Title

Lifecycle emission impacts of subsidies for energy efficiency: Evidence from Cash-for-Clunkers

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Lifecycle emission impacts of subsidies for energy efficiency: Evidence from Cash-for-Clunkers

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Lifecycle emission impacts of subsidies for energy efficiency: Evidence from *Cash-for-Clunkers*

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Abstract

One popular policy option to address environmental and economic concerns arising from current patterns of energy use is to subsidize increase in energy efficiency or renewable energy. In this paper we evaluate the lifecycle environmental benefits of the Car Allowance Rebate System (CARS) (or commonly 'Cash-for-clunkers') which provided a subsidy for voluntary early retirement and replacement of low fuel economy automobiles with new, higher fuel economy vehicles. We find that the estimates of benefits hinge crucially on the assumption about what type of vehicle would have been purchased in the counterfactual scenario. Estimates are significantly less sensitive to assumptions about the remaining useful life of vehicles traded-in and the rebound effect. Our prediction is that CARS program lead to a reduction of 9.1 to 17.8 million metric tonnes in greenhouse gas (GHG) emissions and 850 to 1600 million gallon reduction in gasoline use over a 13 year period. The average subsidy per tonne of avoided GHG lies between $142 and $278. Disaggregation of benefits based on the fuel economy of the clunker reveals opportunities for better aligning incentives and program benefits in future.

Keywords: transportation, fuel, biofuel, energy efficiency, subsidy, pollution, lifecycle assessment.

1 Introduction

Current patterns of energy use are responsible for a range of societal concerns such as energy insecurity, resource depletion, pollution and high cost of energy. While there exist a variety of different ways in which public policy can mitigate these concerns and with different implications for efficiency and equity, such as establishing a fee for pollution, setting a cap on pollution and allocating tradable pollution rights, setting standards, mandating new technologies, providing information etc., a popular approach is to subsidize an increase in energy efficiency or renewable/clean energy. One such subsidy is to rebate the voluntary early replacement of energy intensive durable goods with more energy efficient substitutes. In this paper we evaluate the lifecycle environmental benefits of one such program, namely, Car Allowance Rebate System (CARS), commonly referred to as 'Cash-for-clunkers'. CARS was created with the passage of the Consumer Assistance to Recycle and Save Act in 2009[1]. The program aimed to both provide a stimulus to the U.S. economy at a time of recession by boosting auto sales, and also reduce pollution from road transportation by causing the early retirement of fuel inefficient vehicles or 'clunker' with more efficient vehicles. To

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[1] www.cbo.gov/doc.cfm?index=10323

this end, it offered a rebate of either $3500 or $4500 depending the fuel-economy of the clunker and the increase in the fuel economy as a result of the trade-in. Government records indicate that as of October 23, 2009 more than 677,081 clunkers were retired in exchange for a total rebate amount to $2.85 billion. Judging by the consumer response, one may describe the CARS program as a success. The economic and environmental merits of CARS are both however a topic of controversy with critics pointing out inefficiencies resulting from either the premature abandonment of functioning goods from future use (Abrams and Parsons, 2009, Miron, 2011) or subsidizing purchases that would have regardless of the policy (Miron, 2011); incentives for getting rid of a rarely used vehicle (Dill, 2001), higher driving than otherwise (Knittel, 2009); minimal to no effect of the economy and jobs (Mian and Sufi, 2010); and the high cost of greenhouse gas (GHG) abatement (Sachs, 2009). Others however argue that the program was successful in simultaneously aiding economic recovery and job creation(Ching et al., 2010), achieving energy and environmental goals and demonstrating that rapid change toward sustainability is possible(Tyrrell and Dernbach, 2011).

The focus of this paper is on estimating the lifecycle impact of CARS on air emissions (both GHG and non-GHG) and fuel consumption, and the subsidy provided per unit of avoided GHG emissions. There exists a large literature analyzing both the environmental impacts of CARS and previous experience with accelerated vehicle retirement programs. Lenski et al. (2010) calculate that the CARS avoided 4.4 million metric tonnes of carbon di-oxide equivalent (tCO_2e) emissions. Different from most of the earlier literature Lenski et al. compute the lifecycle effect by taking into account additional emissions attributable to vehicle manufacturing and disposal. Using the average fuel economy of the clunker, the average fuel economy of the new vehicle purchased, Abrams and Parsons (2009) hypothesize that CARS avoided about 840 gallons per year per vehicle over the three remaining years of the average clunker while Sachs (2009) predicts 1390 gallons per year per vehicle over a five period. The National Highway Traffic Safety Administration (2009) estimates a total savings of 823 million gallons of gasoline, and avoided lifecycle GHG emissions of about 9.5 million metric tons over a 25 year period. Voluntary accelerated vehicle retirement programs have also previously been implemented by several national and sub-national agencies. A survey of several programs in the U.S. and abroad, suggests that unlike CARS which was designed as an economic stimulus, reduce fuel use to improve energy security and to reduce GHG emissions, the former were focussed on reducing air pollutants such as volatile organic compounds (VOC), nitrogen oxide (NO_x), carbon monoxide emissions (CO) and particulate matter (PM) (Dill, 2004). The survey reveals that while vehicle retirement programs may likely reduce emissions, emissions of NO_x and CO did not decline as expected. The survey also suggests that previous U.S. programs generally did not attempt to influence the participants choice of replacement transportation although several

European programs, similar to CARS, required purchase of a new vehicle. Dill (2001) however points out that the estimates hinge crucially on the assumption about how the owner replaces the transportation provided by the scrapped vehicle.

