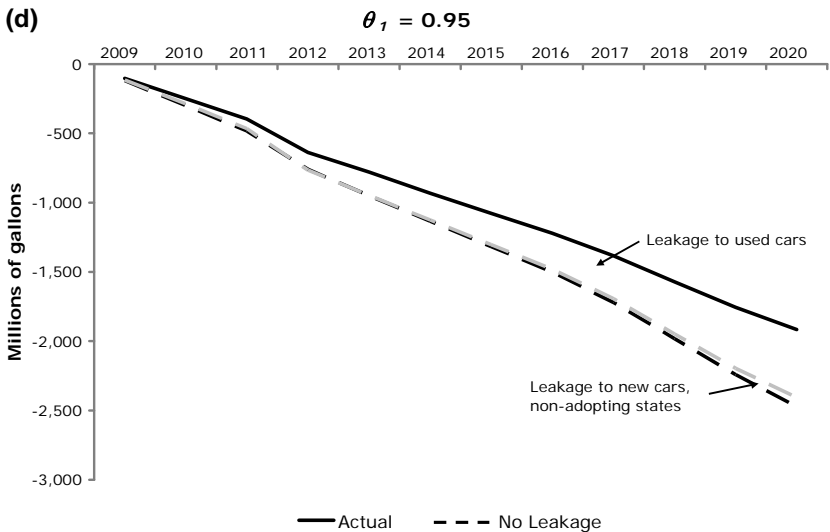
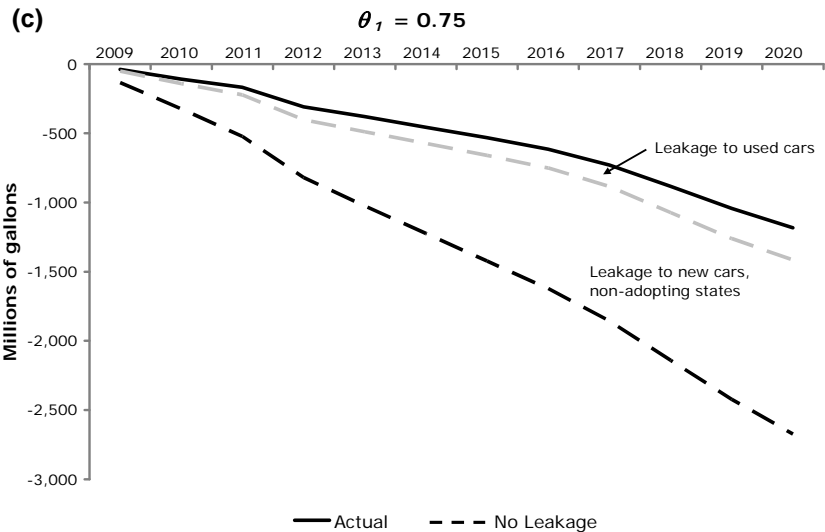
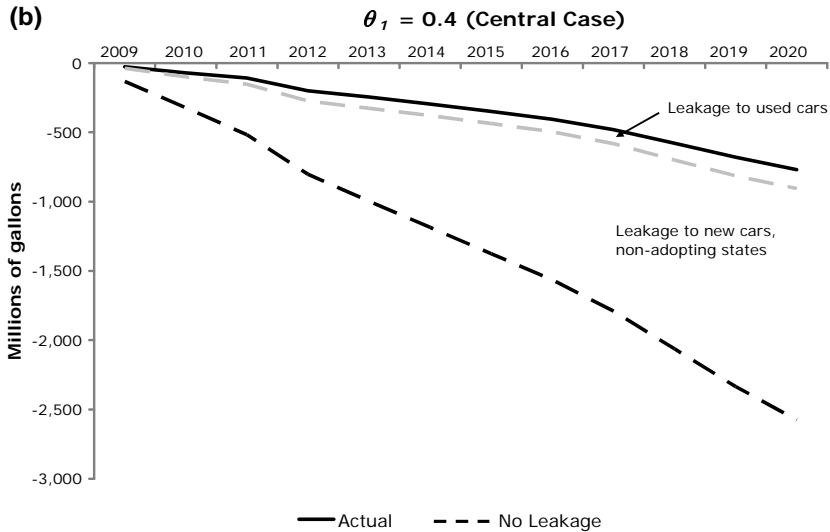
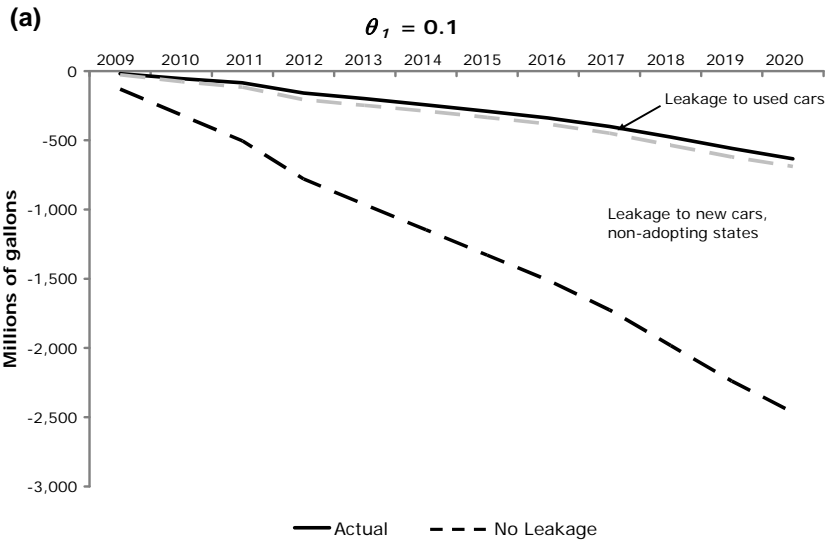


