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Unintended consequences from nested state and federal regulations: The case of the Pavley greenhouse-gas-per-mile limits[☆]

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ABSTRACT

This paper reveals significant unintended consequences from recent 14-state efforts to reduce greenhouse gas emissions through limits on greenhouse gases per mile from new cars. We show that while such efforts significantly reduce emissions from new cars sold in the adopting states, they cause substantial emissions increases from new cars sold in other (non-adopting) states and from used cars. The costs per avoided ton of emissions are approximately twice as high once such offsets are recognized.

Such offsets (or “leakage”) reflect interactions between the state-level initiatives and the federal fuel-economy standard: the state-level efforts effectively loosen the national standard, giving automakers scope to profitably increase sales of high-emissions automobiles in non-adopting states. Although the state-level efforts spur invention of fuel- and emissions-saving technologies, interactions with the federal standard limit the nationwide emissions reductions from such advances.

Our multi-period simulation model estimates that a recent state-federal agreement avoids what would have been 74% leakage in the first phase of the state-level effort, and that potential for 65% leakage remains for the second phase.

This research confronts a general issue of policy significance—namely, problems from “nested” state and federal environmental regulations. Similar leakage difficulties would arise under several newly proposed state-level initiatives.

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1. Introduction

In response to the prospect of climate change, many U.S. states have proposed policies to reduce greenhouse gas emissions from the transport sector. Especially noteworthy are a series of initiatives, 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) require manufacturers to reduce

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per-mile GHG emissions starting in 2009. The first (Pavley I) phase of this effort requires manufacturers to reduce emissions by about 30% by 2016; the second (Pavley II, scheduled to start in 2017) phase implies a reduction of 45% by 2020 [8].

Since CO₂ emissions and gasoline use are nearly proportional, these 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 [8] estimated that the limits would account for over 18% 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, and 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, selling more large 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 Pavley requirements would lead to "emissions leakage" of 100% at the margin: the reductions within the Pavley states would be completely offset by emissions increases outside of those states!¹

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 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.²

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.

Recent policy developments relate to the potential impacts of these channels. 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 reductions in GHGs per mile consistent with the goals of the first (Pavley I) initiative. In return, the 14 states agreed to halt the Pavley I effort. This agreement effectively eliminates the problem of leakage to new car markets in non-adopting states through 2016. However, it does not address such leakage after that year, when the Pavley II effort begins. In addition, the agreement with the Obama administration does not eliminate the potential for leakage to the used car market, and the issue of induced technological change remains important.

This paper develops a numerical simulation model to assess the impact of the Pavley I and Pavley II standards on gasoline consumption and GHG emissions. With regard to Pavley I, it examines how much leakage would have occurred if this 14-state effort had not been converted to a nationwide standard, and it considers how much leakage (to used car markets) remains even after such conversion. With regard to the second, Pavley II initiative, it examines the extent of leakage that is likely to occur if there is no further substitution of a federal standard for this 14-state effort. We also analyze the implications for leakage and cost-effectiveness of the replacement of Pavley I by increments to the federal CAFE standard, and the possible replacement of Pavley II by subsequent further increments to the federal standard.

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, as well as consumers' automobile purchase decisions.

We find that there is great potential for serious leakage in new car markets. For example, if the Pavley II standard remains in place (that is, is not replaced by an equivalent federal standard), total leakage is 65%. Substitutions from new to used cars and reduced used vehicle scrap rates contribute slightly to the leakage (three percent). In nearly all scenarios considered, technological spillovers offset only a small fraction of the leakage. 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.

¹ 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 [19] discusses qualitatively the potential for such leakage in connection with interactions between cap-and-trade climate policies at the state and federal levels.

² A similar phenomenon is examined in Gruenspecht [13].

Thus, emissions leakage, traditionally analyzed in the context of producer relocation³ and more recently in the context of incomplete regulation,⁴ is also an important consequence from nested state and federal regulation.⁵ We find that the form of leakage examined here implies that the costs per avoided ton of greenhouse gas emissions (or avoided gallon of gasoline consumed) are about 50% higher than would be the case under a comparable national policy with no leakage.

Leakage from nested state and federal regulation is becoming increasingly important in other contexts. Similar issues arise with the nesting of states' renewable fuel standards within the Federal Renewable Fuel Standard, and would arise as well if states' cap-and-trade programs were enveloped within either a federal cap-and-trade system or federal performance standards applying to greenhouse gas emissions. They would also occur if, as is currently under consideration, the California Air Resources Board introduced restrictions beyond Pavley II by way of a state-level "feebate" system.⁶

In all of these cases, the state-level actions reduce pressures on the federal system, thereby triggering offsetting adjustments in states without binding state-level regulations. As state and federal environmental activities expand, the potential for serious leakage associated with nested state and federal regulation grows. By focusing on the Pavley initiative, this paper aims to reveal the mechanisms that lead to unintended consequences from nested regulation and assess their quantitative importance.

The rest of the paper is organized as follows. Section 2 describes the two Pavley initiatives and the declared profile of CAFE standards up to the year 2020. Section 3 identifies the various factors that influence the potential for leakage and explains how these factors operate. Section 4 presents the structure of the simulation model, while Section 5 describes the model's data and parameters. Section 6 displays and interprets the results from policy simulations. Section 7 offers conclusions.

2. Limits imposed by the Pavley and CAFE regulations

Here we describe the key requirements under the Pavley I and II standards and the federal CAFE rules. In the absence of a federal-level response, the Pavley I standards would have co-existed (in the adopting states) with the previously established Bush Administration CAFE standards ("Bush CAFE"). The Bush CAFE standards aimed to reach a fleetwide fuel-economy of 35 miles per gallon (MPG) by 2020. The Obama Administration supplanted the Pavley I effort with accelerated CAFE standards ("Obama CAFE"), requiring that the 35 MPG target be reached by 2016. The Pavley II requirements, which are planned to go into effect in 2017, are more stringent than the 35 MPG federal standard. As mentioned above, it is possible that Pavley II will be replaced by federal CAFE standards that are tightened further. Below we suggest potential future increments to federal standards based on requirements laid out in prior legislation and subsequent rulemaking.⁷

2.1. The federal CAFE standards

The federal CAFE standards apply at the manufacturer level and place a lower bound on the miles per gallon achieved by the fleet of vehicles each firm produces.⁸ The limits are set separately for passenger cars (currently a 27.5 MPG average) and light duty trucks (currently a 23.5 MPG average). 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.⁹

The Bush standards were expected to increase to 39.6 MPG for cars and 31.7 MPG for light trucks by the year 2020 along the time path shown in panel (a) of Fig. 2.1. In contrast, panel (b) shows that Obama CAFE will reach the same fleetwide average (35 MPG) four years earlier—by 2016.