Our paper differs from the previous literature in the following aspects. First, we estimate the lifecycle GHG and gasoline use reduction relative to different three different counter-factual scenarios and thus derive a range of estimates. Second, for each counterfactual scenario we analyze the sensitivity of impact to different assumptions about the remaining useful life of retired vehicles and to different magnitudes of the rebound effect. Third, we calculate the impact on emissions of criteria air pollutants. Fourth, we estimate the total benefits by aggregating the estimates for every clunker traded-in instead of estimating simply based on total average or average by vehicle class. We also disaggregate the impact based on the fuel-economy of the clunker and derive insights for improving program design. We begin by describing a simple model of the choice the owner of a clunker, or more generally a durable energy consuming good, faces.

2 Model

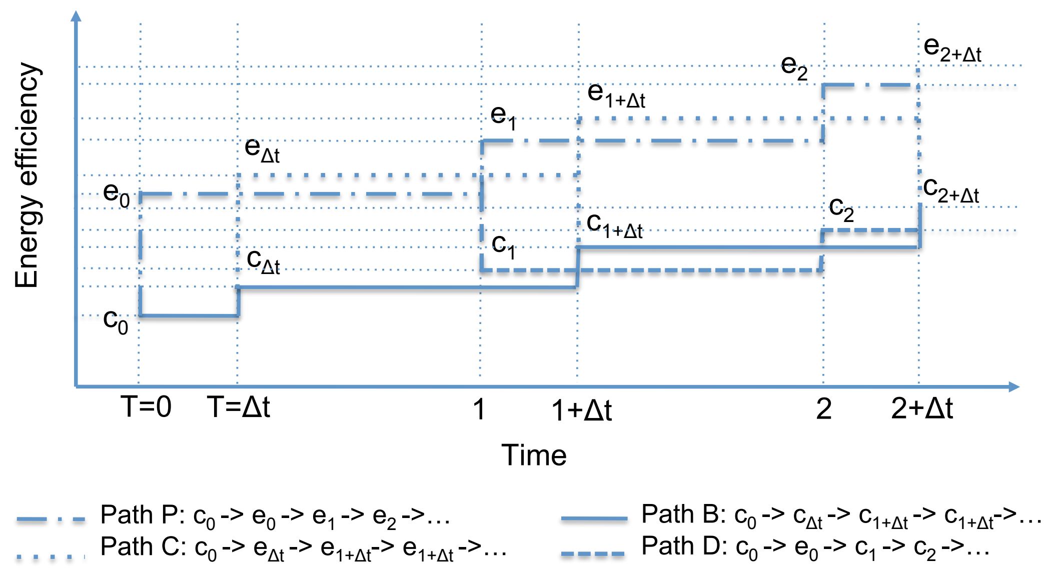


Figure 1: The choices the owner of an inefficient durable good faces over time

Figure 1 describes a generic model of replacement choices over time for the owner of low-efficiency durable good under a program such as CARS. Let c and e represent the energy use efficiency of the low-efficiency and the high-efficiency good respectively. Let subscripts $0, 1, 2..$ denote time. Δt represent remaining life span of the inefficient good at $T = 0$. It should be pointed out that even if the current owner sells the inefficient good prior to its end of useful life, the good would continue to be operated by a second-hand buyer and from a lifecycle emissions perspective, our concern is only with the utilization of the good rather than the its utilization by a given owner. This is significant departure from the assumptions of previous literature. Without loss of generality, let one unit of time interval denote the expected life span of the durable good, which is assumed the same for both c and e, and therefore $0 < \Delta t < 1$. Let us also assume that goods that are not traded-in at $T = 0$ and all new newly purchased goods will not be retired before end of expected useful life and that the energy efficiency for both goods increases over time i.e., $\frac{\partial c}{\partial t} > 0, \frac{\partial e}{\partial t} > 0$. Since the number of combinatorial choices increase exponentially with time, we depict the possibilities only through $T = 2 + \Delta t$. Path P denoted by ($c_0 \rightarrow e_0 \rightarrow e_1 \rightarrow e_2 \rightarrow$ ...) represents a combination of choices where in the owner of a clunker trades-in and switches permanently to a high-efficiency vehicle i.e., his future purchases are also high efficiency models. Path B denoted by ($c_0 \rightarrow c_{\Delta t} \rightarrow c_{1+\Delta t} \rightarrow c_{2+\Delta t} \rightarrow$ ...) implies that owner of a clunker does not trade-in and continues to purchase low efficiency vehicles into the future. Path C denoted by ($c_0 \rightarrow e_{\Delta t} \rightarrow e_{1+\Delta t} \rightarrow e_{2+\Delta t} \rightarrow$ ...) implies that even in the absence of CARS, the owner whould have switched to a high efficiency vehicle upon retirement of the clunker. Finally, path D denoted by ($c_0 \rightarrow e_0 \rightarrow c_1 \rightarrow c_2 \rightarrow$ ...) implies that despite opting into the program, the owner reverts to a low-efficiency vehicle for his next purchase.

