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Optimal policy instruments for externality-producing durable goods under present bias

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ABSTRACT

When consumers exhibit present bias, the standard solution to market failures caused by externalities—Pigouvian pricing—is suboptimal. I investigate policies aimed at externalities for present-biased consumers. Optimal policy includes an instrument to correct the externality and an instrument to correct the present bias. Either instrument can be an incentive-based policy (e.g. a tax on fuel economy) or a command-and-control policy (e.g. a fuel economy mandate). Under consumer heterogeneity, a command-and-control policy may dominate an incentive-based policy. Calibrated to the US automobile market, simulation results suggest that the second-best gasoline tax is 3–30% higher than marginal external damages. The optimal price policy includes a gasoline tax set about equal to marginal external damages and a fuel economy tax that increases the price of an average non-hybrid car by about \$550–\$2200 relative to the price of an average hybrid car.

Introduction

A growing body of evidence suggests that consumers regularly and predictably deviate from the predictions of rational choice theory. In particular, they appear to exhibit present bias: they "underweight" future periods in the present period. Present bias is one way in which preferences can be time-inconsistent. This affects decisions over purchases of durable goods with variable operating costs; present bias makes a consumer less likely to spend money upfront to reduce a durable's future operating costs. Many durable goods are energy-intensive and create externalities with consumption, like cars consuming gasoline or appliances consuming electricity. The standard incentive-based solution to the market failure caused by externalities is Pigouvian pricing, but the efficiency of this solution assumes time-consistent preferences.

If consumers are present-biased, does Pigouvian pricing of externalities still lead to a socially optimal outcome? If not, what is the optimal policy? Do incentive-based policies dominate command-and-control policies? How can policies address consumer heterogeneity? The purpose of this paper is to answer these questions by developing a model of optimal policy for externality-producing durable goods in the presence of quasi-hyperbolic preferences. I consider heterogeneity in consumer preferences and in present bias, and I compare incentive-based policies with command-and-control policies. Then, I calibrate the model to the automobile market, simulate, and solve for optimal policy.

The question addressed here is policy-relevant for two reasons. First, empirical support for the existence of behavioral anomalies, especially present bias, is growing. Consumers seem to discount the far future more heavily than the near future, behavior that can be modeled by hyperbolic or quasi-hyperbolic discounting (Laibson, 1997). This has been observed in

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laboratory experiments (Thaler, 1981), in individuals' decisions over exercising (Dellavigna and Malmendier, 2006) and doing homework assignments (Ariely and Wertenbroch, 2002).[1] It also may be relevant to decisions over the energy efficiency of durable goods. The purported "energy paradox" or "energy efficiency gap" finds that households seem to apply very high discount rates in their decisions over energy-intensive durable goods like air conditioners (Allcott and Greenstone, 2012). Gillingham et al. (2009) summarize the literature and find implicit discount rates ranging from 25% to 100%.[2] This paradox may be explained by present bias.

A second reason the question addressed in this paper is relevant is that environmental and energy policy seems to be moving in a direction towards incentive-based policies, especially tradable permits, and away from command-and-control policies. This transition has been fueled by arguments from economists that incentive-based policies achieve substantial cost savings compared to command-and-control policies; some empirical evidence has verified this for some policies (Carlson et al., 2000). If Pigouvian pricing is inefficient under present bias, and if consumers are present-biased, then this push towards these policies may be misguided. More so, if present bias leads to a dominance of some command-and-control policies over Pigouvian pricing, then the push away from command-and-control policies may also be misguided (Shogren and Taylor, 2008).

The theoretical results provide insight into policy design. I show that a Pigouvian tax that only accounts for externalities does not bring about the first-best outcome under present bias. A Pigouvian tax leads to cars that are not fuel-efficient enough and are driven too few miles, compared to the first best. In general, gasoline consumption under present bias can either exceed or fall below the first-best level. In a representative agent model the first-best outcome can be attained through a combination of a Pigouvian tax and a policy to address present bias, which can be either a command-and-control mandate or a fuel-economy tax. Present bias means that future costs are not fully realized by the consumer, but they can be introduced through a price instrument, e.g. a tax on fuel (in)economy. Thus, the common argument that behavioral anomalies give credence to command-and-control mandates over incentive-based mandates is not true in the representative agent case; either policy achieves the first best.

Under consumer heterogeneity incentive-based policies do not necessarily dominate command-and-control policies, in contrast to policies that address market failures caused by externalities. When consumers are heterogeneous only in their degree of present bias, then a uniform performance standard induces the first-best outcome, but a uniform fuel economy tax does not. Under more general forms of heterogeneity, neither a uniform tax nor a uniform performance standard induces the first best, and their welfare ranking is ambiguous. Because of this theoretical ambiguity, I conduct simulations to evaluate the relative performance of different instruments.

The simulation results suggest that, for the automobile market, the welfare gains from policies that address present bias are substantial, and policies that ignore present bias are substantially different from the optimal policies. The deadweight loss of a policy that addresses externalities from gasoline consumption but does not address present bias ranges from \$81 to \$226 per new vehicle sale, which amounts to an economy-wide deadweight loss of \$720 million to \$2.01 billion annually. Optimal price policy includes a tax that reduces the price differential between the average hybrid car and the average non-hybrid car by \$750 to \$2200. The best tax rate on gasoline is 3% to 30% higher than marginal external damages. While in theory a uniform fuel economy standard can achieve higher welfare than a uniform fuel economy tax, the calibrated simulation results suggest that in practice the opposite holds true.

A small number of recent papers ask related questions. O'Donoghue and Rabin (2006) solve for optimal "sin" taxes on goods that cause future damages (e.g. to health) that are underweighted due to present bias. Many of the intuitions developed in that paper can be seen in the results of this paper, for instance, present bias creates an "internality" that can be corrected through price policy (taxation). However, O'Donoghue and Rabin (2006) do not consider externalities; the only market failure is from present bias. In this paper there are two market failures – externalities and internalities – and I consider various policies to address them. Fischer et al. (2007) model both externalities and consumers who are "myopic" about the valuation of fuel costs; some consumers may correctly value fuel costs when purchasing a car, but some may undervalue fuel costs and therefore underestimate fuel savings from high fuel economy. They model two policies: a tax on fuel and a fuel economy regulation (e.g. CAFE standards). They find that fuel economy standards are welfare-increasing only under a scenario where consumers are very myopic. However, their paper does not consider any other policy to counter myopia other than standards; i.e. they do not model a fuel economy tax.

Allcott et al. (2014) study energy policy when consumers undervalue energy costs. In their model, consumers purchase a durable good in the present and pay energy costs in the future. Thus, undervaluation of energy costs can be thought of as an application of time-inconsistent, present-biased preferences.[3] Many of the results from their model mirror results here; for instance their Proposition 2 describes an optimal gasoline tax/energy-efficiency tax policy combination, as does my

[1] The field evidence for this and other types of behavioral anomalies is reviewed in DellaVigna (2009). See also Mastrobuoni and Weinberg (2009), Fang and Silverman (2009), Brown et al. (2009), and Viscusi et al. (2008).

[2] See also Table 1 in Sanstad et al. (2006). By contrast, Greene's (2010) reading of the econometric literature estimating consumers' valuations of fuel economy finds mixed results, with some studies finding under-valuing and some finding over-valuing of improvements in fuel economy (see his Table 2). Allcott and Greenstone (2012) ask the question "is there an energy efficiency gap?" They find that much of the large literature finding the gap suffers from credibility problems, and what evidence there is of a gap indicates that it is small.

[3] Their paper also allows (but does not require) consumers to undervalue other utility differences, for instance the utility from the use of energy-efficient appliances.

Proposition 2.a. Allcott et al. (2014) do not consider other policies besides a fuel economy tax that deals with the internality from undervaluation of fuel costs; i.e. they do not model fuel economy standards.

Tsvetanov and Segerson (2013) conduct a welfare analysis in a behavioral economics model where consumers suffer from temptation and self-control. In this model, preferences are not time-inconsistent, and so welfare analysis is more straightforward than in the case of quasi-hyperbolic preferences. Rather, in this model temptation comes at a real welfare cost that both individuals and the planner face. Despite the different specifications of the models, some of that paper's results mirror the results here, e.g. their Proposition 6 and my Proposition 1 both show that a Pigouvian tax alone cannot achieve first best. Tsvetanov and Segerson (2013) consider a gasoline tax and a fuel economy standard, either used in combination or as substitutes. They find cases where the standard alone can dominate the tax alone. They consider a tax/subsidy policy targeting the behavioral failure, i.e. a fuel economy tax, but in their specification this policy is equivalent to a product standard. They thus cannot compare the two policies to each other.[4]

In this small but growing literature that examines energy policy in the context of behavioral anomalies, this paper's contribution is threefold. First, I explicitly model time-inconsistent preferences using a quasi-hyperbolic discounting specification, motivated by the large body of evidence supporting this particular model of time preferences.[5] Second, I consider and compare both an incentive-based policy (a fuel economy tax) and a command-and-control policy (a fuel economy standard) intended to address the behavioral internality. Third, though other papers model heterogeneous consumers, I model heterogeneity in both present bias and consumption utility, and I compare how different policies perform in the presence of different specifications of heterogeneity. While some results from this specification mirror those of other papers, there are significant contributions as well. For instance, I theoretically show that heterogeneity over present bias can lead to command-and-control policies dominating incentive-based policies, and I numerically demonstrate that a larger heterogeneity in present bias reduces the second-best gasoline tax rate.[6]

The next section below presents the representative agent model. Then, I extend the model to multiple heterogeneous agents. The following presents simulation results.