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 [10] and Barker et al. [4] 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. This is the case because the limits are imposed based on the location of an auto's registration (demand), not its production.

⁴ Fowle [11] 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 et al. [7] 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 Problems of nested regulation relate to fiscal federalism and the issue of the proper assignment of functional responsibilities among various levels of government. Oates's [24] "decentralization theorem" recommends centralization in the presence of inter-jurisdictional spillovers. Emissions leakage is such a spillover.

⁶ 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. A recent interim report [6] concludes that a "moderate" feebate program with average fees of \$700 (per new vehicle) and average rebates of \$600 will lead to an average CO₂ reduction of 9 grams per mile (3%) in California over the period 2011–2025.

⁷ Specifically, the rules are based on the Energy Independence and Security Act of 2007 and subsequent rulemaking by the National Highway Traffic Safety Administration [20–22] under the two administrations.

⁸ 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. We abstract from the issue by assuming they comply with new regulations. The issue of compliance becomes important only insofar as there are differences in the extent of compliance with the federal and state policies. To the extent that firms comply with the federal policy but not the regional one, our estimates will understate the extent of leakage.

⁹ 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.

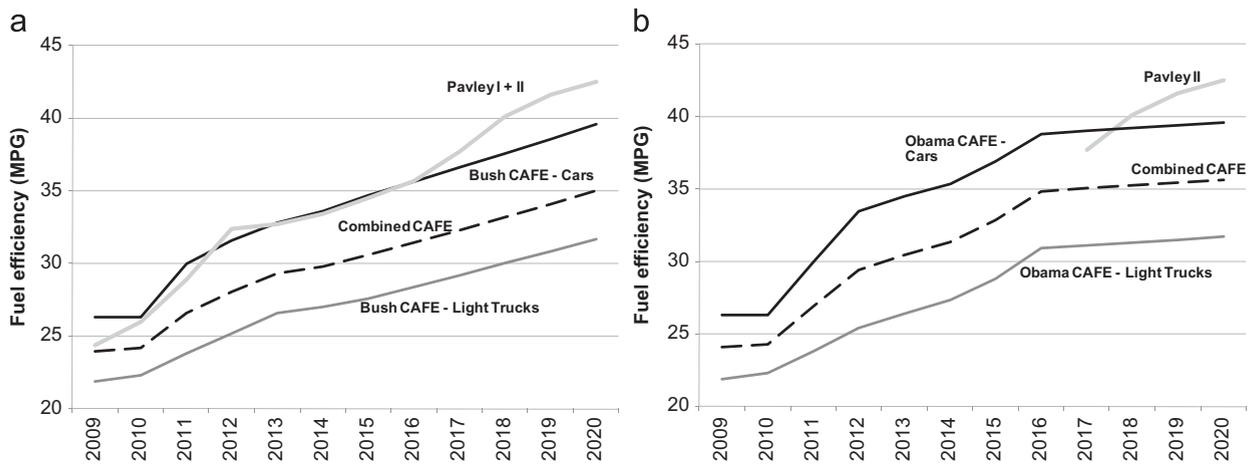


Fig. 2.1. (a) Pavley I+II versus Bush CAFE standards for the period 2009–2020; (b) Pavley II versus Obama CAFE standards for the period 2009–2020.

2.2. 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 correspond closely to limits on average gasoline consumption per mile.¹⁰

Panel (a) of Fig. 2.1 compares the implicit MPG requirements of Pavley I and II with the requirements under Bush CAFE. The dashed line in this panel indicates a “combined CAFE measure”—the weighted average of the Bush CAFE standards for cars and light trucks.¹¹ Importantly, the Pavley standards do not apply separately to cars and trucks (or vehicles with different footprints) as under CAFE. Instead, a single standard applies for the entire new vehicle fleet of each firm.¹² Panel (a) indicates that the Pavley I and II standards are significantly more stringent than the average standards under Bush CAFE.

Panel (b) of Fig. 2.1 accounts for the superseding of Pavley I by the CAFE increments instituted under the Obama administration. The substitution of the CAFE increments for Pavley I removes the issue of leakage in the new car (but not used car) market up through 2016. However, the potential for new-car-market leakage remains after 2016. Panel (b) shows that the Pavley II requirements are more stringent than the average fuel-economy requirements under the Obama administration’s tightened CAFE standards.

2.3. 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. Illinois and Delaware also planned to adopt the Pavley rules. These states represent about 41.5% of new car sales under the status quo ante.

3. Factors determining overall impacts on gasoline consumption and GHG emissions

3.1. Impacts on emissions from new cars in the adopting states

The Pavley standards give manufacturers several 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

¹⁰ We employ the same conversion factor used in the California Air Resources Board [8] analysis of the Pavley standards: each gallon of gasoline is assumed to release 8887 grams of CO₂ when burned.

¹¹ While the “combined CAFE” measure gives a rough sense of the stringency of the CAFE standard relative to the standard implied by Pavley, it should be noted that for a given manufacturer the overall requirement implied by CAFE can differ depending on the division of its own fleet between cars and trucks.

¹² 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.

improves the fuel economy associated with a given set of car features).¹³ 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.

3.2. Impacts on emissions in other markets

But the Pavley efforts affect 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:

3.2.1. Impacts in the new car market in non-adopting states

3.2.1.1. 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%: the improvement in fuel economy in the adopting states is entirely offset by a worsening of fuel economy elsewhere.

3.2.1.2. 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.

3.2.2. 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 (including 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.

3.3. Factors controlling the strength of the leakage channels

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

- 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 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 4 and 5) considers both factors controlling the strength of this first channel. First, it accounts for the fact that several producers of automobiles sold in the U.S. are not initially constrained by the federal CAFE standard. In addition, it 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.

¹³ In using the terms “static” and “dynamic,” we contrast moving along a given technological frontier (static substitution) with moving the technological frontier itself (dynamic technological progress). Here the term “dynamic” does not refer to the type of optimization model solved.

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. See Davis and Kahn [9].

Table 4.1
Vehicle categories.

Manufacturer	Age	Size	Type	Region
Ford	New	Small	Car	Adopting states
Chrysler	1 Year old	Large	Truck/SUV	Other states
General Motors	2 Years old			
Honda				
Toyota				
Other Asian				
European	18 Years old			

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

- The nature of consumer preferences—in particular, 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.

4. Model structure

4.1. 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 1064 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.