Because the CARS program's primary objective was to stimulate the U.S. economy during a time of recession by boosting sales of automobiles and also because the future is uncertain, we restrict our analysis to time $T \in [0, 1]$. However, we consider two types of counterfactual scenarios for owners of clunkers that were not to traded-in but in the near future i.e., $T = \Delta t$, may need to be retired, namely, their next purchase is a clunker albeit more-efficient and that their next purchase is a high-efficiency vehicle. Thus we confine our analysis to comparing emissions under paths P, B, C in the time interval $[0, 1]$[2]. To the extent that the program induces a permanent switch to a higher efficiency category of vehicle, by confining our analysis to $T \in [0, 1]$ we under-estimate the program benefits. Let μ represent the emissions per gallon of gasoline and η represent the fuel efficiency of a vehicle in miles per gallon. Let $z = \frac{\mu}{\eta}$, represent emissions per mile. Let $\bar{L}$ represent the expected mileage before vehicle retirement and L represent the odometer reading on a vehicle at the time of trade-in. Let $\bar{Z}$ represent the emissions from vehicle production and disposal and $\bar{z} = \frac{\bar{Z}}{\bar{L}}$ represent the average emissions per mile attributable to production and disposal. We assume that each type of vehicles becomes more fuel-efficient with time i.e., $\eta^k_{t2} > \eta^k_{t1}$ for any $t2 > t1$, where $k \in (c, e)$.

[2]Emission under paths P and D are equivalent

The emissions under the three paths are,

$$\begin{aligned} Z_P &= (z_0^e + \bar{z})\bar{L} + \bar{z}(\bar{L} - L_c) \\ Z_B &= (z_0^c + \bar{z})(\bar{L} - L_c) + (z_{\Delta t}^c + \bar{z}_{\Delta t}^c)L_c \\ Z_C &= (z_0^c + \bar{z})(\bar{L} - L_c) + (z_{\Delta t}^e + \bar{z}_{\Delta t}^e)L_c \end{aligned} \tag{1}$$

Accounting for rebound: Thus far we assumed that total VMT between $T = 0$ and $T = 1$ is fixed and equal to $\bar{L}$. However, it has been argued by several researchers that one unintended consequence of increase energy efficiency is *rebound* in energy consumption (Greening et al., 2000, Hertwich, 2005, Small and Van Dender, 2007, Sorrell and Dimitropoulos, 2008). Rebound arises from the reduction in the marginal cost of energy as a result of energy efficiency. In the context of increase in automobile fuel economy, this implies a result of lower marginal cost of driving and increase in driving as a consequence. Furthermore, there may also be an additional rebound from switching to a newer, low-maintenance and more comfortable vehicle. We modify the system of equations (1) in the following manner to account for rebound. Let, p_g denote price of gasoline; $p_f^k = \frac{p_g}{\eta^k}$, $k \in \{e, c\}$ the cost per mile for a given type of vehicle; $\epsilon < 0$ the price elasticity of demand for gasoline. Then, the percentage increase in gasoline consumption as a result of increase in energy efficiency and reduction in cost of driving ($p_f^e < p_f^c$ since, $\eta^e > \eta^c$) assuming constant elasticity of demand is given by,

$$\frac{dq}{q} = \epsilon \frac{dp_f}{p_f} = \epsilon \frac{\frac{p_g}{\eta^e} - \frac{p_g}{\eta^c}}{\frac{p_g}{\eta^e}} = \epsilon \left(\frac{\eta^c}{\eta^e} - 1 \right) \tag{2}$$

Since $q = \frac{L}{\eta}$ and holding η fixed once a new vehicle has been purchased, the increase in driving with the new vehicle as a result of the increase in gasoline consumption is

$$\frac{dL}{L} = \frac{dq}{q} = \epsilon \left(\frac{\eta^c}{\eta^e} - 1 \right) \tag{3}$$

Equations (2) and (3) show that the rebound effect on fuel use and driving is a function of the elasticity of demand and ratio of the fuel economy of the old and new vehicle. Since $\epsilon < 0$ and $\eta^e > \eta^c$, the rebound effect increases with increase in elasticity of demand and increase in $\frac{\eta^e}{\eta^c}$. We can now rewrite (1) as

$$
\begin{aligned}
Z_P &= (z_0^e + \bar{z})(\bar{L} + d\bar{L}(\eta_0^e)) + \bar{z}(\bar{L} + d\bar{L}(\eta_0^c) - L_c) \\
Z_B &= (z_0^c + \bar{z})(\bar{L} + d\bar{L}(\eta_0^c) - L_c) + (z_{\Delta t}^c + \bar{z}_{\Delta t}^c)(L_c + d\bar{L}(\eta_{\Delta t}^c)) \\
Z_C &= (z_0^c + \bar{z})(\bar{L} + d\bar{L}(\eta_0^c) - L_c) + (z_{\Delta t}^e + \bar{z}_{\Delta t}^e)(L_c + d\bar{L}(\eta_{\Delta t}^e))
\end{aligned} \tag{4}
$$

Gasoline use under each path is

$$
\begin{aligned}
q_P &= \frac{1}{\eta_0^e}(\bar{L} + d\bar{L}(\eta_0^e)) \\
q_B &= \frac{1}{\eta_0^c}(\bar{L} + d\bar{L}(\eta_0^c) - L_c) + \frac{1}{\eta_{\Delta t}^c}(L_c + d\bar{L}(\eta_{\Delta t}^c)) \\
q_C &= \frac{1}{\eta_0^c}(\bar{L} + d\bar{L}(\eta_0^c) - L_c) + \frac{1}{\eta_{\Delta t}^e}(L_c + d\bar{L}(\eta_{\Delta t}^e))
\end{aligned} \tag{5}
$$