Representative agent model

Consider a consumer making a decision over a durable good lasting T periods. The good is purchased in the initial period ($t=0$). In each subsequent period ($t=1$ through $t=T$), the consumer chooses the operating intensity of the good. To work with a concrete example, let the durable good be an automobile, where the intensity of use is the number of miles driven.

Under quasi-hyperbolic discounting, the discount factor applied in the present between any two consecutive future periods is δ, while the discount factor used between the current period and the following period is $\beta\delta$, where $\beta<1$. The parameter β represents a "present bias" in preferences, and δ is sometimes called the "long-run" discount factor.

Let gpm be the fuel economy in gallons of gasoline per mile. Let m_t be the number of miles driven in period t, so that the total fuel consumption for the consumer in period t is $gpm \cdot m_t$. The consumer gets utility (in dollar equivalents) from driving described by a utility function $U(m_t)$, where $U'>0$ and $U''<0$. The cost (in dollars) to the consumer per gallon of fuel is $gas_t+\tau_t$, where gas_t is an exogenous gasoline price and τ_t is a tax set by the government. The consumer's surplus in period t is $U(m_t)-(gas_t+\tau_t)\bullet gpm \bullet m_t$.[7]

Next consider the consumer's problem in period 0: her decision over the fuel economy of the car (gpm).[8] Suppose that the car is not driven in period 0 so that period 0 utility is just the negative of the cost of the car, c. A car with fuel economy gpm costs $c(gpm)$. Assume a continuous choice of gpm and that $c'<0$, so that less fuel efficient cars (those with higher gpm) are less expensive, and that $c''>0$.[9]

The consumer's full problem is thus

$$\max_{gpm,\{m_t\}_{t=1}^{T}} -c(gpm)+\beta\sum_{t=1}^{T}\delta^t[U(m_t)-(gas_t+\tau_t)\cdot gpm\cdot m_t]$$

[4] They do, however, compare a "partial" tax/subsidy, policy, less stringent than the optimum, and consider its welfare effects in conjunction with an externality tax Tsvetanov and Segerson 2013 (Proposition 14).

[5] Though support for quasi-hyperbolic preferences is not unanimous. Andreoni and Sprenger (2012) cite laboratory evidence that fails to find any present bias in preferences, but they suggest that no such bias is expected in laboratory experiments involving money rather than consumption utility.

[6] Two earlier papers examine externality policy in the presence of other behavioral anomalies. Johansson (1997) considers Pigouvian taxation when individuals exhibit altruism, and Lofgren (2003) considers Pigouvian taxation when individuals exhibit addiction.

[7] In this model the consumer purchases and uses gasoline in the same period. However, paying for gasoline is usually not an immediate cost but rather a delayed cost; the benefit of driving one mile is immediate, though its cost is not. Depending on credit constraints, expenditures on gasoline may not affect other consumption in the same period. This model does not capture misoptimization on the intensive margin of gasoline consumption, and instead it focuses on misoptimization on the extensive margin of vehicle choice. A useful extension would be to consider misoptimization on the intensive margin with a model that allows for timing differences between purchasing and consuming gasoline.

[8] Here where the purchase decision over the durable good occurs in just the first period, this is equivalent to a multiple-self subgame perfect Nash equilibrium, as in Laibson et al. (1998).

[9] The continuous choice of gpm is modeled for theoretical tractability; it allows for a first-order condition to be imposed and analyzed. The calibrated simulations model a discrete choice of automobile type.

This yields a set of first-order conditions, for gpm and for each m_t. Assume that an interior solution is reached and it is unique.[10] Call the solution to the consumer's problem gpm^* and m_t^*.

$$-c'(gpm^*)+\beta\sum_{t=1}^{T}\delta^t[-(gas_t+\tau_t)\cdot m_t^*]=0$$
$$U'(m_t^*)-(gas_t+\tau_t)\cdot gpm^*=0,\qquad \forall t$$

In the first equation, the first term including the negative sign is positive. It represents the current-period benefit of a marginal increase in gpm: it is cheaper. The summation is negative, and it represents the discounted cost of a marginal increase in gpm: each future period's utility is lower because the cost of driving is higher. The second equation equates the marginal benefit of an additional mile of driving with its marginal cost for each period t.[11]

Consider next the social planner's problem. There is an externality associated with the use of fuel. The total number of gallons of gasoline used in period t is $m_t \bullet gpm$; let the external damages from gasoline be $d(m_t \bullet gpm)$, where $d(0)=0$, $d'>0$, and $d''\geq 0$.

The consumer's preferences are time-inconsistent since $\beta<1$. The social planner thus encounters a dilemma over deciding what to maximize, since different "selves" of the consumer at different periods have different utility functions. One approach is to maximize a function identical to the initial period consumer's utility function but omitting the present bias, i.e. setting $\beta=1$. This approach, because it has the planner applying only the long-run discount factor and not the present bias term, is sometimes called the long-run criterion. One interpretation of this criterion is that it represents the preferences of the consumer if she were to decide what to do in the period *before* she had to purchase the car (Gruber and Koszegi, 2001). Another interpretation is that the consumer is, in a welfare-relevant way, making a mistake when she applies the present bias term β. That is, the consumer's "decision utility" includes a $\beta\neq 1$ while her "true utility" does not. The social welfare function maximizes her true utility. (True utility is sometimes also called "hedonic utility" or "experienced utility.")[12]

Papers using the long-run criterion to conduct welfare analysis include Duflo et al. (2011), Carroll et al. (2009), O'Donoghue and Rabin (2006), and Gruber and Koszegi (2001). A justification for the social planner using a discount rate that differs from the market discount rate is found in Caplin and Leahy (2004). Robson and Samuelson (2011) develop a model based on biological evolution to explain the existence of the discrepancy between decision and true utilities. The long-run criterion, though, requires the paternalistic assumption that individuals' decisions are not indicative of their true, welfare-maximizing preferences.[13]

Under the long-run criterion and accounting for the externality from pollution d, the social planner's problem is

$$\max_{gpm,\{m_t\}_{t=1}^{T}} -c(gpm)+\sum_{t=1}^{T}\delta^t[U(m_t)-gas_t\cdot gpm\cdot m_t-d(m_t\cdot gpm)]$$

Call the solution to the planner's problem gpm^{opt} and m_t^{opt}. The first-order conditions for the social planner's problem are

$$-c'(gpm^{opt})+\sum_{t=1}^{T}\delta^t[-\left(gas_t+d'(m_t^{opt}\cdot gpm^{opt})\right)\cdot m_t^{opt}]=0$$
$$U'\left(m_t^{opt}\right)-\left(gas_t+d'\left(m_t^{opt}\cdot gpm^{opt}\right)\right)\cdot gpm^{opt}=0,\qquad \forall t$$

By comparing the first-order conditions of the consumer and the planner, it is apparent that when $\beta=1$ the first-best outcome will be chosen by the consumer when $\tau_t=d'(m_t^{opt}\bullet gpm^{opt})$ for all $t\in[1,\ldots,T]$. This is the Pigouvian tax rate on gasoline; call it τ_t^{pig}.

[10] The second-order condition ensuring a unique maximum solution is: $-c''(gpm)U''(m)-\beta\delta(gas+\tau)^2>0$. The gasoline tax τ is exogenous for the consumer but a choice variable for the planner, and so the planner's solution for τ must be such that it, along with the solution to the consumer's problem given τ, satisfies this condition.

[11] In the model, the distinction between sophisticated present bias and naïve present bias is irrelevant. In every period after the initial period, the agent's decision only affects her utility in that period. In the initial period, whether she realizes that she is being time-inconsistent (sophisticated) or does not realize it (naïve) does not affect either her decision in the initial period nor in any other period. However, in the simulations, when an endogenous choice of vehicle scrappage is added, the naïve-sophisticated distinction matters.

[12] An analogous behavioral failure is contained in models where consumers "undervalue" fuel costs, which are paid in the future, as in Allcott et al. (2014) or Fischer et al. (2007). There is a potentially important distinction, though: in those models consumers are assumed to undervalue only fuel costs, whereas with quasi-hyperbolic preferences, consumers undervalue everything in the future, both costs and benefits. While in general those two different types of specifications can yield different behaviors and policy outcomes, in this model the distinction is irrelevant (because when consumers choose fuel economy they only consider the costs of fuel economy versus the costs of fuel). Note also that the model in Allcott et al. (2014), although described as one where consumers undervalue fuel costs, also has consumers undervaluing all future costs and benefits (see their inequality 2 on p. 8; the valuation weight Γ applies to both fuel costs and utilization benefits). The critical difference in this study relative to those others is the comparison of alternate policies to address the behavioral failure under alternate forms of consumer heterogeneity.

[13] To avoid the concerning paternalistic assumption that the planner discounts differently than the agent does, alternative welfare criteria, including those presented by Bernheim and Rangel (2009), have been proposed. In order to be agnostic about what welfare criterion to employ, I adopt the following strategy. I solve for optimal policy under the long-run criterion, and then I investigate how robust those policy solutions are to alternate welfare criteria. In the online appendix, I show conditions under which a first-best solution defined according to the long-run criterion is also considered welfare-improving under the alternate criteria.

The main results concern the case where $\beta<1$: the consumer discounts quasi-hyperbolically, but the social planner does not. Proposition 1 summarizes the results from the representative agent model. The proof is presented in the online appendix.