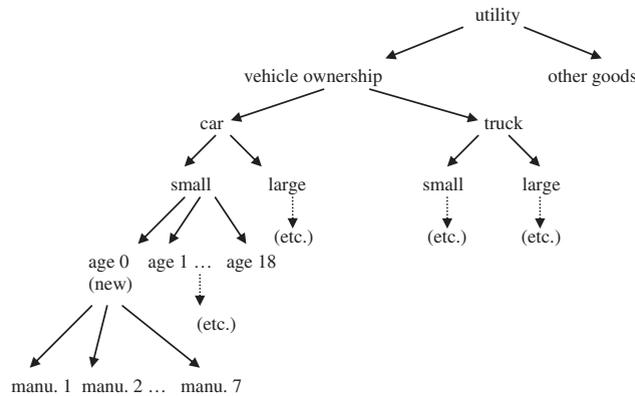
The model solves for supply–demand equilibrium in the new and used car markets. These equilibria are calculated at one-year intervals.

4.2. 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

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.

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 car or truck of a given size and age) the mix of manufacturers that yields the composite for that 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:

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

subjected to

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

and non-negativity constraints, where M is total income, p_v is the implicit rental price of the vehicle ownership composite (which includes expected depreciation and fuel cost), 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](http://www2.econ.iastate.edu/jeeem/supplement.htm) (available at <http://www2.econ.iastate.edu/jeeem/supplement.htm>) describes the optimal solution to the consumer problem in detail and indicates how the distribution parameters are calibrated to the data.

4.3. 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, 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 subjected 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 fleetwide 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, $Z_{t,s}$:

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

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 7500 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. [5], 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 [15].

subjected to the CAFE standards for cars and trucks:

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

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

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

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

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, respectively; \bar{e}_P refers to the Pavley requirement.

For a given vehicle, 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 Eq. (4.3).¹⁸ 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 5. 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 5.5 provides details on the solution method.

4.4. Used car and scrap markets

4.4.1. 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,

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

where τ indexes time, a indicates age and $a=0$ refers to new cars and $\phi_{t,s,a,m,r}$ 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 an one-year-older used car this year. Used car purchase prices can be solved for recursively according to

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

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

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.

¹⁸ 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.

Table 5.1
Parameter values.

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

4.4.2. 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

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

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.

4.5. Solution method

The model solves for a set of rental prices for all vehicles that equates supply and demand in the new and used car markets. It also solves for the fuel economies of new vehicles that are consistent with firms' profit-maximizing behavior. 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).¹⁹ This procedure is repeated every year, yielding a sequence of equilibria over the simulation period (2009–2020).

5. Data and parameters

5.1. Aggregate data

A set of aggregate statistics describes the size of the car market, GDP, interest rates and gasoline prices and usage.²⁰ Table 5.1 lists the aggregate values used and their sources. We have taken estimates for 2009 where available to generate a realistic scale. In all simulations, we specify the rate of income growth as two percent per year. The utility function in the model is homothetic; hence in the absence of price changes the demands for automobile travel would grow at this rate as well. We also assume an autonomous rate of improvement of 1.8% in the technology available for fuel economy, based on Knittel [18]. Vehicle sales and income are then divided into two regions, which in our central case are identical except for size.²¹ 41.5% of the income and vehicles are assigned to the group of adopting states on the basis of November 2008 vehicle registrations available from the Department of Transportation (DOT).

5.2. 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

¹⁹ 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.

²⁰ Usage measured as vehicle miles traveled is assumed constant. Relaxing this assumption is likely to increase the cost of both the Pavley initiative and nationwide fuel economy standards via a "rebound" effect. Small and Van Dender [25] estimate the magnitude of this effect.

²¹ 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).

Table 5.2

Vehicle age composition and scrap rates.

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

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 values used by the EPA in computing regulatory compliance.

5.3. 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, and we employ the same parameter values in each of the two regions. Following Austin and Dinan [3], we use Kleit [16]'s estimates of new car demand elasticities taken from a 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.²² 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 .²³

5.4. 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, an 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. [1] and in Hahn [14]. 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

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

Given used car purchase prices and the scrap elasticity η , this determines the constants $b_{t,s,a,m,r}$. Table 5.2 shows the vehicle age composition and scrap rates that would apply in 2009 and beyond in the absence of new policy interventions or other changes in economic conditions.

5.5. 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 [23] estimates the costs of fuel economy using engineering data. Their results can be approximated very closely with a function quadratic in fuel economy. We further divide that function into the “dynamic” and “static”

²² 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.

²³ The corresponding value used for ρ_u is -0.33 .

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.²⁴

Because the fraction of technology in the dynamic category is uncertain but central to our consideration of spillovers we simulate a large range of possibilities, varying it between 10% and 95% in sensitivity analysis. For our central case we examine the list of efficiency-enhancing technologies in [23] 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% dynamic for the central case.²⁵ In Eq. (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 MPG 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 online [appendix](#).

Our treatment of technological change may in practice give even more weight to spillovers due to the aggregation of vehicle models in the policy simulation: changes in vehicle mix within one of our aggregate models (for example a switch from 6-cylinder to 4-cylinder versions of a large car) implicitly appear as part of our technology function. We allow 40% of the corresponding improvements in fuel economy to spill over, when in fact such changes would likely be confined to the adopting states.

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 [15] and combined with consumer willingness to pay to determine the baseline slope of the quadratic cost function.²⁶ To model the curvature of the aggregate cost function as producers move away from the baseline, we use the parameters estimated from fitting a quadratic to the results of the NRC study.²⁷

6. Policy impacts

Here we explore the impacts of the two Pavley initiatives. We first consider the consequences of the Pavley I and Pavley II efforts in the absence of responding federal action. We then examine the implications of the May 2009 federal-state agreement to replace Pavley I with higher federal CAFE standards, as well as the implications of potential additional CAFE changes that could substitute for Pavley II. We focus on the implications for leakage and for the costs per avoided gallon of gasoline consumption.

6.1. Reference case outcomes

We compare results from policy simulations with those of a reference case representing the economic path absent policy changes. In our assessment of the impacts of Pavley I, the reference case focuses on the interval 2009–2016 and represents the economy with the pre-existing Bush CAFE standards. In our examination of Pavley II, the reference case focuses on the interval 2017–2025. The reference cases reproduce the expected increases in stringency of federal fuel economy standards described in Section 2.²⁸ These increases in stringency counter the effect of overall economic growth on gasoline demand, and overall gasoline use declines slightly. 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, as shown in Table 6.1.

²⁴ Although we classify many developments in engine technology as dynamic (to give considerable weight to the potential for spillovers), Klier and Linn [17] 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.

²⁵ *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” (“Path 3”) technologies, 37 (43)% were classified as dynamic.

²⁶ 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.

²⁷ 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.

²⁸ Two further changes are anticipated for the CAFE standards: (1) a limited amount of trading will be allowed across vehicle fleets, and (2) adjustment of the standards based on the “footprint” (width times wheelbase) of a manufacturer’s new vehicles. Our model does not incorporate the limited trading. Including it would give rise to greater leakage, since it would introduce a shadow price on fuel economy (the market price of fuel economy credits) for manufacturers such as Toyota for which the standards currently do not bind. By making the federal standards bind more broadly, trading would magnify leakage. Our model also does not capture the footprint component of the revised CAFE rules. This effectively introduces shadow prices on the footprint as well as on fuel economy. The impact on leakage of this component is analytically ambiguous.