Equations (4) and (5) suggests that the benefits of program increase with increase in fuel economy,η_0^e, of the newly purchased vehicle; decrease with increase in fuel economy, η_0^c, of the clunker; decrease with increase in fuel economy of the vehicle purchased in the counterfactual $\underline{\eta}_{\Delta t}^c$ or $\underline{\eta}_{\Delta t}^e$; decrease with increase in VMT of the clunker, L_c; and increase with increase in emission intensity of gasoline μ (since $z = \frac{\mu}{\eta}$). Our model under-estimates emission reduction benefits of the vehicle retirement program in the counterfactual B in case the program induces a permanent switch to a higher efficiency category of vehicle. Total avoided emissions and gasoline use over all vehicles traded-in, N, with respect to counterfactual $j \in B, C$ is given by ,

$$
\sum_{i=1}^{N} \Delta Z_{P,j}^i = \sum_{i=1}^{N} Z_P^i - Z_j^i \tag{6}
$$

$$
\sum_{i=1}^{N} \Delta q_{P,j}^i = \sum_{i=1}^{N} q_P^i - q_j^i \tag{7}
$$

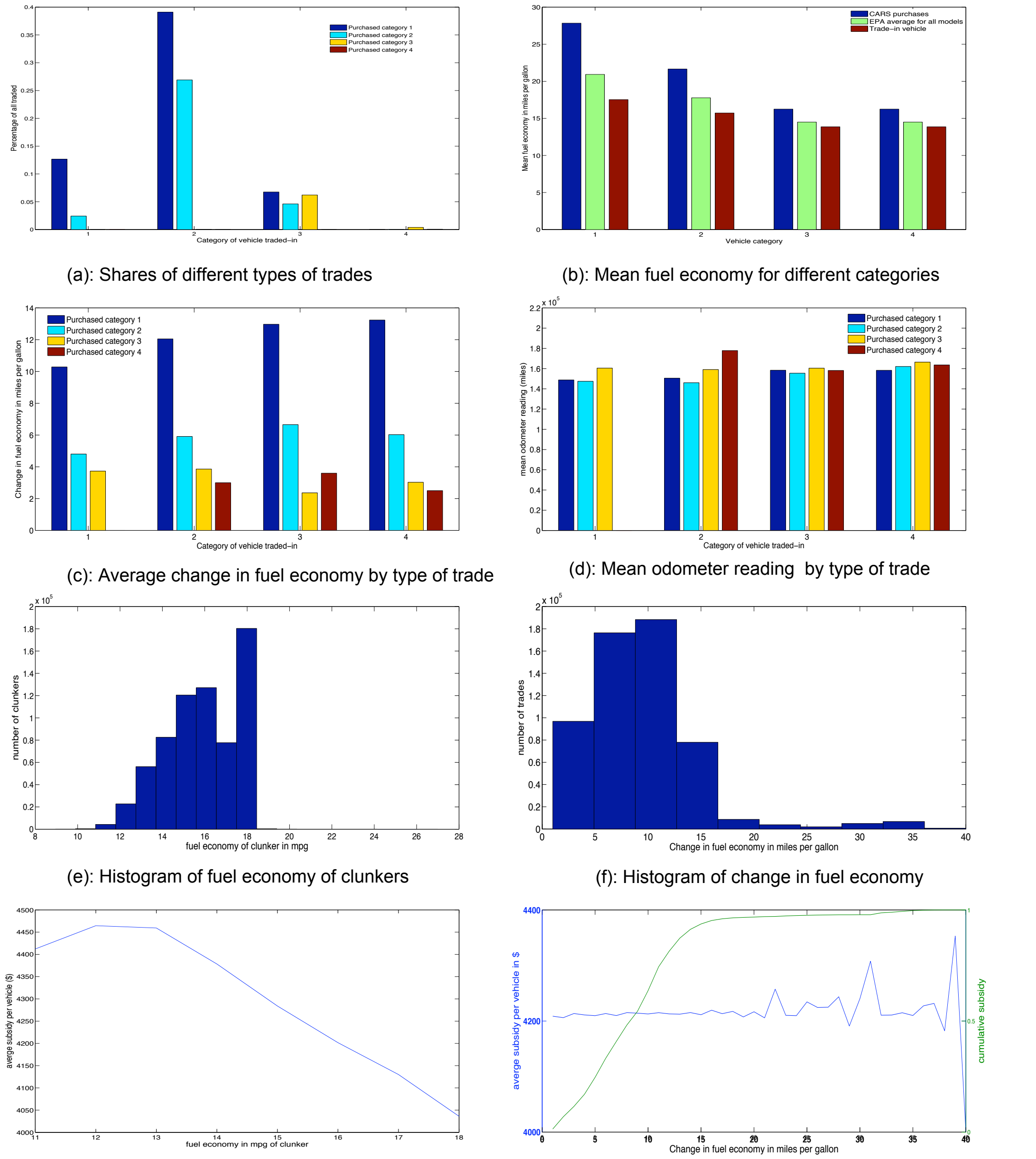
The average subsidy, per unit of emission reduction for clunker of given fuel economy, $\eta = \eta_k$, with respect to counterfactual j, is computed as

$$
\bar{s}_{\eta_k,j} = \frac{\sum_{i=1}^{n_k} s^i}{\sum_{i=1}^{n_k} \Delta Z_{P,j}^i} \text{ for each } \eta_k \in (\underline{\eta}, \bar{\eta}) \tag{8}
$$

where, n_k is the number of clunkers with $\eta = \eta_k$ and s^i is subsidy for vehicle i. It is worth pointing out that $\bar{s}_{\eta_k,j}$ does not reflect the cost-effectiveness of GHG abatement which requires taking to consideration the difference in purchase cost and lifecycle fuel cost. The average subsidy per unit of emission avoided by the program is computed as,

$$\bar{s}_j = \frac{\sum_{k=\underline{\eta}}^{\bar{\eta}} \sum_{i=1}^{n_k} s^i}{\sum_{k=\underline{\eta}}^{\bar{\eta}} \sum_{i=1}^{n_k} \Delta Z_{P,j}^i} \tag{9}$$