Proposition 1. *Let* $\beta<1$.

a) *There does not exist any set of gasoline tax rates* $\{\tau_t\}$ *for all* $t\in[1,\ldots,T]$ *that lead to the first-best outcome* gpm^{opt} *and* m_t^{opt}. *If* $\tau_t=\tau_t^{pig}$ *for all* $t\in[1,\ldots,T]$, *then* $gpm^*>gpm^{opt}$ *and* $m_t^*<m_t^{opt}$ *for all* $t\in[1,\ldots,T]$.
b) *The first best is achieved by setting* $\tau_t=\tau_t^{pig}$ *in each period* $t>0$ *and setting a fuel economy standard that mandates a maximum gpm of* gpm^{opt}.
c) *The first best is achieved by setting* $\tau_t=\tau_t^{pig}$ *in each period* $t>0$ *and setting a fuel economy tax* $\tau_{gpm}=(1-\beta)\bullet\Sigma_{t=1}^{T}\delta^t\cdot(gas_t+\tau_t^{pig})\cdot m_t^{opt}$.
d) *When* $\tau_t=0$ *for all* $t>0$ *then no policy on gpm, whether a tax* τ_{gpm} *or an efficiency standard* gpm^{max}, *can achieve the first best.*

The first part of the proposition states that no set of gasoline taxes exist, not even the Pigouvian taxes, that lead to the first-best outcome gpm^{opt} and m_t^{opt}, and it describes the direction of the error when using the Pigouvian taxes.

The Pigouvian tax τ_t^{pig} will not achieve the first best,[14] but if it is levied, what outcome does it lead to? Intuitively, since the consumer underweights the future operating costs of the car, she will pay too little for fuel efficiency in period zero and buy a car with a *gpm* that is too high. But once that inefficient car is bought, the consumer faces a higher per-mile price of driving compared to the optimal fuel efficiency. So the number of miles driven is fewer than optimal in each period.

Thus, it is not clear how total gasoline consumption (the product of fuel economy and mileage) under the Pigouvian tax compares to the optimal level of gasoline consumption. The present bias in preferences could cause total gasoline consumption and emissions to be greater than or less than the optimal level of gasoline consumption and emissions. Suppose that utility over mileage is iso-elastic with a coefficient of relative risk aversion φ, so that $u(m)=m^{1-\varphi}/1-\varphi$. The price elasticity of demand for miles driven is $-1/\varphi$ (this is also equal to the price elasticity of demand for gasoline). Under this functional form, present bias ($\beta<1$) leads to an over-consumption of gasoline if and only if $\varphi>1$, that is, the absolute value of the price elasticity is less than 1. Your car has too low of a fuel economy because of present bias. If your demand for mileage is price-inelastic, then the decrease in miles driven because of the low fuel economy is small and is not enough to offset the lower fuel economy, and total gasoline consumption increases. Contrariwise, if you are price-elastic, then the decrease in miles driven is large and more than offsets the decreased fuel economy, and total gasoline consumption decreases.

Not just the Pigouvian gasoline tax rates, but no set of gasoline tax rates produces the first-best outcome when $\beta<1$. However, regulators may be constrained and only have gasoline taxes at their disposal. What might a second-best policy instrument, using only gasoline taxes, look like? Intuitively, one might think that in each period, the second-best τ_t is higher than the Pigouvian tax rate τ_t^{pig} to attempt to overcome the present bias. However, this intuition is not true in general. As discussed above, present bias could cause gasoline consumption to either increase or decrease. It follows that the second-best gasoline tax may exceed the Pigouvian tax or may fall below the Pigouvian tax. Under present bias, the consumer is underweighting future costs of gasoline consumption. The consumer is also underweighting future benefits of gasoline consumption, that is, the utility from driving. If the underweighting of the future benefits dominates the underweighting of the future costs, then the consumer will consume too little gasoline relative to the optimum, and the second-best gasoline tax will be lower than the Pigouvian gasoline tax.[15] Present bias does not necessarily increase pollution, and therefore a second-best gasoline tax is not necessarily higher than the Pigouvian tax.

The regulator needs a second policy instrument to achieve the first best. One such instrument is a fuel economy standard, and Proposition 1.b shows that a fuel economy standard combined with a gasoline tax can achieve the first-best.[16] This may provide some rationale for having gasoline taxes in conjunction with corporate average fuel economy (CAFE) standards for new passenger automobiles.

Two policy instruments are necessary to achieve the first-best outcome, but the second instrument need not be a command-and-control standard. Instead, the regulator can set a tax to be paid in period zero based on the car's fuel economy. Call this tax τ_{gpm}. Proposition 1.c shows that a policy that combines this fuel economy tax with a gasoline tax can achieve the first best.

The summation in the optimal fuel economy tax τ_{gpm}, $\Sigma_{t=1}^{T}\delta^t\cdot(gas_t+\tau_t^{pig})\cdot m_t^{opt}$, is the full discounted benefit of a marginal decrease in *gpm*. The consumer only accounts for a fraction β of the full benefit, and so the remaining $(1-\beta)$ is in the tax, bringing about the first-best. The intuition behind the tax on fuel economy τ_{gpm} is analogous to the intuition behind

[14] This finding of Proposition 1a echoes Proposition 6 from Tsvetanov and Segerson (2013).

[15] Suppose that utility is iso-elastic. When $\varphi>1$, then the second-best tax exceeds the Pigouvian tax; the opposite holds when $\varphi<1$. This result can be compared to Allcott et al. (2014) Corollary 1, which shows that the second-best gasoline tax is greater than marginal external damages because the externality tax provides an “internality dividend.” Their result relies on their assumption that demand is inelastic (p.8); more generally the “internality dividend” could be positive or negative. See also the discussion in O'Donoghue and Rabin (2006), p. 1833, of the interaction between an internality-targeting tax and other pre-existing tax distortions.

[16] The policy is here modeled as a maximum *gpm*, but it is equivalent to a mandated *gpm* in the representative agent case (since without it, the agent would choose a car with *gpm* higher than gpm^{opt}).

the tax on the externality τ_t^{pig}. With an externality, there is a cost that is not faced by the agent, and a tax that forces the agent to face that cost (a Pigouvian tax) yields the first best. With present bias here characterized as an "internality," there is another cost that is not faced by the agent: part of the future cost of lower fuel economy. The optimal fuel economy tax τ_{gpm} forces her to face the full cost. This result is extending the intuition from O'Donoghue and Rabin (2006), where the only market failure is the internality, to an economy where there are two market failures (internality and externality).[17]

Behavioral anomalies are often invoked as justification for command-and-control policies over incentive-based policies (Greene, 1998). But just like with externalities, behavioral anomalies can be internalized through price-based incentives. Empirical evidence suggests that consumers do in fact respond to price when making decisions on energy-efficiency investments (Hassett and Metcalf, 1995). In this representative agent model, there is no difference between the command-and-control standard and the *gpm* tax. With heterogeneous agents, though, there is reason to suspect that incentive-based policies and command-and-control policies may differ. This will be investigated in the following section.

In the homogeneous case, the two market failures can be remedied with two instruments. Proposition 1.a shows that no set of gasoline taxes, without a policy on *gpm*, can achieve the first best. Similarly, Proposition 1.d shows that no policy on *gpm*, without a policy on gasoline consumption, can achieve the first best. A policy is needed in period $t>0$ to correct the market failure from the gasoline externality. A policy is needed in period zero to correct the market failure from the behavioral anomaly.

Model with heterogeneous agents

The findings in Proposition 1 are very intuitive but are based on a representative agent model, and thus they rely on homogeneity among consumers. A more realistic and interesting case is consumer heterogeneity. In the representative agent model, either a performance standard (e.g. a minimum miles-per-gallon requirement) or an incentive-based policy (e.g. a tax on fuel economy) brings about the first-best outcome. One may suspect that under consumer heterogeneity, the incentive-based policy dominates the command-and-control policy; this result is well-known in policies that address externalities in the presence of heterogeneous abatement costs.

However, this is not true of policies that address present-biased preferences. With heterogeneous agents, neither a uniform tax on fuel economy nor a uniform performance standard necessarily brings about the first best outcome. By "uniform" I mean one that does not vary by individual. The source of the heterogeneity affects whether or not the first-best can be achieved. When consumers are heterogeneous in their present bias but homogeneous in their instantaneous utility over mileage, then a uniform gasoline tax and fuel economy performance standard *can* achieve the first-best. The comparison of fuel economy taxes to fuel economy standards has not been previously considered in other papers studying energy policy under behavioral biases.

Consider a model with $J>1$ agents. Each agent i's instantaneous utility over mileage in period t is $U_i(m_{i,t})$. Assume that all agents have the same long-run discount factor δ but each agent's present bias discount factor is β_i. All agents face a uniform fuel economy tax τ_{gpm} and a uniform gasoline tax in each period τ_t.

Consumer i's first-order conditions are

$$U_i'(m_{i,t})-(gas_t+\tau_t)gpm_i=0$$
$$-c'(gpm_i)-\tau_{gpm}+\beta_i\sum_{t=1}^{T}\delta^t\left[-(gas_t+\tau_t)m_{i,t}\right]=0$$

These first-order conditions implicitly define each consumer's demand for mileage and for fuel economy as functions of the policy variables; call these $m^*_{i,t}(\{\tau_t\}_{t=1}^T,\tau_{gpm})$ and $gpm^*_{i,t}(\{\tau_t\}_{t=1}^T,\tau_{gpm})$.