Table 6.1
Baseline statistics.

Class	Year 1 (2009)		Year 8 (2016)	
	Fleet composition (%)	Fuel economy (MPG)	Fleet composition (%)	Fuel economy (MPG)
<i>Ford</i>				
Small car	2.7	28.7	2.8	39.5
Large car	3.3	23.3	3.1	31.3
Small truck/SUV	2.8	24.4	3.1	32.3
Large truck/SUV	8.2	17.6	8.0	23.5
Avg.		20.8		28.0
<i>Chrysler</i>				
Small car	1.8	25.5	1.8	35.9
Large car	2.5	24.4	2.4	33.0
Small truck/SUV	4.9	21.5	5.1	28.5
Large truck/SUV	4.4	17.7	4.3	23.6
Avg.		20.9		28.1
<i>General Motors</i>				
Small car	5.2	29.0	5.4	40.0
Large car	9.0	25.7	8.1	33.9
Small truck/SUV	4.3	22.3	4.5	29.6
Large truck/SUV	7.1	18.0	7.0	24.0
Avg.		22.9		30.6
<i>Honda</i>				
Small car	4.7	33.0	4.8	37.2
Large car	0.6	25.0	0.6	28.0
Small truck/SUV	2.3	23.8	2.3	29.1
Large truck/SUV	1.8	22.7	1.8	27.6
Avg.		27.5		32.2
<i>Toyota</i>				
Small car	7.4	33.4	7.6	37.6
Large car	1.3	26.2	1.3	29.5
Small truck/SUV	5.1	25.6	5.2	30.4
Large truck/SUV	1.2	18.1	1.2	21.8
Avg.		28.0		32.4
<i>Other Asian</i>				
Small car	8.3	28.8	8.4	36.9
Large car	1.4	23.2	1.4	29.3
Small truck/SUV	3.4	23.0	3.5	29.7
Large truck/SUV	2.1	20.3	2.1	26.4
Avg.		25.4		32.6
<i>European</i>				
Small car	2.2	32.5	2.2	39.6
Large car	1.5	25.4	1.5	30.9
Small truck/SUV	0.2	24.2	0.2	31.2
Large truck/SUV	0.6	21.2	0.6	27.5
Avg.		27.6		34.1

6.2. Impacts of the Pavley efforts

6.2.1. Pavley I

In the first year (2009), the Pavley I law required manufacturers to reach an average fuel-economy of 24.4 MPG, increasing to 35.7 MPG by 2016. Results for the first year are in Table 6.2. The tighter fuel economy requirements lead to reductions of about 8.5% in gasoline consumption from new cars sold in the adopting states. 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, Pavley I would have led to very serious leakage. As indicated in the table, it induces a 4.1% increase in gasoline consumption in the non-adopting states. This offsets about 71% of the gasoline savings in the adopting states' new car market. The increase in the non-adopting states 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 sold in these states.

Table 6.2
Impacts of Pavley I on gasoline consumption in year 1 (2009).

	New cars		Used cars	Total
	Adopting states	Other states		
Baseline	1484	2227	33,526	37,237
Pavley I MPG standards				
Gasoline use change	–126.9	90.5	10.9	–25.5
Leakage (%)	–8.55%	4.07%	0.03%	–0.07%
Change due to		71.31%	8.60%	79.91%
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

Note: gasoline consumption in millions of gallons.

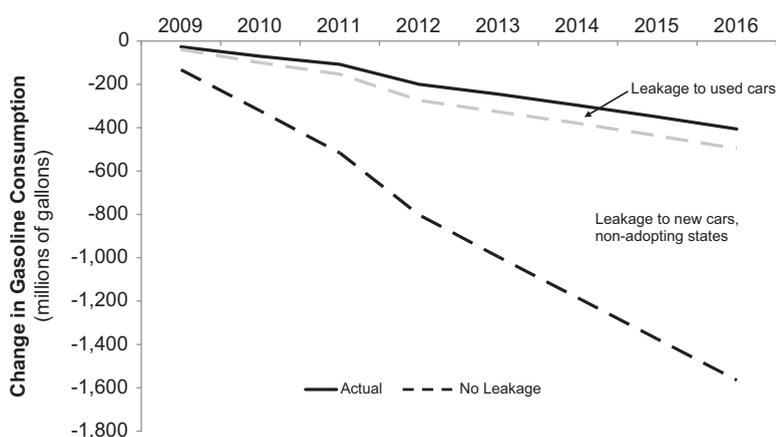


Fig. 6.1. Impacts of Pavley I on gasoline consumption over time.

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.²⁹ 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 that 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.

Together, these adjustments imply overall leakage of about 80% in the first year.

Fig. 6.1 indicates how leakage changes over time. The black dashed line indicates the reduction in gasoline consumption attributable only to the changes in sales of new cars in the adopting states. Thus, this line ignores potential leakage. However, it does take account of the fact of the continued impact on gasoline consumption associated with these new cars after the year in which they are sold.³⁰ 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 solid 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. It reveals much smaller reductions in gasoline consumption. Leakage in any year corresponds to the difference between the two black lines. Leakage to the used car market corresponds to the difference between the solid black and the gray dashed line. In Fig. 6.1, the absolute amount of overall leakage increases substantially through time. In 2016, overall leakage is about 74% of the reduction in gasoline consumption in the adopting states, as compared with 80% in 2009.

²⁹ After imposing the Pavley restrictions, the price of new cars in the new equilibrium (on average) increases about 1.5% relative to used cars.

³⁰ 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.

Table 6.3
Impacts of Pavley II on gasoline consumption in year 1 (2017).

	New cars		Used cars	Total
	Adopting states	Other states		
Baseline	1196	1793	33,476	36,465
Pavley II MPG standards				
Gasoline use change	–177.7	116.5	29.6	–31.6
	–14.86%	6.50%	0.09%	–0.09%
Leakage (%)		65.56%	16.68%	82.24%
Change due to				
Change in fleet composition	–22.6	–1.4	3.2	–20.9
Change in individual models' fuel economy	–105.8	105.5	0.0	–0.3
Change in total fleet size	–49.3	12.4	26.4	–10.4

Note: gasoline consumption in millions of gallons.

The Pavley I 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 lower portion of Table 6.2 displays this decomposition as it applies in the first year. The 25 million gallon net reduction in gasoline use derives mainly from changes in fleet composition and changes in individual models' fuel economy, which account for reduced consumption of 11.3 and 9.2 million gallons, respectively. Changes in total fleet size have a somewhat smaller contribution, accounting for a reduction of about five million gallons.