3 Data, results and sensitivity analysis



(a): Shares of different types of trades

(b): Mean fuel economy for different categories

(c): Average change in fuel economy by type of trade

(d): Mean odometer reading by type of trade

(e): Histogram of fuel economy of clunkers

(f): Histogram of change in fuel economy

(g): Average CARS subsidy per mpg of clunker

(h): Average & cumulative subsidy vs. change in mpg

Figure 2: Basic statistics from CARS database

The various attributes of the vehicle traded-in and the vehicle purchased for every transaction that involved a CARS rebate is recorded in the CARS database[3]. In these transcations, 85% of trade-ins under the program were vehicles in category 2 and above, while 59% of new vehicle purchases were category 1[4](see Figure 2a). Also more than 50% of all trades involved a switch to more efficient category of vehicle while 45% involved a switch to a new vehicle within the same category. Figure 2b shows that even in the case of the latter, average fuel economy of vehicles purchased was 28% higher than the average fuel economy of all new models currently available. Figure 2c shows that change in average fuel economy for each type of trade while figure 2d shows that the average clunker was driven more than 147K[5] miles. More than 99.9% of clunkers had an EPA fuel economy rating less than 18 mpg (see figure 2e). Figure 2f shows the distribution of the increase in fuel economy. Although the program offered only a two-tiered incentive structure, namely, $3500 for fuel economy increase of less than 10 mpg and $4500 for more than 10 mpg increase, figure 2g shows that the average subsidy declines with increase in fuel economy of the clunker. Figure 2h however, shows that the average subsidy was not strongly correlated with change in fuel economy for an owner after trade-in.

Other sources of data: We relied on the GREET model[6] for data on various types of air emissions during the fuel lifecycle (version 1.8d.1 of fuel-cycle model) and for emissions during vehicle production and disposal (version 2.7 of vehicle cycle model). For the fuel economy of the new vehicle purchased in the counterfactual scenario, we used the simple average of the fuel economy reported in EPA fuel economy guide 2009[7] for all models within a given category.

Sensitivity with respect to the counterfactual scenario: Since we do not observe the fuel economy for the counterfactual future purchase and since there exists a large number of possibilities for $z^c_{\Delta t}$ and $z^e_{\Delta t}$, we assume that future purchases fall into one of four categories as in the CARS database, namely , *Passenger cars, Category 1 Truck, Category 2 Truck*, and *Category 3 Truck*, henceforth referred to simply as categories 1, 2, 3 and 4 respectively, with average fuel economy such that $\underline{z}_1 < \underline{z}_2 < \underline{z}_3 < \underline{z}_4$. Path B can now be described as one in which the owner upon natural retirement of his vehicle in the future purchases a vehicle of the same type that he owns today, and path C as one in which he purchases a vehicle that is classified as being in a higher category

[3]Available for download http://www.cars.gov/

[4]We dropped about 11% of the observations from the CARS data set because that violated certain conditions, which led us to believe there might have been measurement/reporting error. The conditions for exclusion of observations were the following (numbers in parentheses denote the number of dropped observations in each case): missing fuel economy for either the vehicle traded-in or new purchase (n=5189); fuel economy of new vehicle less than fuel economy of clunker (n=5043); odometer reading $> 250,00$ (n=31175); yearly average vehicle miles travelled (VMT) below the 10^{th} percentile (n=31175); and yearly average VMT greater the 97.5^{th} percentile (n=16925)

[5]K =1000

[6]The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model available for download http://greet.es.anl.gov/

[7]http://www.fueleconomy.gov/feg/download.shtml

of fuel efficiency compared to that of the vehicle he owns today. For C, we consider two further possibilities wherein a owner would have a vehicle in the next higher category, termed $C1$ and one in which the owner would have purchased a vehicle from two categories higher, termed $C2$. $C1$ is applicable to clunkers in category 2, 3 and 4 which would have been replaced by new vehicles in category 1,2 and 3 respectively while category 1 vehicles are replaced with more efficient vehicles within the same category. Similarly scenario $C2$ is relevant only for clunkers in category 3 and 4, which would be replaced with vehicles in categories 1 and 3 respectively. In this scenario, category 2 vehicles are replaced with category 1. See 1 for the values used in the different scenarios.

Table 1: Average fuel economy by vehicle category in miles per gallon

	Trade-in (clunker)	CARS purchase	B[a]	C1	C2[c]
Category-1	17.5	27.0	20.9	22.9[b]	24.9[c]
Category-2	15.9	25.5	17.8	20.9	22.9[d]
Category-3	14.1	21.8	14.5	17.8	20.9
Category-4	6.3	16.6	14.5[e]	14.5	17.8

[a] EPA average fuel economy for model year 2009; [b] Fuel economy in counterfactual B + 2; [c] Fuel economy in counterfactual B + 4; [d] Fuel economy in counterfactual C1 + 2; [e] EPA does not report fuel economy for category 4 and so we used the value for Category-3. This affects only 0.35% of the observations used