The planner's problem is

$$\max_{\{\tau_t\}_{t=1}^T,\tau_{gpm}}\sum_{i=1}^{J}\left[-c(gpm_i)+\sum_{t=1}^{T}\delta^t\left(U_i(m_{i,t})-(gas_t gpm_i m_{i,t})-d\left(\sum_{j=1}^{J}m_{j,t}gpm_j\right)\right)\right]$$

Subject to the constraints that $m_{i,t}=m^*_{i,t}(\{\tau_t\}_{t=1}^T,\tau_{gpm})$ and $gpm_{i,t}=gpm^*_{i,t}(\{\tau_t\}_{t=1}^T,\tau_{gpm})$. This yields a set of first-order conditions for the planner's problem (one for each of the policy variables). After substituting in the consumers' first-order conditions, the planner's first-order condition for the choice of τ_{gpm} can be written as

$$\tau_{gpm}\left(\sum_{i=1}^{J}\frac{dgpm_i^*}{d\tau_{gpm}}\right)+\sum_{i=1}^{J}\left[\frac{dgpm_i^*}{d\tau_{gpm}}\sum_{t=1}^{T}\delta^t\left(\beta_i(gas_t+\tau_t)m^*_{i,t}-gas_t m^*_{i,t}\right)\right]$$
$$+\sum_{i=1}^{J}\left[gpm_i^*\sum_{t=1}^{T}\delta^t\tau_t\frac{dm^*_{i,t}}{d\tau_{gpm}}\right]-J\sum_{t=1}^{T}\delta^t d'\left(\sum_{j=1}^{J}g^*_{j,t}\right)\sum_{j=1}^{J}\frac{dg^*_{j,t}}{d\tau_{gpm}}=0$$

[17] Although in most of O'Donoghue and Rabin (2006) the internality from present bias is the only market failure or distortion, a discussion on pp. 1832–1833 considers internality taxation in an economy with pre-existing distortionary taxes elsewhere. This discussion is somewhat analogous to the mode here with two distortions (the internality and the externality).

The planner's first-order conditions for the choice of τ_s are identical, except for replacing all derivatives with respect to τ_{gpm} with derivatives with respect to τ_s. Each consumer's gasoline consumption $g^*_{j,t} = m^*_{j,t} gpm^*_j$; total gasoline consumption is $G^*_t \equiv \Sigma^J_{j=1} g^*_{j,t}$.

This yields a system of $T+1$ equations to solve for the $T+1$ policy variables. To allow for a tractable solution, assume that there is only one period of driving following the period zero in which the car is purchased; i.e. assume $T=1$.[18] With this assumption, the optimal gasoline tax and the optimal fuel economy tax can be evaluated.

The regulator may instead use a gasoline tax in combination with a fuel economy standard. Suppose that the fuel economy is a maximum gpm_{max} that may bind for some consumers and not for others. Let the first M_1 consumers be the ones for whom the standard binds, and the remaining $M_2 = J - M_1$ consumers be those for whom it is non-binding. The optimal gasoline tax and the optimal fuel economy standard can be evaluated under either specification for the standard. Furthermore, the planner may choose to employ three policies simultaneously: a gasoline tax, a maximum gpm_{max}, and a fuel economy tax τ_{gpm}.

Proposition 2 describes policies under consumer heterogeneity. Proofs are in the online appendix.

Proposition 2. *Consider the model with J heterogeneous agents where T=1.*

a) *The optimal gasoline tax/fuel economy tax combination is:*

$$\tau = \frac{1}{D}\left[\frac{dZ^*}{d\tau}\frac{dgpm^*_{avg}}{d\tau_{gpm}} - \frac{dZ^*}{d\tau_{gpm}}\frac{dgpm^*_{avg}}{d\tau}\right] + \frac{MED}{D}\left[\frac{dG^*}{d\tau}\frac{dgpm^*_{avg}}{d\tau_{gpm}} - \frac{dG^*}{d\tau_{gpm}}\frac{dgpm^*_{avg}}{d\tau}\right]$$

$$\tau_{gpm} = \frac{\delta}{D}\left[\frac{dZ^*}{d\tau_{gpm}}\frac{dG^*}{d\tau,\beta_i} - \frac{dZ^*}{d\tau}\frac{dG^*}{d\tau_{gpm},\beta_i}\right] + \frac{\delta MED}{D}\left[\frac{dG^*}{d\tau_{gpm}}\frac{dG^*}{d\tau,\beta_i} - \frac{dG^*}{d\tau}\frac{dG^*}{d\tau_{gpm},\beta_i}\right]$$

b) *The optimal gasoline tax/fuel economy maximum combination is*:

$$\tau = MED \cdot \frac{\frac{dG^*}{d\tau}}{\frac{dG^*}{d\tau,\beta_i}} + \frac{\sum_{i=M_1+1}^{J}(1-\beta_i)m^*_i gas\frac{dgpm^*_i}{d\tau}}{\frac{dG^*}{d\tau,\beta_i}}$$

gpm_{max} defined by

$$M_1(-c'(gpm_{max})) + \delta gpm_{max}\sum_{i=1}^{M_1}\frac{dm^*_i}{dgpm_{max}}\left(\tau - \frac{M_1}{J}MED\right) - \delta\sum_{i=1}^{M_1} m^*_i\left(gas + \frac{M_1}{J}MED\right) = 0$$

c) *The optimal gasoline tax/fuel economy tax/fuel economy maximum combination is*:

$$\tau = \frac{1}{D}\left\{\left(\delta gas M_2 \frac{dZ^*_2}{d\tau}\right) + MED\left(\frac{dG^*}{d\tau}M_2\frac{dgpm^*_{avg2}}{d\tau_{gpm}} - \frac{dG^*}{d\tau_{gpm}}M_2\frac{dgpm^*_{avg2}}{d\tau}\right)\right\}$$

$$\tau_{gpm} = \frac{1}{D}\left\{-\delta^2 M_2^2 gas\frac{dZ^*_2}{d\tau}\frac{dG^*_{2,\beta}}{d\tau_{gpm}} + MED\left(\frac{dG^*}{d\tau_{gpm}}\delta\left(\frac{dG^*_{2,\beta}}{d\tau} + gpm_{max}M_1\frac{dm^*_{avg1}}{d\tau}\right) - \frac{dG^*}{d\tau}\delta\frac{dG^*_{2,\beta}}{d\tau_{gpm}}\right)\right\}$$

gpm_{max} defined by

$$M_1(-c'(gpm_{max})) + \delta\left[gpm_{max}\tau\sum_{i=1}^{M_1}\frac{dm^*_i}{dgpm_{max}} - gas\sum_{i=1}^{M_1} m^*_i\right] = Jd'(G^*)\frac{dG^*}{dgpm_{max}},$$

d) *When consumers are heterogeneous in instantaneous utility (U_i) but homogeneous in present bias ($\beta_i = \beta$), then neither a gasoline tax/fuel economy tax combination nor a gasoline tax/fuel economy standard (mandate or maximum) combination can achieve the first-best.*

e) *When consumers are homogeneous in instantaneous utility ($U_i = U$) but heterogeneous in present bias (β_i), then a gasoline tax/fuel economy tax combination cannot achieve the first-best, but a gasoline tax/fuel economy standard (mandate or maximum) combination can achieve the first-best.*

In this proposition, $MED \equiv Jd'(G^*)$ is the marginal external damages from pollution. The expressions $dG^*/d\tau,\beta_i$ and $dG^*/d\tau_{gpm},\beta_i$ are weighted averages of the derivative of G^*_i with respect to the policy variable and the derivative of G^*_i with

[18] An alternative assumption that would yield substantively identical results is to assume that all periods $t>0$ are identical to each other (same exogenous gasoline price, same gasoline tax). The solutions under that assumption are identical to solutions under the given assumption, except that where the long-run discount rate δ appears, it is replaced by the expression $\delta(1-\delta^T)/(1-\delta)$.

respect to the policy variable holding constant fuel economy, weighted by present bias β_i. Formally,

$$\frac{dG^*}{d\tau, \beta_i} \equiv \sum_{i=1}^{J} \beta_i m_{i,t}^* \frac{dgpm_i^*}{d\tau} + gpm_i^* \frac{dm_i^*}{d\tau}$$

and

$$\frac{dG^*}{d\tau_{gpm}, \beta_i} \equiv \sum_{i=1}^{J} \beta_i m_{i,t}^* \frac{dgpm_i^*}{d\tau_{gpm}} + gpm_i^* \frac{dm_i^*}{d\tau_{gpm}}.$$

When $\beta_i = 1$ (no present bias), $dG_i^*/d\tau, \beta_i = dG_i^*/d\tau$ and $dG_i^*/d\tau_{gpm}, \beta_i = dG_i^*/d\tau_{gpm}$. The expression $Z^* \equiv \Sigma_{i=1}^J (1-\beta_i) m_i^* gpm_i^* gas$ measures the extent of the distortion created by present bias. The denominator

$$D \equiv \left[\frac{dG_i^*}{d\tau, \beta_i} \frac{dgpm_{avg}^*}{d\tau_{gpm}} - \frac{dG_i^*}{d\tau_{gpm}, \beta_i} \frac{dgpm_{avg}^*}{d\tau} \right].$$

Given these definitions, the expressions for the optimal taxes τ and τ_{gpm} in part a of Proposition 2 can be interpreted. First consider τ. When $\beta_i = 1 \ \forall i$, then the expression reduces to $\tau = MED$ (no internality from present bias). When at least one consumer exhibits present bias, the second-best gasoline tax does not equal marginal external damages. The second term in the numerator (with *MED* out front) represents how the gasoline tax attempts to account for the externality from pollution. Because $dG_i^*/d\tau, \beta_i \neq dG_i^*/d\tau$, this term is not exactly *MED*. The smaller the average β_i, the larger is the deviation between $dG_i^*/d\tau, \beta_i$ and $dG/d\tau$, and the larger is the deviation between this part of the tax and *MED*. The first term in the numerator represents how the gasoline tax attempts to account for the internality from present bias. The variable Z^* represents how large the distortion from present bias is (it is proportional to the sum over $(1-\beta_i)$). As β_i deviates from 1, the first term in the numerator becomes non-zero. In general it cannot be signed. A larger value of *MED* implies a larger optimal gasoline tax, intuitively. The first term in brackets in the expression for τ will be larger when Z^* is more sensitive to τ than it is to tau_{gpm}, that is, if τ is effective at reducing the distortion from present bias. Similarly, the second term in brackets will be larger when G^* is more sensitive to τ than it is to τ_{gpm}, that is, if τ is effective at reducing total gasoline consumption.