Importantly, the high rates of leakage persist despite the technological spillovers induced by Pavley I. Holding fixed the composition of the automobile fleet, the induced technological progress yields methods for achieving fuel-economy improvements at lower cost, and this works toward reduces gasoline consumption in both the adopting and non-adopting states. On the other hand, as long as the CAFE standard binds, the policy-induced technological progress also magnifies the changes in the composition of the automobile fleet, promoting increased sales of cars with relatively low fuel economy in the non-adopting states.³¹ We find that because of these offsetting effects, the ability of induced technological change to counter the other leakage effects is fairly weak.³² (We explore this more fully in Section 4.4.)

The Pavley standard induces the most additional technological change in compact cars. By 2016, the additional technological change corresponds to an additional 0.8 MPG in these cars (which spills over to both regions).

6.2.2. Pavley II

Pavley II calls for a further tightening of GHG-per-mile limits. Its implied fuel economy standards are considerably higher than those pledged by the Obama administration in response to Pavley I. As indicated in panel (b) of Fig. 2.1, the Pavley II standards exceed federal standards beginning in 2017 and these requirements continue through 2020.

Here we apply the model to gauge the economic implications of this further 14-state initiative. Table 6.3 shows the impacts on gasoline consumption in the first year of Pavley II. Note that these are changes relative to a baseline that includes the tighter CAFE standards introduced previously by the Obama administration as a substitute for Pavley I. The pattern of results is similar to that under Pavley I. Leakage to the new car market offsets about two thirds of the reduced gasoline consumption in the adopting states' new car market. Leakage to the used car market offsets another 17%. Overall leakage is about 82%. The lower half of Table 6.3 decomposes the emissions reductions into those attributable to changes in fleet composition, in the fuel-economy of individual models, and in fleet size.³³

Fig. 6.2 displays the projected impacts over time. By 2025, leakage to the new car market in non-adopting states offsets about 62% of the reduction associated with new cars in the adopting states. This is somewhat smaller than the 68%, which applied in the Pavley I case. It reflects the fact that a greater portion of the fuel savings under Pavley II come from reductions in fleet size due to a sharper increase in average new vehicle cost.³⁴ Such reductions in fleet size do not fully leak away since they do not influence compliance with the average-based CAFE standard.

³¹ We find that by 2016 the CAFE constraint has stopped binding for only one fleet: Toyota's light trucks. The rapid increase in stringency has caused CAFE to bind for most manufactures, and this limits the degree of cross-manufacturer leakage. This effect is discussed in Jacobsen [15] and involves unconstrained manufacturers increasing the size and horsepower of their fleets and expanding their shares of the markets where the CAFE standard puts constrained firms at a disadvantage.

³² The model assumes that all of the technological advances are devoted to fuel economy improvements. This gives technological progress considerable potential to counterbalance the leakage. As suggested by Knittel [18], if some technological change were focused elsewhere – e.g., toward increased horsepower – the counterbalancing effect of induced technological change could be even weaker.

³³ The patterns are very similar to the leakage in the Pavley I scenario, with the most significant difference that a larger share of the savings in adopting states now comes from reduction in total new car fleet size.

³⁴ The increases in vehicle cost cause more potential new-car buyers to leave the market than under Pavley I. The cost increases are the result of convex technology costs combined with the stringency of the reference case Obama CAFE standards.

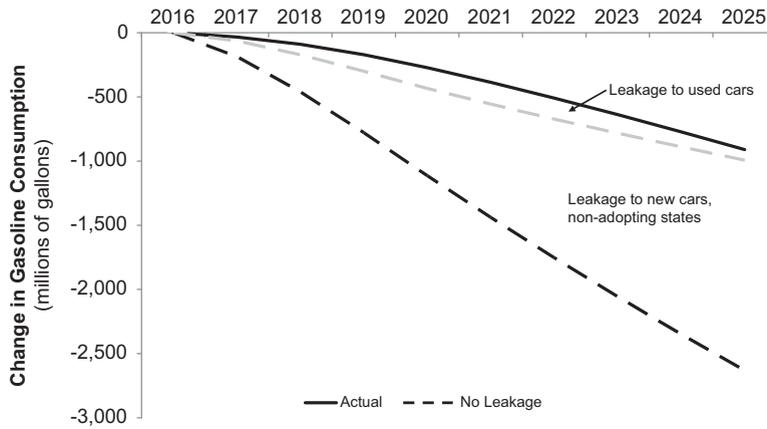


Fig. 6.2. Impacts of Pavley II on gasoline consumption over time.

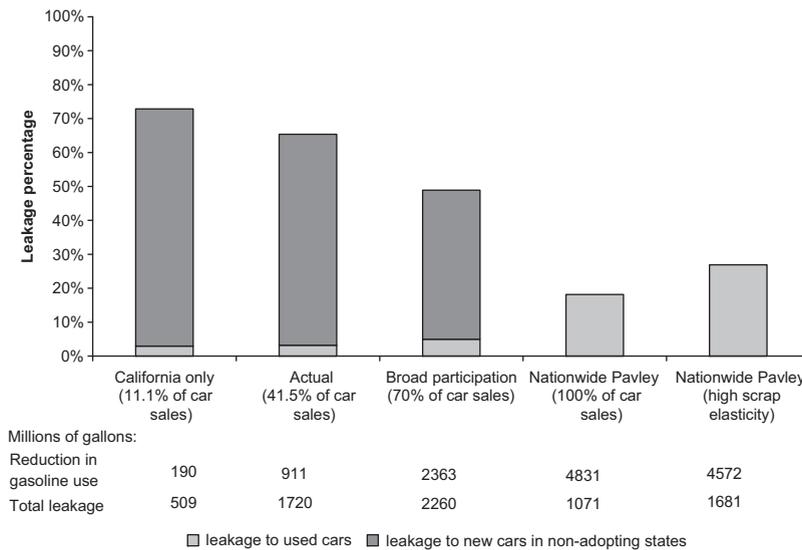


Fig. 6.3. Cumulative contributions (2016–2025) to leakage under different Pavley II adopting region sizes.

For Pavley II (2016–2025), the discounted present value of the welfare changes in the adopting region is –56.6 billion. The present value of welfare changes in the non-adopting region is 3.1 billion. Consumers in the non-adopting region enjoy a welfare gain because the policy compels automakers to reduce prices in order to sell additional cars in that region.