Sensitivity with respect to remaining clunker life $\bar{L}$: Equations (4) and (5) indicate that the benefits of the program depend on the assumption regarding the average vehicle life, $\bar{L}$, and which determines the clunker life remaining ($\bar{L} - L_c$), where L_c is the odometer reading. Following GREET model, we assume $\bar{L} = 160K$ miles. This is reasonable given that the average odometer reading for all clunkers, $\bar{L}_c$ was 147K miles (figure 2d). Furthermore, more than 36% of the clunkers had an odometer reading exceeding 160K while more than 25% had been driven more than 175K miles. For clunkers with $L_c \leq 160K$, we set $\bar{L} - L_c = 160K - L_c$ miles. For clunkers with $L_c > 160K$ miles we analyzed the sensitivity to three different assumptions of $\bar{L} - L_c$ namely, 5K, 10K and 15K miles. Even though the consumer survey suggests that program participants would have kept their vehicles on average for another 2.5 years without CARS, and half intended to keep them for less than two years, the fact that more than 50% of the vehicles had been driven less than 145K miles suggests they would have on average been used for another 15K miles by subsequent owners of the clunker before being retired. This marks a departure from the assumptions of the previous literature.

Sensitivity to price elasticity of gasoline demand: The rebound effect is a function of the price elasticity of gasoline demand, ϵ. One estimate of this effect is by Small and Van Dender (2007), who estimate a long-run rebound elasticity of 0.11 over a four year period spanning 1997 to 2001. We therefore analyze the sensitivity of benefits to three different values of $\epsilon = \{0, -0.1, 0.2\}$ that are representative of the elasticity of demand.

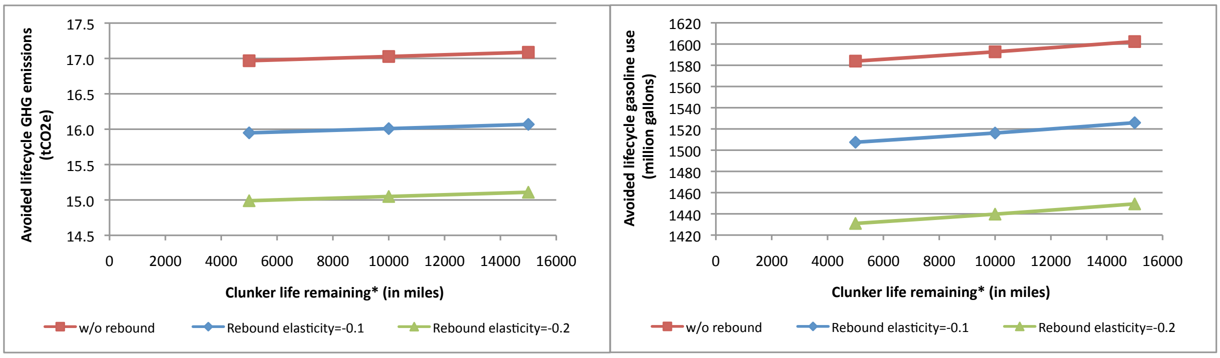


Figure 3: Sensitivity of total avoided emissions and total avoided gasoline consumption to assumptions about remaining life and elasticity of rebound for counterfactual B

Figures 3 suggests that both avoided GHG emissions in tCO_2e and avoided gasoline consumption in million gallons, which albeit increasing, is relatively insensitive to $\bar{L} - L_c$ and slightly more sensitive to ϵ. As the analytical model suggested, the benefits increase with increase in remaining life and decrease with increase in price elasticity of gasoline demand. Figure 4 suggests that the benefits are highly sensitive to assumption about the counterfactual. The benefits are highest when the counterfactual is B, i.e., the owner's next purchase in the absence of CARS would be a clunker and least when the counterfactual is $C2$, i.e., the owner's next purchase in the absence of CARS would be a vehicle two categories higher in fuel efficiency (for clunkers in category 3 and 4). Overall, we find that depending on the assumption about when and what type of vehicle would have been purchased in the counterfactual scenario, GHG benefits range from 5.2 to 17.8 million tCO_2, reduction in gasoline use ranges between 500 to 1600 million gallon. Assuming average yearly VMT of 12000 miles these benefits are realized over a 13 year period. The average subsidy per tonne of avoided GHG lies between \$142 to \$492. One might thus refer to scenarios $\{B, C1, C2\}$ as optimistic or high, medium and pessimistic or low scenario respectively. In our calculations, the same counterfactual scenarios applies to all vehicles simultaneously. One can perform simulations for which the counterfactual scenario is chosen at random from among $\{B, C1, C2\}$ for any given vehicle. The estimates from such simulations should lie within the range we calculate here.

Figure 5 shows the average lifecycle emission reduction (left y-axis) and the average subsidy per tonne of carbon di-oxide (tCO_2e) (right y-axis) for a given fuel economy of clunker. Average