Next consider τ_{gpm}. When $\beta_i = 1 \quad \forall i$, then the expression reduces to $\tau_{gpm} = 0$ (with no internality from present bias, no need for a policy on fuel economy). When at least one consumer exhibits present bias, then this expression consists of two terms. The first term represents how the fuel economy tax attempts to account for the internality from present bias; it depends on the measure of the distortion from present bias Z^*. The second term (with *MED* out front) represents how the fuel economy tax attempts to account for the externality from pollution. Just like with the gasoline tax τ, a larger value of *MED* implies a larger value of τ_{gpm}. The magnitudes of the two terms in brackets in the expression for τ_{gpm} depend on the same things as do the magnitudes of the two bracketed terms in the τ expression, but the effects are opposite. The first term in brackets is larger when Z^* is more sensitive to τ_{gpm} than to τ, and the second term in brackets is larger when G^* is more sensitive to tau_{gpm} than to τ.

When consumers are homogeneous ($\beta_i = \beta \quad \forall i$ and $U_i = U \quad \forall i$), then the expressions in Proposition 2.a simplify to

$$\tau = MED$$
$$\tau_{gpm} = \delta(1-\beta)m(gas + MED).$$

These are the expressions for the representative agent case in Proposition 1.c.

Proposition 2.a is similar to Proposition 2 in Allcott et al. (2014), which also considers two-dimensional optimal tax policy in the presence of heterogeneous internalities. That proposition demonstrates how both taxes depend on the marginal internality with respect to both taxes. Similarly, Proposition 2.a demonstrates that each instrument depends on both the magnitude of the externality (*MED*) and of the internality (Z^*). Allcott et al. (2014) focus just on two tax instruments, while the rest of Proposition 2 in this paper considers alternate policy instruments to address the internality.

Proposition 2.b considers the fuel economy maximum, which can bind for some consumers ($i = 1 \ldots M_1$) but not for others ($i = M_1 + 1, \ldots, J$). Here, the gasoline tax is not identical to marginal external damages MED. The coefficient in the first term multiplying MED is positive and greater than one, and the other term is positive. Thus, $\tau > MED$, so that the tax is higher to in part account for the market failure from present bias. The second term in the expression for τ is summed over just the consumers for whom the *gpm* maximum does not bind, since for the other consumers the gasoline tax has no effect on the fuel economy chosen. The optimal gpm_{max} can be implicitly defined by a first-order condition; the expression accounts for the fact that only a subset of consumers are affected by the constraint. Only a fraction of marginal external damages ($(M_1/J)MED$) are affected by the choice of gpm_{max}.[19]

When the regulator uses three instruments together, Proposition 2.c describes the optimal policy values. As in Proposition 2.b, the equations reflect the fact that the fuel economy maximum gpm_{max} only affects a subset of the population. As in Proposition 2.a, both tax rates (τ and τ_{gpm}) are partially correcting for both the externality and the internality. The externality is corrected for in the second term in each equation, with *MED*. The internality appears in the first term, which includes the expression Z_2^*. This measures the extent of the internality among those M_2 consumers for whom the fuel economy maximum does not bind, since those are the

[19] A simpler but unrealistic policy is one with a mandated, not maximum, *gpm*, which must bind for all consumers. In that case, it can be shown that the optimal gasoline tax is exactly *MED*, and the optimal mandated fuel economy is defined by $-c'(\overline{gpm}) - \delta(gas + MED)\Sigma_{i=1}^J m_i^{opt} = 0$.

consumers for which the taxes will correct for the internality. The fuel economy maximum itself is defined from the third equation in Proposition 2.c, which accounts for the fact that only a subset of consumers will be bound by it. In the expression for τ, the first term will be larger when Z_2^* is more sensitive to τ, that is, when the distortion from present bias among those whose *mpg* choice responds to τ can be affected by τ. The second term in parentheses (multiplied by *MED*) is larger when gasoline consumption G^* is more sensitive to τ than to τ_{gpm}. Similarly, the first term in the expression for τ_{gpm} is smaller when Z_2^* is sensitive to τ, and the second term (multiplied by *MED*) is larger when G^* is more sensitive to τ_{gpm} than to τ.

Admittedly, the expressions in Propositions 2.a–2.c are difficult to interpret. They provide some, but limited, qualitative insights into how, for instance, present bias affects optimal gasoline and fuel economy taxes. Do taxes increase or decrease as consumers become more present-biased? How does the demand elasticity affect optimal policy? To answer these questions, I will make assumptions about the functional forms and parameter values and investigate how they affect an optimal gasoline and/or fuel economy tax. These results are presented in Table 6 below in the simulations section.

An alternative policy with a simpler interpretation is one in which τ is fixed at the Pigouvian level *MED* and τ_{gpm} is allowed to vary. In this case, the optimal τ_{gpm} is $\sum(1-\beta_i)\delta^t\left(gas_t+\tau_t^{pig}\right)\cdot m_{i,t}^*(dgpm_i^*/d\tau_{gpm})$. This expression represents the weighted average of consumers' distortions due to present bias. As will be shown in the simulations, in the more general policies the optimal τ is not too different from *MED*, so this interpretation is valuable.[20]

Proposition 2.d shows that the first-best cannot be achieved with either policy combination under heterogeneity in U_i. Why would an incentive-based policy like a uniform emissions tax and a uniform fuel economy tax not achieve the first-best outcome? The externality in this model is a pure public bad; for a given level of emissions, an additional unit of emissions causes the same marginal external damage regardless of who produces it. So, optimal policy has everyone facing the same marginal cost (tax). On the other hand, the marginal cost of the market failure from present bias is not identical across consumers. It is, in fact, equal to the expression for τ_{gpm} in the proof of Proposition 2.c. The cost that consumer *i* fails to face in her decision utility function is a part of her future periods' utility. But, this cost differs between consumers since the heterogeneity in utility functions leads to heterogeneity in optimal mileage m_i. The non-uniformity of the optimal tax is analogous to a non-uniform optimal Pigouvian externality tax in a case where damages from emissions are not independent across sources. For instance, if emissions from power plants located close to densely populated areas cause more damage than emissions from power plants far away from populated areas, then the Pigouvian emissions tax rate on the closer power plants is higher than the tax rate on the other plants (Mauzerall et al., 2005).

A policy that includes a command-and-control instrument has an advantage relative to one that includes only incentive-based instruments when consumers are heterogeneous only in present bias, as shown in Proposition 2.e. The intuition is that when consumers are heterogeneous only over present bias, then the first-best outcome is homogeneous for all consumers (since the first-best outcome ignores present bias). The homogeneous first best can be achieved by invoking a uniform fuel-economy standard ($\overline{gpm}$). However, levying a uniform fuel-economy tax (τ_{gpm}) will not achieve the homogenous first best since consumers with different values for β_i will respond differently to the same tax.

This stands in contrast to the well-known result that a flexible, price-based policy dominates a less-flexible, command-and-control policy in the presence of other types of heterogeneity. For instance, under heterogeneity in abatement costs, a pollution tax dominates a command-and-control pollution abatement policy. The result here only arises in the very special (and unrealistic) case where present bias is the only source of consumer heterogeneity. More generally, when consumers are heterogeneous in present bias and in other aspects of utility, neither policy combination can achieve the first best, and the ranking between policy options is unclear. Proposition 2.e suggests that when the heterogeneity in present bias is large relative to the heterogeneity in utility, a fuel economy standard will dominate a fuel economy tax. To explore this, I next provide simulation results that examine the role that consumer heterogeneity plays in optimal policy.

All of the previous results have considered policies that are linear (e.g. a constant tax rate) and uniform (e.g. the same tax rate applied to all consumers). Such policies are perhaps more realistic, but these limitations inhibit the policies from achieving the first-best. Consider instead a policy that includes a constant, uniform gasoline tax τ and a fuel economy tax τ_{gpm} that can be non-linear: $\tau_{gpm}(gpm)$.[21] In this case, the consumer's first-order condition for choice of *gpm* is $-c'(gpm_i^*)-\tau'_{gpm}(gpm_i^*)+\beta_i\delta(gas+\tau)m_i^*=0$. The first-best can be achieved by the planner setting the gasoline tax equal to marginal external damages ($\tau=Jd'(G^{opt})$) and setting the fuel economy tax schedule such that the following equation holds for all consumers: $-\tau'_{gpm}\left(gpm_i^{opt}\right)=(1-\beta_i)\delta(gas+\tau)m_i^{opt}$. That is, the marginal cost of fuel economy from the fuel economy tax must just equal the portion $(1-\beta_i)$ of the future fuel costs that the present-biased agent neglects to consider in period zero. This amount on the right-hand-side differs for different individuals, both because of heterogeneity in present bias β_i and because of heterogeneity in optimal mileage m_i^{opt} that arises from heterogeneity in the utility function.

Can such a tax schedule be implemented to achieve the first-best? In the case where the planner can observe each individual's utility function and β_i, it is trivial that each consumer can be assigned his or her first-best τ_{gpm} and the first best will be reached. More interesting is the case where the planner knows the distribution of utility functions, m_i^{opt}, and β_i, but cannot identify the values for any particular individual. The planner can set a tax schedule such that the marginal cost of fuel economy $\tau'_{gpm}\left(gpm_i^{opt}\right)$ is set at the series of optimal values, but the planner cannot in general ensure that individuals sort

[20] I thank an anonymous referee for this suggestion and interpretation.