Figure 6.3: Cumulative Contributions to Leakage under Different Adopting Region Sizes.

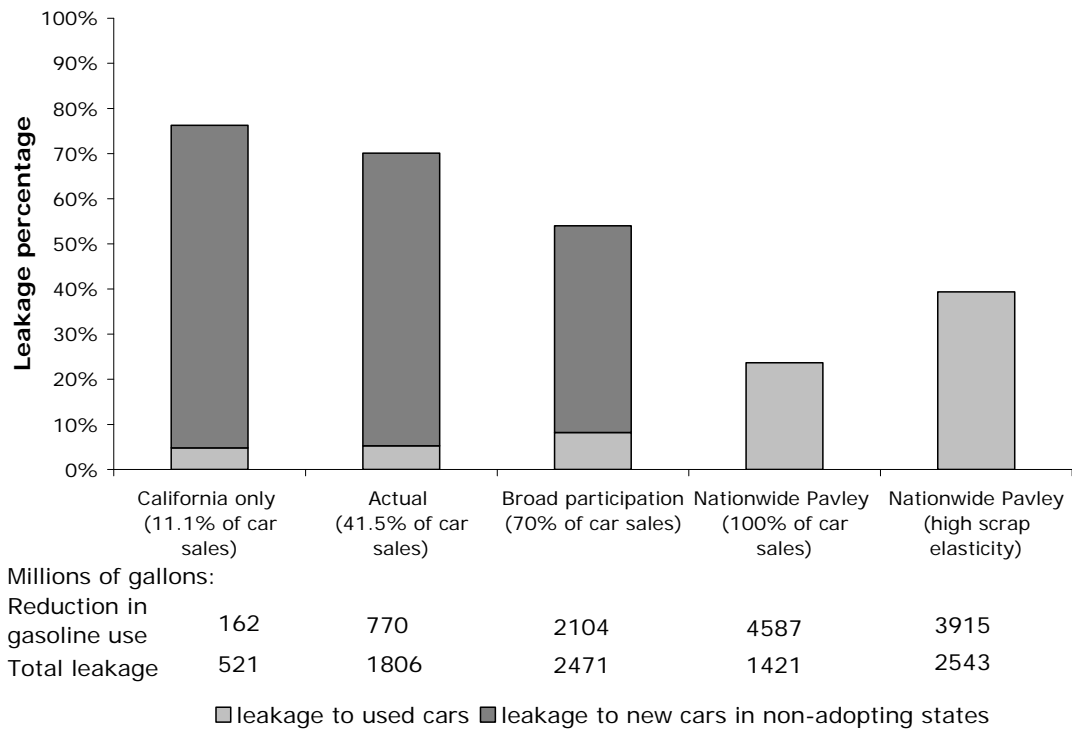


Figure 6.4: Implications of Policy Scope for Gasoline Consumption: (a) 11.1% of National Car Sales (California Only), (b) 41.5% of National Car Sales (Actual Pavley Case), (c) 70% of National Car Sales, (d) 100% of National Car Sales.