6.2.3. Policy breadth and leakage

Thus, our simulations indicate that Pavley I had the potential for very significant leakage, and that Pavley II continues to raise this prospect. Additional, counterfactual, simulations explore the connection between the breadth of the Pavley initiative – that is, the percent of the new car market accounted for by the adopting states – and leakage. Results for Pavley II are displayed in Fig. 6.3. 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 II 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 a nationwide Pavley II initiative would eliminate leakage in the new car market, while generating used car leakage between 18% and 27%, depending on the elasticity of the scrap vehicle market.

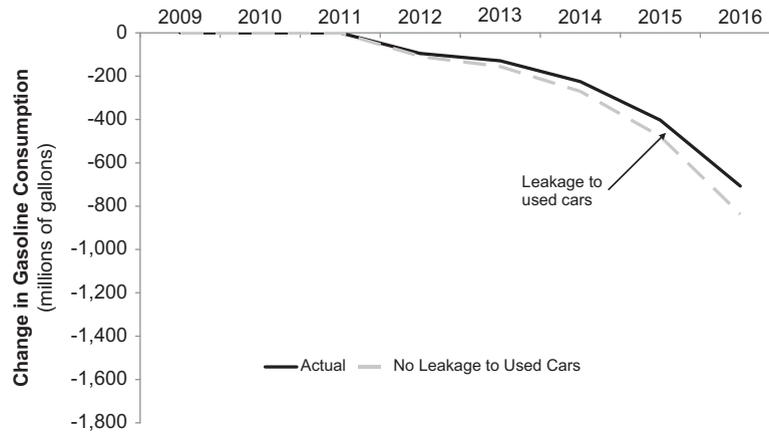


Fig. 6.4. Gasoline reductions from the Obama CAFE standards.

6.3. Avoiding leakage through federal action

6.3.1. Implications of the 2009 Obama administration agreement replacing Pavley I

In a May 2009 agreement, the Obama Administration pledged to tighten the federal CAFE requirements so that, when averaged over cars and trucks, they corresponded to the fuel economy requirements implied by Pavley I. In return, the 14 states agreed to halt Pavley I.

Here we compare the impacts of the pre-empting federal policy with what would have occurred had Pavley I remained in place. Fig. 6.4 shows the time-profile of reductions in gasoline consumption that our model predicts under the pre-empting federal CAFE increment, which is slated to go into effect in 2011. Starting around 2014 the incremented CAFE standards imply annual reductions in gasoline consumption (and GHG emissions) only about half as large as those that Pavley I would have achieved—if one ignores leakage. However, after accounting for the leakage from Pavley I, the incremented CAFE standards yield larger reductions in gasoline consumption by 2014, and even further gains by 2016. Note that because the incremented CAFE standards apply nationwide, they yield no cross-state leakage in the new car market.³⁵ At the same time, they do yield some leakage to the used car market, as indicated in the figure.

The difference in impacts between Pavley I and federal action depends importantly on two factors: (1) differences in the stringency of standards, and (2) differences in coverage. As Fig. 2.1(b) showed, in every year from 2011 through 2016, the new standards under the Obama administration are somewhat weaker than the fuel economy standards implied by Pavley I. However, the broader coverage of the CAFE increments more than offsets the relative weakness. As a result, overall gasoline consumption is reduced more by the change in the federal program than would have occurred under Pavley I. Had Pavley I been introduced nationwide, gasoline consumption in 2016 would have been reduced substantially more: seven times as much as under the actual Pavley effort and four times as much as under the Obama administration's tighter CAFE standards.

6.3.2. Implications of potential future CAFE changes that could replace Pavley II

Pavley II is slated to go into effect in 2017. However, it is possible that eventually a new agreement will lead to changes to the federal CAFE standards—changes that supplant Pavley II much as the earlier agreement substituted for Pavley I.

Here we consider potential implications of such an agreement for gasoline consumption and cost-effectiveness (cost per avoided gallon consumed). The specifics of any agreement remain uncertain, although discussions seem to center around changes to the federal CAFE standard that would yield similar overall reductions in gasoline consumption to those contemplated by Pavley II. We therefore consider the implications of a federal replacement of the Pavley II effort that is calibrated to achieve the same cumulative reductions in gasoline consumption, net of leakage. We assume equal absolute increments to the CAFE standard for both cars and light trucks, and increase the standard linearly over time so as to achieve the same cumulative reductions as Pavley II over the interval 2016–2025.

Fig. 6.5 displays the time-profile of changes in gasoline consumption that result from these changes to the federal CAFE standard. These changes are relative to a baseline that includes the tighter CAFE standards introduced previously by the Obama administration as a substitute for Pavley I. Note that, like Pavley II, these changes to the CAFE standard imply leakage to used car markets, but such leakage offsets less than 10% of the reduction in gasoline consumption.

By construction, these changes to CAFE yield the same overall changes to gasoline consumption as Pavley II. But, as indicated in Table 6.4, the two policies differ significantly in terms of overall cost and cost per gallon saved. The table

³⁵ Heterogeneity across states could imply differential impacts of the incremented CAFE, but not leakage in the sense that changes in one state cause offsets in another.

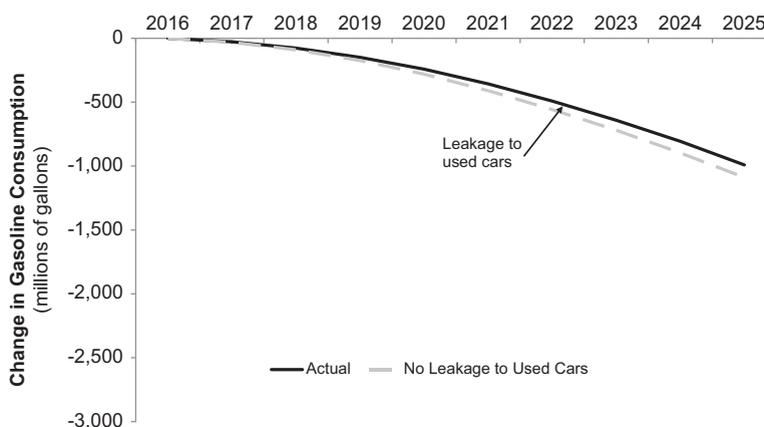


Fig. 6.5. Impacts of CAFE standards yielding the Same cumulative gasoline reductions as Pavley II.

Table 6.4

Cost and cost per gallon under actual and nationwide Pavley II, and under equivalent increments to the federal CAFE standards^a.

	Cost		Gallons saved			Cost per gallon saved	
	Adopting states	Other states	Total	Adopting states	Other states	Total	All States
(1) Actual Pavley II: 41.5% of national market	46.0	-2.4	43.6	-7.1	3.5	-3.6	12.04
(2) CAFE standards achieving reductions equal to actual Pavley II^b	13.0	19.4	32.4	-1.4	-2.2	-3.6	8.95
(3) Nationwide Pavley II: 100% of national market	124.4	0.0	124.4	-21.6	0.0	-21.6	5.75
(4) CAFE standards achieving reductions equal to nationwide Pavley II^b	100.8	151.2	252.0	-8.6	-12.9	-21.6	11.69

^a Costs in billions of discounted dollars; gallons in billions of gallons saved over the period 2016–2025.