[21] The distinction between a linear and non-linear fuel economy tax is not relevant to the model of Allcott et al. (2014), since that model considers only two products.

themselves into the appropriate fuel economies such that the first-best first-order condition holds for all individuals. In some cases a tax policy may hold that will be able to achieve the first-best, but it depends on the distribution of consumer types. Note that assuming constant present bias $\beta_i = \beta$ does not ensure that the first-best is implementable; the optimal tax schedule depends also on m_i^{opt}, which varies due to heterogeneity in instantaneous utility.

Numerical simulation

I now turn to a model to be solved computationally, in an attempt to find the magnitude of the effects described in the analytical models above. The model is calibrated to consider consumer decisions over automobile purchases and gasoline consumption. I solve the model under four different specifications. First, I assume homogeneous consumers. This simulation presents results from the representative agent model. Second, I consider heterogeneous consumers, a simulation of the model with heterogeneous agents The third and fourth specifications include an extension that is not included in the theoretical model: an endogenous vehicle scrapping decision. Instead of a fixed vehicle lifetime, in each period each agent can choose to scrap her vehicle and replace it with a new vehicle. The endogenous scrapping decision is not included in the theoretical model because the solution is not tractable. In the simulation, it is solved computationally through backward induction. In the third simulation, the agent is assumed to be *sophisticated* about present bias, and in the fourth simulation the agent is assumed to be *naively* present-biased. If the consumer knows that his future selves are time-inconsistent, it is said that he is sophisticated about his time-inconsistency. In contrast, a naïve agent would act now as if his future selves would be consistent, although in the future they would not (O'Donoghue and Rabin, 1999). Some evidence suggests that consumers are in fact naïve about their present bias (Dellavigna and Malmendier, 2006). The inclusion of the endogenous scrapping decision is included because present bias may have an important effect on this dimension of consumer behavior. All of the intuitive results from the theoretical model without endogenous scrapping are maintained in the simulation with endogenous scrapping.

The details of the calibration are presented in the online appendix, but Table 1 summarizes the calibration. Some of the parameters are calibrated using data from the 2001 National Household Travel Survey (NHTS), while others are taken from the literature. Consumer heterogeneity is modeled on two different dimensions: heterogeneity in the instantaneous utility function U_i and heterogeneity in present bias β_i. There are four different types of instantaneous utility functions and four different values of β_i, for a total of 16 different consumer groups. All consumers finance their car purchases.

Given a representative agent's solution, policy options can be analyzed by evaluating the agent's true utility at his solution. The true utility includes the external damages from gasoline consumption and does not include the present bias factor β. Then, optimal or second-best policy can be found by maximizing the value of true utility over the policy variable, for example the gasoline tax. The first-best solution can also be found for comparison, by evaluating the agent's problem without present bias ($\beta = 1$) and where the gasoline tax is set to equal marginal external damages. I run simulations based on 100 representative consumers, whose initial vehicle allocation (ages and fuel economy) is chosen to represent the household-owned vehicle fleet described in the NHTS.

Results

Table 2 presents summary statistics from the first specification (homogeneous consumers) under various policy alternatives. In these simulations, all consumers have utility from the car vehicle type (the most fuel-efficient vehicle type), and all consumers are present-biased ($\beta = 0.7$). The first column presents statistics from the first-best outcome. The row for “policy instrument” is not relevant to the first-best outcome. The first statistic is the deadweight loss of the policy, equal to the discounted value of true utility evaluated at the solution minus the value for the first-best outcome. The units of deadweight loss are dollars, and the values are per vehicle. The remaining statistics are the mean annual mileage, the mean annual gas consumption, the mean fuel economy in gallons per mile, and the mean total tax payments (either gasoline tax

Table 1
Calibration of numerical model.

Function or parameter	Description	Value	Source
φ	Inverse of short-run price elasticity of gasoline demand	2.941	Brons et al. (2008)
C	Utility function scale parameter	Varies by vehicle type	Calibrated from mileage data in NHTS
$c(gpm)$	Cost of car as function of fuel economy	Varies by vehicle type	Calibrated from EPA fuel economy data and MSRP data.
d	External damages from gasoline consumption	\$1.23/gal	Parry (2011)
β	Present bias discount factor (annual)	.7, .9, 1.0, or 1.1	Laibson et al. (2007); Bradford et al. (2014)
δ	Long-run discount factor (annual)	.96	
D	Consumer disutility from vehicle age	Varies by vehicle type	Calibrated to match average vehicle age in NHTS

Table 2
Summary statistics from simulation with homogeneous consumers, fixed vehicle lifetime.

Policy instrument(s)	(1) First-best N/A	(2) Pigouvian gasoline tax $\tau=1.23$ $\tau_{gpm}=0$	(3) Second-best gasoline tax $\tau=1.60$ $\tau_{gpm}=0$	(4) Optimal gasoline tax and fuel economy standard $\tau=1.23$ $gpm_{max}=.0335$	(5) Optimal gasoline tax and fuel economy tax $\tau=1.23$ $\tau_{gpm}=148{,}440$	(6) Second-best fuel economy standard $\tau=0$ $gpm_{max}=.0333$
Deadweight loss ($)	0	226	192	0	0	525
Mean mileage	11,417	11,070	10,743	11,417	11,417	13,309
Mean gas consumption (gal)	382.49	405.61	388.46	382.49	382.49	442.82
Mean fuel economy (gpm)	.0335	.0366	.0362	.0335	.0335	.0333
Mean tax payment ($)	N/A	6231	7741	5876	10,850	0

Notes: Deadweight loss is the total discounted value, per new car, over the lifetime of the car ($T=18$ years). Gasoline taxes τ are in dollars per gallon.

or fuel economy tax). The entry under mean total tax payment is the total discounted value (discounted only using the long-run discount factor) of all tax payments over the entire lifetime of the car.

The first alternate policy simulation is presented in column 2 of Table 2. In that simulation (as in all simulations subsequent to column 1) the agent exhibits present bias. The gasoline tax is set at the Pigouvian level of marginal external damages ($1.23/gal). Comparing deadweight loss in column 2 to column 1, present bias reduces the level of true utility, making the agent worse off. The value of deadweight loss is $226 per vehicle, which is the discounted sum of deadweight loss over the vehicle's entire lifetime (18 years). The total number of new passenger vehicle sales in the US in 2009 was 8.9 million,[22] so the total annual deadweight loss from the new vehicles purchased in that year is about $2.01 billion. The average mileage is lower, and the average *gpm* is higher, under the Pigouvian tax than in the first best. This and the fact that the outcome under the Pigouvian tax does not achieve the first best confirm Proposition 1.a.

The second-best gasoline tax, that is, the tax that yields the lowest deadweight loss, is $1.60, 30% higher than marginal external damages. This suggests that ignoring present bias can lead to policy prescriptions that are significantly different than optimal levels. Relative to column 2, under the second-best tax of column 3, mileage is lower, gas consumption is lower, and the average fuel economy is higher (*gpm* is lower). Deadweight loss is lower with the second-best tax, but still not zero (the first best is not achieved). This verifies Proposition 1.a.

Proposition 1.b shows that the first best is achieved with the Pigouvian gasoline tax and a fuel economy standard requiring a maximum *gpm* equal to its optimal level. (In the simulations I consider just a fuel economy maximum, not a mandate that must bind for all consumers.) Column 4 enacts these policies, and the outcomes are identical to those in column 1. Proposition 1.c shows that the first best is achieved with the Pigouvian gasoline tax and a tax on *gpm*. The optimal *gpm* tax equals 148,440. This tax rate is multiplied by a vehicle's *gpm*. For the average non-hybrid car, with a *mpg* of 23.11, this tax payment is $6423. For the average hybrid car, with a *mpg* of 35.18, this tax payment is $4219. Thus the optimal fuel economy tax increases the price of a non-hybrid relative to a hybrid by $2200. Before the fuel economy tax, the relative price difference between the two cars is $5500. The row for mean tax payment indicates that the tax burden under the policy combination in column 5 is much greater than the tax burden under the policy combination in column 4. The tax payments have no effect on social welfare (since all tax revenues are returned lump-sum), but they might generate political constraints.[23]

In column 6, the sole instrument is a fuel economy standard; the gasoline tax rate is set to zero. As Proposition 1.d predicts, the first best is not achieved. This policy is the worst of all policies, based on deadweight loss. Although the fuel economy is actually higher (lower *gpm*) than the first best, mileage and gas consumption are both much higher.

All of the results in Table 2 perfectly corroborate Proposition 1. Next, I simulate the theoretical model of heterogeneous consumers. Table 3 presents results from a specification including the 16 consumer types described earlier. The assumption of a fixed vehicle lifetime (of 18 years) is maintained. Each summary statistic presented in the table is an average of the statistic for all consumer types, weighted by the market share of the vehicle types from the NHTS and the distribution of β values calibrated based on Bradford et al. (2014).[24] Since many of the results from the theoretical section on heterogeneous agents depended on parameter values and functional forms, the simulation results in Table 3 allow me to examine the quantitative importance of consumer heterogeneity.

[22] Available from the Bureau of Transportation Statistics: http://www.bts.gov/publications/national_transportation_statistics/html/table_01_17.html.

[23] Additionally, the amount of tax revenue might be relevant to social welfare in an economy where governments seek to raise revenue, perhaps in place of other distortionary taxes.

[24] There are four different values of β: [.7, .9, 1.0, 1.1], each taken by 25% of the population.

Table 3
Summary statistics from simulation with heterogeneous consumers, fixed vehicle lifetime.