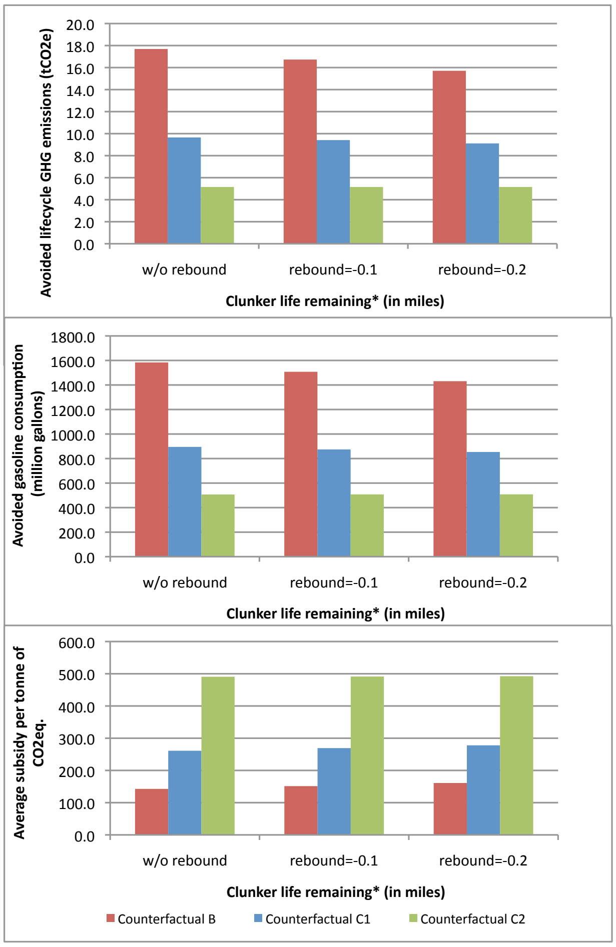
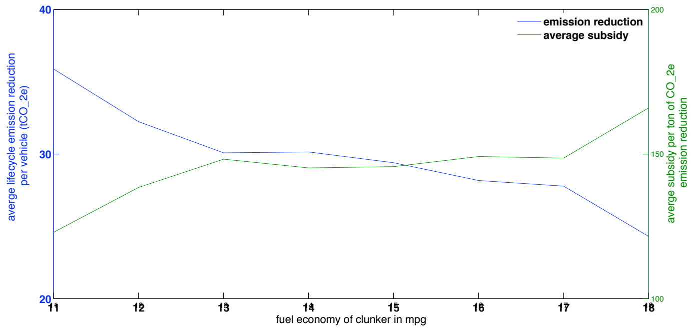
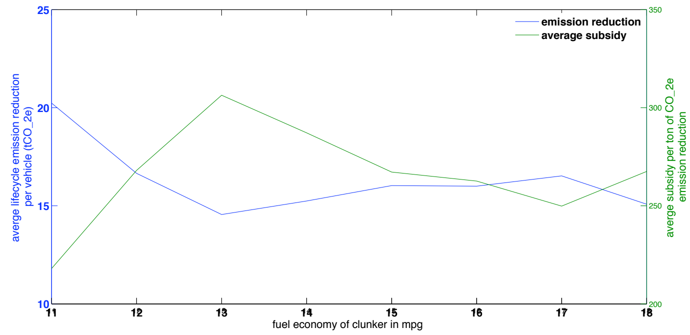


Figure 4: Sensitivity to counterfactual and and elasticity of rebound for counterfactual B when clunker life remaining = 5K miles (*assumption applies only clunkers with $\bar{L} - L_c > 160K$)

emission reduction achieved by the policy decreases with increase in fuel economy of the clunker while average subsidy per tCO_2e increases with fuel economy (excluding clunkers whose fuel economy is 13 mpg in the case C scenario). For B, when remaining VMT is 5K, average lifecycle GHG emission reduction across all clunkers with a given fuel economy ranges from 24.3 to 35.9 tCO_2e while average reduction in lifecycle gasoline consumption per vehicle is between 2200 and 3200 gallons. Average subsidy ranges between \$123 and \$166 per tCO_2e. If the true counterfactual is C, the policy leads to lower emission reduction (14.5 to 20.2 tCO_2e), lower reduction in gasoline consumption (1400 to 1800 gallons per vehicle) and higher subsidy per tCO_2 (\$218 and \$306 per tCO_2e) for a given fuel economy compared to B. The impact on emissions of other air pollutants is shown in 2. Again, as with CO_2, emission reduction is higher for all pollutants under B relative to $C1$ which in turn is higher relative to $C2$.



(a): Counterfactual B



(b): Counterfactual C1

Figure 5: CARS outcomes as a function of fuel economy of clunkers

4 Discussion

We show that changing the assumptions used to calculate the emission and fuel use reductions from early vehicle retirement can imply a large range for benefits. The benefits are highest when the counterfactual is B, i.e., the owner's next purchase in the absence of CARS would be a clunker and least when the counterfactual is $C2$, i.e., the owner's next purchase in the absence of CARS would be a vehicle two categories higher in fuel efficiency (for clunkers in category 3 and 4). Our prediction based on scenarios B (or optimistic) and $C1$ (or mid) is that CARS program lead to a reduction of 9.1 to 17.8 million metric tonnes in greenhouse gas (GHG) emissions and 850 to 1600 million gallon reduction in gasoline use over a 13 year period. The average subsidy per tonne of avoided GHG lies between \$142 and \$278. Since we do not calculate the private economic cost and benefits such as the difference in the purchase price of the old and new vehicle, the difference in lifecycle fuel cost (Knittel, 2009) or the general equilibrium effects of CARS and their associated environmental impacts, we would like to emphasis that subsidy per unit of emission reduction does not represent the social cost of GHG abatement and therefore should not be compared as such with other policies such as a carbon tax or a biofuel subsidy. Disaggregation of benefits based on the fuel economy of the clunker reveals opportunities for better aligning incentives and program

Table 2: Average lifecycle emission reduction (in kg) of non-GHG pollutants under different counterfactual scenarios and different rebound elasticities (clunker life remaining =5000 miles)*