^b The equivalent CAFE standards increase linearly over time with equal increments to the car and the truck standards.

shows a measure of the cost per gallon saved over a period of 10 years (2016–2025). Row 1 displays our estimate that Pavley II involves a cost of about \$12 per gallon. This reflects the policy's significant leakage. In contrast, the equivalent CAFE standard (row 2) involves a much lower cost: about \$9 per gallon.³⁶ Much of this difference is due to the fact that the broader coverage of the federal CAFE policy avoids cross-state leakage: the same net reductions can be achieved with lower (and thus less costly) MPG standards.

To help confirm the importance of broader coverage, we calculate the costs per gallon under Pavley II when, counter to fact, it is introduced on a nationwide basis. Row 3 of the table shows that this cuts by more than half the costs per gallon.

Another source of the difference in costs per gallon is the difference in the nature of the constraints posed by Pavley and CAFE. As mentioned, the Pavley measures introduce a single constraint for cars and light trucks, while the federal CAFE standards impose separate MPG requirements.³⁷ To assess the importance of these different structural features, we compare a nationwide Pavley II policy with federal CAFE standards equivalent to the standards implied by Pavley II. The equivalent CAFE case is constructed as in 6.3.2.

Rows 3 and 4 of Table 6.4 offer this comparison. In these results, both policies are introduced nationwide; hence they control for policy breadth. The table indicates that, controlling for policy breadth, Pavley II is more cost-effective: the cost per gallon saved is over \$11 under the CAFE policy, as compared with \$5.75 under (nationwide) Pavley II. The federal CAFE policy's separate constraints on cars and light trucks prevent automakers from achieving increases in MPG via substitution of cars for light trucks. Closing off this channel raises costs relative to the Pavley standard.

³⁶ These costs per gallon also reflect the significant distortions imposed by the Obama CAFE standards through 2016: further improvements along our central case technology cost curves are very costly. More optimistic assumptions for the technological growth rate scale down the costs while preserving our findings on leakage and relative cost.

³⁷ As discussed, the federal standards introduced by the Obama administration impose separate requirements for each vehicle based on the vehicle's footprint and they allow limited trading of credits. These provisions have offsetting effects on cost relative to those captured by our simplified model: further separation of the requirements by footprint tends to exacerbate the wedge in shadow costs across car types, while the limited trading helps reduce it. Hence the direction of the bias introduced by our simplifications is not clear.

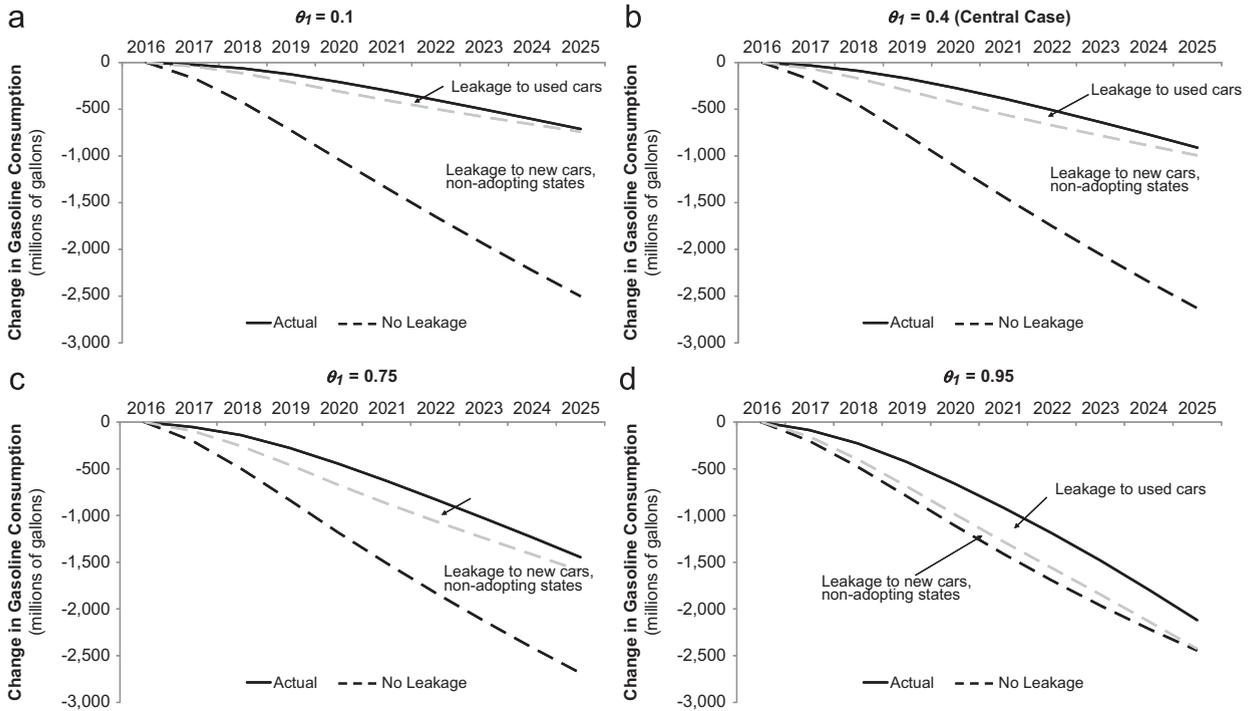


Fig. 6.6. Implications of alternative technology spillover assumptions.

In sum, replacing Pavley II with tighter federal CAFE standards would lower the costs of achieving nationwide reductions in gasoline use by about 25%. These costs could be lowered further by a similar magnitude if the federal policy allowed car-truck substitution.

6.4. Implications of alternative technological change assumptions

As indicated in 4.3, we distinguish 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_1 , which defines the fraction of fuel economy improvement at the margin that stems from new advances in technology. This parameter is defined explicitly in Part II of the online appendix. Our central case value of θ_1 is 0.4, based on considerations described in Section 5.

Fig. 6.6 displays leakage for four scenarios that differ according to the value of θ_1 . Leakage to new cars declines only slightly as θ_1 varies between 10% and 75% (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. 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_1 exceeds 90% (far above the plausible range in the engineering studies discussed in Section 5) does CAFE stop binding for the majority of firms. Leakage to new cars then drops off sharply and, as shown in panel (d) of Fig. 6.6, it nearly disappears as the fraction exceeds 95%.