	(1) First-best	(2) Pigouvian gasoline tax	(3) Second-best gasoline tax	(4) Second-best gasoline tax and fuel economy standard	(5) Second-best gasoline tax and fuel economy tax	(6) Second-best fuel economy standard	(7) Pigouvian gasoline tax and second-best fuel economy tax	(8) Second-best gasoline tax, fuel economy tax, and fuel economy standard
Policy instrument(s)	N/A	$\tau=1.23$ $\tau_{gpm}=0$	$\tau=1.27$ $\tau_{gpm}=0$	$\tau=1.27$ $gpm_{max}=.0745$	$\tau=1.20$ $\tau_{gpm}=37{,}546$	$\tau=0$ $gpm_{max}=.0752$	$\tau=1.23$ $\tau_{gpm}=35{,}157$	$\tau=1.20$ $\tau_{gpm}=37{,}542$ $gpm_{max}=.0811$
Deadweight loss ($)	0	50	49	49	40	883	41	40
Mean mileage	11,800	11,743	11,701	11,701	11,833	13,447	11,802	11,833
Mean gas consumption (gal)	489.30	493.39	490.97	490.97	490.69	588.53	489.38	490.70
Mean fuel economy (gpm)	.0412	.0417	.0417	.0417	.0412	.0434	.0412	.0412
Mean tax payment ($)	N/A	7580	7796	7796	8921	0	8967	8921

Notes: Deadweight loss is the total discounted value, per new car, over the lifetime of the car ($T=18$ years), averaged over the four vehicle types, weighted by their market shares. Gasoline taxes τ are in dollars per gallon.

Comparing columns 1 and 2 again verifies the predictions of Proposition 1.a. The Pigouvian tax fails to achieve the first-best outcome and leads to vehicles being too fuel-inefficient and mileage too low. The second-best gasoline tax rate is again higher than marginal external damages, here by 3.2%.[25]

Column 4 considers a gasoline tax combined with a fuel economy maximum, and column 5 considers a gasoline tax combined with a fuel economy tax. All policies are uniform across all consumer types. With heterogeneity in β, Proposition 2 shows that no such set of policies attains the first best, so long as the fuel economy tax rate and the fuel economy standard are uniform across consumers. The gasoline tax is not equal to marginal external damages in either column. In column 4, the gasoline tax is equal to the second-best gasoline tax in column 3. In column 5, the gasoline tax is less than the Pigouvian tax.[26] The outcomes under the gasoline tax and fuel economy tax are closer to the first-best outcomes than are the outcomes under the gasoline tax and the fuel economy standard.

The theoretical model shows that neither policy achieves the first best in an economy where consumers are heterogeneous over both instantaneous utility and present bias.[27] The numerical simulation shows that the policy that includes a fuel economy tax dominates the policy that includes a fuel economy standard. Why? A uniform gasoline tax (equal to marginal external damages) plus a fuel economy standard unique to each consumer type would achieve the first best, as would the same uniform gasoline tax plus a fuel economy tax unique to each consumer type. The optimal fuel economy standard varies across consumer types from a minimum of.0335 gpm to a maximum of.0558 gpm, a range that equals 67% of the minimum value. By contrast, the optimal fuel economy tax varies across consumer types from a minimum of 148,440 dollars per gpm to a maximum of 171,870 dollars per gpm, a range that equals just 16% of the minimum value. By this measure, the heterogeneity in the optimal standard exceeds the heterogeneity in the optimal tax. Therefore, a uniform standard gets it “more wrong” than does a uniform tax.[28]

The sixth column in Table 3 presents the policy simulation that finds the second-best fuel economy standard when the gasoline tax is fixed at zero. As in Table 2, this policy is the worst of all presented by far. The second-best fuel economy standard ($gpm_{max}=.0752$) has almost the same value as the second-best standard when the gasoline tax is allowed to be

[25] This is lower than the second-best gasoline tax from the homogeneous case (column 3 of Table 2), but that is not simply because of heterogeneity. Rather, Table 2 only includes consumers of the most fuel-efficient type of vehicle (car). By adding in consumers of less fuel-efficient vehicles in Table 3, the second-best tax is reduced. If, instead, the heterogeneity in Table 3 arose from adding consumers who demand even more fuel-efficient vehicles than those in Table 2, then this table's second-best gasoline tax would be higher than that in Table 2. Furthermore, Table 3 includes both present-biased and future-biased consumers.

[26] This is consistent with the theoretical results in Allcott et al. (2014).

[27] When simulating an economy where consumers are heterogeneous only over present bias, it can be shown that the optimal gasoline tax/fuel economy standard policy (column 4) achieves the first best, verifying Proposition 2.d.

[28] The welfare ranking of the optimal standard and the optimal tax is reminiscent of the prices vs. quantities literature (e.g. Weitzman (1974)). However, the motivation for most of that literature is uncertainty in marginal costs or benefits; here the motivation is heterogeneity among consumers and a uniform policy variable.

non-zero (column 4). In fact, this value is also almost equal to the first-best fuel economy for the most fuel-inefficient vehicle type, the pickup truck. Because the cost of higher fuel economy for pickups is so high, any standard that forces those consumers to increase fuel economy creates costs that outweigh any benefits.

Given that the second-best gasoline taxes are close in value to the Pigouvian tax, another policy scenario modeled, in column 7, is a policy that fixes the gasoline tax at the Pigouvian rate and maximizes utility by choosing the fuel economy tax. As mentioned earlier, in this case the optimal fuel economy tax has a simple closed-form solution and interpretation. The simulation shows that this policy is indeed quite similar to the policy where both taxes are allowed to vary (column 5) with just a slightly higher deadweight loss. Lastly, column 8 presents a simulation that uses all three policy instruments, as in Proposition 2.c. This simulation is almost identical to the case where only a gasoline tax and fuel economy tax are used (column 5). The fuel economy standard added in column 8 does not bind for most consumers.[29]

Tables 4 and 5 add in the endogenous choice of scrapping. In Table 4, consumers are sophisticated about their present bias; in Table 5 they are naïve. These tables present the same summary statistics as the earlier tables and add a row with the mean age of vehicles. In the earlier specifications, this statistic was invariant to policy because of the absence of a scrapping choice. In Tables 4 and 5, the deadweight loss values are the discounted values over an individual's lifetime (age 21 years to age 90 years), rather than a vehicle's lifetime (and thus the deadweight loss values are not directly comparable between Tables 2 and 3 and Tables 4 and 5).

In column 2, the average car age is about one half of a year older, and the average annual mileage and gas consumption are about the same, compared to column 1. These changes decrease utility, with a per-person discounted deadweight loss of $2100 over the person's lifetime (this is the weighted average deadweight loss over the eight consumer types). The mean fuel economy is higher in *gpm*, meaning that the average car is less fuel efficient. These results conform to the theoretical predictions of Proposition 1: the chosen level of *gpm* is higher than the optimal level and the chosen level of m is lower than the optimal level. The level of gasoline consumption is higher under column 2 because gasoline demand is price inelastic.

The second-best gasoline tax, shown in column 3, is $1.48. This is about 20% higher than marginal external damages. Deadweight loss decreases from column 2 to column 3. The average car age increases. Annual mileage actually decreases and is farther away from the optimal level than it was under the Pigouvian tax. Gasoline consumption is lower than optimal. Cars are more fuel efficient than under the Pigouvian policy, but not at the optimal level of fuel efficiency.

Column 4 presents the results for the best combination of a gasoline tax and a uniform fuel economy standard, while in column 5 the policy combines a gas tax with a fuel economy tax. The optimal level of the fuel economy tax in column 5 is $50,643 times the car's *gpm*. For the average non-hybrid car, with a fuel economy of 23.1 miles per gallon, this equals $2193. For the average hybrid car, with a fuel economy of 35.2 miles per gallon, this equals $1440. The optimal fuel economy tax thus makes the average non-hybrid car about $750 costlier relative to the average hybrid car.

None of these policies achieves the first best. The policy option with the lowest deadweight loss is a tax on gasoline and a tax on fuel economy. Both policy options that contain two policies (columns 4 and 5) achieve lower deadweight loss than either policy option that contains just one policy (columns 2 and 3). Combining a gasoline tax with a fuel economy tax is closer to the first best than combining a gasoline tax with a fuel economy standard.

Some of the outcomes in Table 5, with naively present-biased consumers, are drastically different than those from Table 4. Most notably, the average age of cars is much higher when consumers are naïve compared to when consumers are sophisticated. The large difference in average age between Tables 4 and 5 leads to a large difference in deadweight loss. The deadweight loss differences arise almost entirely from the calibrated coefficient D, the linear utility cost of an extra year on a car's age. This parameter was calibrated from the data, where relatively few cars are as old as the average car age in the simulations from Table 5. Thus the deadweight loss values should be interpreted with caution. Still, the comparison between these two tables indicates that the naïve/sophisticated distinction may be quite important, especially on the extensive choice margin of deciding whether or not to replace a vehicle. When comparing results across columns within Table 5, the intuitive results from the previous simulations remain. Two instruments achieve higher social welfare than just one instrument but do not achieve first-best. A fuel economy tax performs better than a fuel economy standard.

The second-best gasoline tax in column 3 of Table 5 is lower than marginal external damages, in contrast to the analogous tax rate for sophisticated present-biased consumers. Because naïvely present-biased consumers have such older cars, the gas tax need not be as high to implement the optimal (second-best) miles traveled. In this sense, naiveté "helps" on the intensive margin, though that is more than offset by its costly effect on the extensive margin of vehicle choice. A naïve consumer is much less likely to scrap and replace her car now, because she (incorrectly) predicts that her future self will do so. A sophisticated consumer realizes that her future self is unlikely to scrap and is thus more willing to do so now. For the same reason, sophisticated consumers are more likely to buy more fuel-efficient cars.