	No rebound			Rebound elasticity = -0.1			Rebound elasticity= -0.2		
Polluta nt	B	C1	C2	B	C1	C2	B	C1	C2
VOC	8.3	3.3	0.5	7.3	2.9	0.4	6.2	2.6	0.3
CO	137	76	41	130	74	41	123	72	41
Nox	12.6	6.6	3.2	11.7	6.3	3.2	10.9	6.1	3.2
PM10	1.7	0.4	-0.3	1.4	0.3	-0.4	1.0	0.2	-0.4
PM2.5	1.0	0.3	0.0	0.8	0.3	-0.1	0.7	0.2	-0.1
SOX	2.4	0.4	-0.7	1.8	0.2	-0.7	1.3	0.0	-0.8

* This assumption is used only for vehicles for vehicles with odometer reading, L_c, exceeding 160K else it is set equal to (160K -L_c)

benefits in future. One should however be careful in interpreting the benefits of future vehicle retirement programs based on past experience. Given that the average fuel economy of the fleet is increasing with time in response to rising fuel prices, more stringent fuel economy standards and last but least previous CARS-like programs, the average emission reduction per dollar of subsidy may decline in future.

Our estimates for avoided emissions and avoided gasoline use are higher compared to previous estimates of Abrams and Parsons (2009), Knittel (2009), Sachs (2009), Lenski et al. (2010). We believe the main difference lies in the assumption about the average remaining useful life of the clunker[8]. In our calculations, 50% to 60% of the emission and gasoline use reduction stem for clunker miles not driven. It is worth reiterating here that our calculation underestimates benefits if CARS induces a permanent switch to high fuel economy vehicle that would either not have occurred or been delayed beyond the next purchase. For $\epsilon = -0.1$, the counterfactual $C1$ and $\bar{L} - L_c = 5K$, our estimate compares well with the National Highway Traffic Safety Administration (2009)'s estimated benefits of 9.5 million tCO_2e and 823 million gallons for CARS (see figure 4), which they however estimate over a 25 year period.

Although economic theory suggests that in the long-run a policy based on pollution fee is more cost-effective than a subsidy for clean technology (they are equivalent in the short-run), subsidies are nevertheless a popular and widely employed policy instrument and likely to remain so. However, since unlike taxes and standards, subsidies impose a burden on the government's finances, maximizing the environmental benefit per dollar of subsidy is likely one among the several objectives that policy makers consider. The approach employed here can be applied as a screening tool for comparing the relative effectiveness of the different subsidy-driven approaches in a wide range of contexts such as household appliances, agricultural production, land use etc. under

[8]See the detailed discussion in section 3 about the sensitivity to this parameter and how we depart from the literature

different counter-factual scenarios It can also be easily extended to include longer time horizons.

References

B.A. Abrams and G.R. Parsons. Is CARS a Clunker? *The Economists' Voice*, 6(8):4, 2009. ISSN 1553-3832.

A. Ching, M. Clark, T. Dutta, and Y. Zhu. Comment on Abrams and Parsons: CARS is Hardly a Clunker. *The Economists' Voice*, 7(1), 2010. ISSN 1553-3832.

J. Dill. Design and administration of accelerated vehicle retirement programs in North America and abroad. *Transportation Research Record: Journal of the Transportation Research Board*, 1750(-1):32–39, 2001. ISSN 0361-1981.

J. Dill. Estimating emissions reductions from accelerated vehicle retirement programs. *Transportation Research Part D: Transport and Environment*, 9(2):87–106, 2004. ISSN 1361-9209.

A. L. Greening, D.L. Greene, and C. Difiglio. Energy efficiency and consumptionthe rebound effecta survey. *Energy Policy*, 28(6-7):389–401, 2000. ISSN 0301-4215.

T.W. Hertel, A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen. Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses. *BioScience*, 60(3):223–231, 2010.

E.G. Hertwich. Consumption and the rebound effect: An industrial ecology perspective. *Journal of Industrial Ecology*, 9(1-2):85–98, 2005. ISSN 1530-9290.

C.R. Knittel. *The implied cost of carbon dioxide under the cash for clunkers program.* Institute of Transportation Studies, University of California, Davis, 2009.

S.M. Lenski, G.A. Keoleian, and K.M. Bolon. The impact of'cash for clunkers' on greenhouse gas emissions: a life cycle perspective. *Environmental Research Letters*, 5:044003, 2010.

A. Mian and A. Sufi. The effects of fiscal stimulus: Evidence from the 2009 cash for clunkers program. Technical report, National Bureau of Economic Research, 2010.

J.A. Miron. Cash for Clunkers Is a Clunker. *Future*, 2011.

NHTSA National Highway Traffic Safety Administration. U.s. department of transportation. *Consumer Assistance to Recycle and Save Act of 2009. Report to the House Committee on Energy and Commerce, the Senate Committee on Commerce, Science, and Transportation and the House and Senate Committees on Appropriations*, 2009.

D. Rajagopal, G. Hochman, and D. Zilberman. Indirect fuel use change and the environmental impact of biofuel policies. *Energy Policy*, 2010.

J. Sachs. Sustainable Developments-A Clunker of a Climate Policy. *Scientific American Magazine*, 301(5):34–34, 2009. ISSN 0036-8733.

K.A. Small and K. Van Dender. Fuel efficiency and motor vehicle travel: The declining rebound effect. *The Energy Journal*, 28(1):25–51, 2007.

S. Sorrell and J. Dimitropoulos. The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics*, 65(3):636–649, 2008. ISSN 0921-8009.

M. Tyrrell and J.C. Dernbach. The" cash for clunkers" program: A sustainability evaluation. *Widener Law School Legal Studies Research Paper Series no. 11- 08*, 2011.