The welfare costs of the policy also differ with θ_1 , increasing as θ_1 grows smaller and leakage worsens. The central case value for θ_1 is 40%, and is associated with a welfare cost of \$12.04 per gallon saved (see Table 6.4). When θ_1 is set to 10%, leakage is largest and the welfare cost is \$13.78. In contrast, when θ_1 is 95%, leakage is smallest and the welfare cost is \$7.14.

6.5. Further sensitivity analysis

Table 6.5 lists results from further sensitivity analysis for the Pavley II simulations. It reports cumulative gasoline savings by 2025 for new and used cars, as well as total leakage in the year 2025 (leakage in the central case in 2025 is 65.4%).³⁸

³⁸ Here we mention one further sensitivity that is best studied in the context of the Pavley I simulations. Anderson and Sallee [2] find that manufacturers have failed to exploit a loophole in the CAFE regulation and use this to argue that CAFE standards have been almost non-binding in recent years. To account for this possibility we investigate a scenario where the standard just barely binds (zero shadow cost) in 2009. As expected, we find no

Table 6.5

Further sensitivity analysis (cumulative changes from the baseline by 2025, in millions of gallons).

	Accumulated gasoline savings by 2025			Cumulative leakage in 2025 (%)	
	New cars		Used cars		
	Adopting states	Other states			
Central case	–2631	1637	84	–911	65.4
More stringent Pavley II standard	–4440	2007	166	–2266	49.0
Separate used car markets	–2398	1418	295	–685	71.4
Slower autonomous fuel-economy improvement	–2638	1783	103	–751	71.5
Lower cost of fuel-economy improvements	–2628	1665	98	–866	67.1
Higher scrap elasticity	–2753	1624	263	–866	68.5
Lower elasticity of substitution between vintages	–2268	1489	–117	–896	60.5
Higher gasoline price	–2459	1365	73	–1022	58.4

More stringent Pavley standard: the Pavley II target is increased to 40 MPG in 2017 and increases linearly to 50 MPG by 2020. This reduces leakage to 49.0%, and increases gasoline savings to 4,440 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.

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 is 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 second effect dominates, leading to higher leakage (71.4%).

Lower autonomous fuel economy improvements: instead of a 1.8% annual growth rate for the exogenous component of fuel economy, we now assume an one percent growth rate. This applies to both the baseline and the policy case. Leakage increases (71.5%), since more manufacturers are bound by CAFE.

Slower cost of fuel-economy improvements: here we reduce by 25% 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 68.5%.

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 60.5%.

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 increase the value of efficient new cars to consumers, thereby reducing leakage.

7. Conclusions

This paper reveals significant unintended consequences – in the form of emissions leakage and muted implementation of technological improvements – from the Pavley I and II initiatives to limit GHGs per mile from new cars sold in 14 U.S. states.

Most of the emissions leakage derives from interactions between the state-level Pavley limits and the federal CAFE standard. As a result of these interactions, the Pavley limits induce offsetting emissions impacts in the states that do not adopt the limits. The adjustments in non-adopting states' new car markets offset about 74% and 65% of the emissions reductions in the adopting states' new car markets under Pavley I and II, respectively.

Leakage also occurs 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-

(footnote continued)

leakage in the first year. However, the federal CAFE standard ramps up quickly, implying growing shadow costs and expanding levels of leakage. By 2016, cumulative leakage in the experiment has reached 63.8% versus 74.0% in our central case. By 2020, leakage in this experiment is 68.9% versus 70.1% in the central case.

efficient than new cars. Under Pavley I and II, the adjustments in the used car market offset a limited 8% and 5%, respectively, of the reductions from new cars in the adopting states. This effect becomes much larger (18–27%) when the number of states adopting Pavley increases.

The Pavley initiatives stimulate additional investments in research toward new, fuel-saving technologies. The resulting discoveries produce beneficial spillovers, as they work toward improvements in fuel economy not only in the adopting states but in other states as well. Here again interactions with the federal CAFE standard importantly influence the overall outcome. Such interactions neutralize most of the emissions benefits from technology spillovers. So long as the CAFE constraint continues to bind, auto 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 very high values for the relative contribution of technological progress 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.

Leakage associated with the state-level effort leads to considerably higher cost per avoided gallon of gasoline consumption (or avoided ton of greenhouse gas emissions) than would occur in the absence of leakage. Acknowledging the leakage doubles the estimated costs per avoided gallon. Over the period covered by Pavley II, we find the costs per gallon saved to be about 50% higher than would result under an increment to the federal level CAFE standard that achieves the same reductions in gasoline consumption.

The May 2009 agreement between the 14 “Pavley states” and the Obama administration – to replace the Pavley I initiative with increments to the federal CAFE standard that achieve comparable reductions in GHGs – eliminated the across-state leakage problem for Pavley I. However, it did not address leakage to the used car market, and no comparable agreement has been reached regarding Pavley II. Hence the leakage issue remains live.

Moreover, leakage from nested state and federal regulation is becoming increasingly important in other contexts. Similar issues arise with the nesting of states’ renewable fuel standards within the Federal Renewable Fuels Standard, and would arise as well if states’ cap-and-trade programs were enveloped within either a federal cap-and-trade system or federal performance standards applying to greenhouse gas emissions. They would also occur if, as is currently under consideration, the California Air Resources Board introduced restrictions beyond Pavley II by way of a state-level “feebate” system. An increase in state-level gasoline taxes also causes leakage when the federal policy is a CAFE-type regulation. In all of these cases, the state-level actions reduce pressures on the federal system, thereby triggering offsetting adjustments in states without binding state-level regulations. As state and federal environmental activities expand, the potential for serious leakage associated with nested state and federal regulation grows.

Leakage from nested state and federal regulation is not inevitable, however. The outcome would be very different in a world where, instead of the CAFE standard, federal policy to address fuel economy or automobile-related emissions involved a tax on gasoline or some other tax associated with fuel economy. In such a world, the presence or absence of Pavley-type efforts by a subset of states would not affect the marginal penalty from selling a low MPG car in a non-adopting state. Hence under these conditions a Pavley-type initiative would not be an inducement to sell additional cars with low MPG in the other states, and leakage of the type investigated in this paper would not arise [12]. This suggests an advantage of price-based federal regulation when federal and state policies address common activities or issues (e.g., fuel economy).

Given the existence of the federal CAFE standard, the question arises whether additional state-level efforts to reduce automobile emissions or gasoline consumption are 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. Supporters of Pavley I can invoke this argument, claiming that it was a catalyst for the subsequent adjustments to the federal CAFE standard, and that this justifies any initial risk of leakage. Similarly, supporters of Pavley II can argue that its potential to catalyze a second set of federal-level adjustments justifies the current risk of leakage. On the other hand, critics maintain that the Pavley efforts and other state-level initiatives are costly measures that yield little environmental benefit and distract attention from appropriate federal-level action. 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.

Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jeem.2011.07.003.

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