The theoretical results in the case of heterogeneous consumers were difficult to interpret because of their generality. Therefore, in Table 6 I explore how optimal policy depends on the degree and type of heterogeneity across consumers. I consider different specifications of heterogeneity along dimensions of present bias (β) and demand elasticity for miles

[29] The policies in columns 7 and 8 would be redundant in the Table 2 simulations where consumers are homogeneous; both simulations would be identical to those in columns 4 and 5 of Table 2.

Table 4
Summary Statistics from Simulation with Heterogeneous Consumers, Endogenous Vehicle Lifetime, Sophisticated Consumers.

Policy instrument(s)	(1) First-best N/A	(2) Pigouvian gasoline tax $\tau = 1.23$	(3) Second-best gasoline tax $\tau = 1.48$	(4) Second-best gasoline tax and fuel economy standard $\tau = 1.54$, $gpm_{max} = .0579$	(5) Second-best gasoline tax and fuel economy tax $\tau = 1.29$, $\tau_{gpm} = 50{,}643$
Deadweight loss ($)	0	2053	2000	1999	1697
Mean vehicle age (years)	8.5941	9.1299	9.24	9.26	9.60
Mean mileage	11,654	11,652	11,429	11,383	11,691
Mean gas consumption (gallons)	499.89	500.27	484.75	481.27	490.05
Mean fuel economy (gpm)	.0426	.0427	.0422	.0420	.0417
Mean tax payment ($)	N/A	616,740	718,960	743,730	757,430

Notes: Deadweight loss is the total discounted value, per consumer, over his or her entire lifetime, averaged over the four vehicle types, weighted by their market shares. Gasoline taxes τ are in dollars per gallon.

Table 5
Summary Statistics from Simulation with Heterogeneous Consumers, Endogenous Vehicle Lifetime, Naïve Consumers.

Policy instrument(s)	(1) First-best N/A	(2) Pigouvian gasoline tax $\tau = 1.23$	(3) Second-best gasoline tax $\tau = 1.20$	(4) Second-best gasoline tax and fuel economy standard $\tau = 1.79$, $gpm_{max} = .0513$	(5) Second-best gasoline tax and fuel economy tax $\tau = 1.36$, $\tau_{gpm} = 55{,}816$
Deadweight loss ($)	0	26,661	26,613	26,392	25,991
Mean vehicle age (years)	8.5941	19.2573	19.2491	19.3067	18.8108
Mean mileage	11,654	11,576	11,608	11,098	11,475
Mean gas consumption (gallons)	499.89	506.60	508.18	470.93	496.42
Mean fuel economy (gpm)	.0426	.0445	.0445	.0433	.0445
Mean tax payment ($)	N/A	624,120	611,340	845,670	755,040

Notes: Deadweight loss is the total discounted value, per consumer, over his or her entire lifetime, averaged over the four vehicle types, weighted by their market shares. Gasoline taxes τ are in dollars per gallon.

Table 6
Alternative specifications.

		Policy 1—Gasoline tax only	Policy 2—Gasoline tax and fuel economy tax	
		Optimal gas tax (as % of MED) (1)	Optimal gas tax (as % of base-case optimal gas tax) (2)	Optimal *gpm* tax (as % of base-case optimal *gpm* tax) (3)
Vary β	Base case – homogeneous present bias [.7,.7,.7,.7]	1.18	1.00	1.00
	Three-quarters present-biased, one-quarter not [.7,.7,.7,1.0]	1.13	.98	.75
	Half present-biased, half not [.7,.7,1.0,1.0]	1.08	.98	.50
	One quarter present-biased, three quarters not [.7,1.0,1.0,1.0]	1.04	.98	.25
	Larger variance in present bias [.4, .7, .7, 1.0]	1.13	.96	.99
	Even larger variance in present bias [.4, .4, 1.0, 1.0]	1.08	.92	.99
	Half future-biased [1.0, 1.0, 1.1, 1.1]	.96	1.00	−.17
Vary φ	4.0	1.27	1.00	1.01
	Base case (2.9)	1.18	1.00	1.00
	2.0	1.09	1.00	.99
	1.0	1.00	1.00	.93
	.5	.96	1.00	.79

traveled ($1/\varphi$). For each alternative set of parameter values, I consider two policy scenarios: one with just a gasoline tax and one with a gasoline tax and a fuel economy tax. The optimal gasoline tax alone is expressed as a percentage of the Pigouvian tax (marginal external damages). The optimal gasoline tax/fuel economy tax values are expressed as a percentage of the optimal gasoline and fuel economy taxes, respectively, in the base case. The base case for Table 6 is where present bias is homogeneous ($\beta = 0.7$).

The first four rows consider different fractions of the population present-biased. Going down the rows, fewer consumers are present-biased. The optimal gas tax in Policy 1 decreases as fewer consumers are present-biased; the less present bias, the less the gasoline tax (by itself) needs to attempt to remedy the misoptimization from present bias. In the case of two policy instruments, the gasoline tax is close to invariant over the average level of present bias, but the fuel economy tax drops substantially as fewer consumers are present-biased. In fact, to two decimal places, the optimal fuel economy tax as a fraction of its baseline level is just equal to the fraction of present-biased consumers as a fraction of its baseline level. The next two rows in Table 6 consider distributions over β with the same average β as in the base case but a larger variance of β. With the gas tax alone, a larger variance in β reduces the optimal gas tax – the cost of making the gas tax too high for the non-present-biased individuals outweighs the benefit of making it too low for the very-present-biased individuals. With two policies, larger variance has little effect on the fuel economy tax but reduces the gas tax moderately. The last row that varies the β distribution considers a case without present bias but with half the population future-biased; here the optimal gasoline tax is less than marginal external damages and the optimal fuel economy tax is negative (a subsidy for low fuel economy).

The last five rows of Table 6 vary the parameter φ, which is the reciprocal of the demand elasticity for gasoline. As the elasticity gets higher (φ gets lower), the gasoline tax by itself gets smaller. With unit elasticity of demand, the gasoline tax is just equal to marginal external damages, and with elastic demand, the gasoline tax is lower than marginal external damages (since in this case present bias leads to under-consumption of gasoline, as described in the model with heterogeneous agents). With two policies, the gasoline tax is invariant to φ, but the fuel economy tax is lower when demand is more elastic.

Conclusion

Behavioral economics provides growing support for the claim that consumers regularly exhibit time-inconsistent preferences and present bias. Little is known about how this phenomenon impacts optimal policy design or interacts with market failures. This paper examines how policies addressing externalities perform when consumers exhibit present bias. The paper's theoretical model finds that policymakers need to acknowledge present bias to achieve socially optimal outcomes. The dominance of incentive-based policies over command-and-control policies may not hold under present-biased preferences, and in fact the opposite may be true depending on the source of heterogeneity. The numerical simulations suggest that ignoring present bias can yield policy prescriptions that substantially differ from those that bring about the first-best outcome.

The results are based on several assumptions, any of which could be relaxed to provide even more sensitivity analyses. For instance, producer behavior is not modeled; manufacturers also respond to price policies, and this response could affect market prices and quantities. More heterogeneity could be added in many places: more types of consumers, regional or temporal variance in gasoline prices or in external gasoline or mileage damages, more types and features of vehicles. Any of these extensions would no doubt capture more features of the market. But, the purpose of this simulation is not to pin down optimal policy point estimates, but rather to provide an idea of the magnitude of the effects of present bias on policy prescriptions.

Present bias is studied because it is likely to be relevant for energy-intensive durable goods, whose energy costs are paid in the future. However, present bias is not the only psychology that is relevant to decisions over these goods. Consumers may be inattentive to certain features of products; see for instance the focusing model of Koszegi and Szeidl (2013) or the salience model of Bordalo et al. (2012). Consumers may not understand energy costs of different options; see the literature on the “MPG illusion” in Larrick and Soll (2008). Consumers may exhibit projection bias and thus not appreciate features of a good that are less important now but more important in the future. It is therefore admittedly narrow to focus on just one behavioral anomaly. It is beyond the scope of this paper to assess optimal policy under every possible psychological bias. Rather, this paper contributes to the larger literature studying energy policy under psychological biases (e.g. Allcott et al., 2014; Tsvetanov and Segerson, 2013). As this literature grows, a fruitful area of research would be to provide more generalizable results that apply to situations where there is a diversity of biases.

Nevertheless, the model of quasi-hyperbolic discounting provides valuable insights relative to alternative models of behavioral biases. The model in Tsvetanov and Segerson (2013) considers a different type of bias, one in which consumers are not time-inconsistent but rather subject to temptation costs. Some results are analogous across that model and this one, but I introduce new insights and model different policies. For instance, I compare how a fuel economy tax compares to a fuel economy standard in addressing the behavioral bias. The model of Allcott et al. (2014) considers inattention to energy costs, which could be due to present bias or to other psychological biases. Relative to that paper, here I consider both fuel economy taxes and fuel economy standards (mandates and maximums). I also note that there are cases where the “internality dividend” from a tax on externalities can be of the wrong sign. Lastly, relative to both other papers, I consider in the online appendix how robust the policy responses are to alternative welfare criteria, important given the lack of consensus on how welfare analysis ought to be conducted under behavioral biases.

The theory provided a specific example of a market failure: a durable good that creates externalities. The simulation was even more specific: automobiles. The theoretical model is applicable to other externality-producing durable goods, like home appliances or home energy efficiency investments. Furthermore, the framework here may be applicable elsewhere. For example, time inconsistency is often attributed as relevant to the rise in obesity (Ruhm, 2012). The framework developed here could be used to analyze policy options like taxes on unhealthy foods, limitations on the availability of certain foods, or subsidies to gym memberships. These results could similarly be extended with applications to retirement savings or addictive behavior.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jeem.2015.04.002.

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