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LIFE CYCLE ENVIRONMENTAL AND ECONOMIC IMPACTS OF "CASH FOR CLUNKERS"

by

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A thesis submitted
in partial fulfillment of the requirements
for the degree of
Master of Science
(Natural Resources and Environment)
in the University of Michigan
April 2011

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Abstract

Through the \$3 billion US Consumer Assistance to Recycle and Save (CARS) Act of 2009, or “Cash for Clunkers” program, nearly 700,000 consumers scrapped fuel-inefficient vehicles in exchange for rebates of \$3,500 or \$4,500 toward the purchase of a new, more fuel-efficient vehicle. This research aims to provide a more comprehensive, life cycle accounting of environmental and economic benefits associated with CARS.

Environmental benefits included reduction in both greenhouse gas and criteria pollutant emissions. A life cycle accounting suggests that CARS prevented 4.4 million metric tons of CO_2-equivalent greenhouse gas emissions. This is substantially lower than estimates in previous studies, which failed to include the life cycle effect of additional emissions produced during new vehicle production and overestimated vehicle-miles remaining in the life of ‘clunkers’. Using previously estimated damage costs of \$21 per metric ton of CO_2, this benefit is worth \$93 million. About 20,000 metric tons of criteria pollutant emissions were also avoided. Damage costs from criteria pollutants vary by geographic location and source height, which previous studies do not account for. Incorporating these factors suggests the benefits from avoided criteria pollutants were worth \$17 million (two to six times greater than estimates using simple average or median damage costs).

CARS also provided economic stimulus on a macroeconomic level and for participants. The economic literature suggests the program induced sales of up to 450,000 new vehicles; provided up to 62,000 job-years; and contributed up to \$4 billion in gross domestic product. Comparing the market value of scrapped vehicles to the rebate from CARS, the consumer surplus or “gift” to participants is calculated to be up to \$2 billion (about \$2,000 to \$3,000 per vehicle). This is significantly more than offered in previous vehicle scrappage programs, and suggests opportunities to get more environmental and economic “bang for the buck” with lower rebates, an alternate mechanism for setting rebate values, and/or more specific targeting of vehicles for participation.

Acknowledgements

This research has come to fruition with support and guidance from many individuals and organizations. I am immensely grateful to Dr. Gregory Keoleian and Dr. Michael Moore, my thesis committee members, for their enthusiastic encouragement of this research. They provided valuable direction and guidance while leaving me ample room to develop the research according to my own interests. In the classroom and in advising this research, they have both been outstanding advocates for serious scholarship at the graduate level, and I am grateful for everything they taught me and skills they pushed me to learn and develop through this research.

The Center for Sustainable Systems (CSS) at the School of Natural Resources and Environment provided terrific companionship and bright colleagues whose help on numerous occasions improved both the quality of this research and the quality of my experience doing it. In particular, Kevin Bolon was an excellent collaborator on the greenhouse gas paper, with deep and helpful knowledge of transportation policy, and a valued brainstorming partner on the question of CARS' consumer surplus. Robb de Kleine provided support in developing a macro to look up vehicles' trade-in values.

Alex Andrus, Adam Bennett, and Mike Sintetos were team members for the group project, for Dr. Keoleian's Sustainable Energy Systems class, in which this research originated. Their ideas have helped form the foundation of this work. John de Cicco and members of the External Advisory Board of the CSS provided valuable comments on the early stages of this research, which helped provide direction for advancing it.

This research was supported through the National Science Foundation (CMMI 0628162), Alcoa Foundation Conservation and Sustainability Fellowship Program, University of Michigan Transportation Research Institute Doctoral Studies Program, and a University of Michigan School of Natural Resources and Environment Master's Thesis Funding Grant. Any opinions, findings, and conclusions or recommendations expressed in this

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material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Last but not least, I gratefully thank Sam, my parents, and all my friends for their love and support and encouragement, and Ilana, for just being.

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1. Introduction

In 2009, the US Congress passed the Consumer Assistance to Recycle and Save (CARS) Act, also known as the Car Allowance Rebate System or, more popularly, "Cash for Clunkers." Under the three billion dollar program, consumers were invited to scrap their fuel-inefficient vehicles in exchange for a rebate toward the purchase of a new and more fuel-efficient vehicle. The program was intended to provide both economic and environmental benefits by stimulating the struggling economy (and in particular the automotive sector) and removing some of the most inefficient and polluting vehicles from the roads.

CARS was wildly popular among consumers and garnered significant media attention. Following the program's completion, however, there was limited external assessment of the true impacts. The most comprehensive assessment was completed by the administering agency, the National Highway Traffic Safety Administration (NHTSA) [1]. Over the course of the following two years, several academic researchers, think tanks, and other organizations added their own analysis of the program's impacts [2-12].

This research was begun in fall of 2009, shortly after CARS' conclusion, to answer the question: "What impact did CARS have on greenhouse gas emissions from the US vehicle fleet?" Section 2 is devoted to addressing this question, and has been published in *Environmental Research Letters* [6]. It adds to the existing literature by adopting a full life cycle perspective of the greenhouse gas emissions resulting from the program, whereas previous studies primarily focused on those emissions from vehicle usage (fuel combustion) and a few also considered upstream fuel impacts. This research also provides a more detailed analysis than others available at the time of publication, using actual data on scrapped and new vehicles' age, mileage, and other factors that affect life cycle emissions. Finally, it addresses a number of sensitivities around important but unknown factors such as miles remaining in the life of scrapped vehicles.

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Section 3, a paper currently being prepared for publication, builds on the analysis from Section 2 to further understanding of CARS' environmental benefits and also consider the program's economic impacts. Four key questions are asked: What was the impact of CARS on life cycle emissions of criteria pollutants? How much economic benefit did avoided emissions provide? What kind of benefit did participating consumers receive from the program? And how do all of these effects fit into the larger context of CARS' many costs and benefits? To answer these questions, the life cycle framework from Section 2 is used to analyze the impact on criteria pollutant emissions. The mass of avoided pollutants is translated into economic benefit using existing estimates of pollution damage costs. The economic stimulus that the program provided to participants is calculated as the difference between the rebate received and the trade-in market value of scrapped vehicles. All of these benefits are considered in a framework developed to contextualize a number of the program's largest macroeconomic, public good, and individual benefits and costs.

CARS was just one example of an early vehicle retirement, or vehicle scrappage, program, which have been enacted across the US for several decades, though usually on a much smaller scale than CARS. Sections 2 and 3 each review some of the theoretical and empirical literature on these types of programs and their intended and achieved impacts on environmental and economic indicators.

Section 4, the conclusion, reviews the key findings from Sections 2 and 3. It also provides directions for future research on CARS, and highlights ways that this research might be used by policymakers in the design of future vehicle scrappage programs.

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2. The impact of 'Cash for Clunkers' on greenhouse gas emissions: a life cycle perspective

2.1. Introduction

2.1.1. Cash for Clunkers program overview

In June 2009, the U.S. Congress passed the Consumer Assistance to Recycle and Save (CARS Act, also known as the Car Allowance Rebate System or, more commonly, Cash for Clunkers. Under the program rules, consumers traded in qualifying vehicles – passenger cars or light trucks getting less than 18 miles per gallon (mpg) and less than 25 years old – and received a $3,500 or $4,500 rebate toward the purchase of a new, more fuel-efficient vehicle. Retired vehicles were then destroyed, permanently removing them from the U.S. vehicle fleet. By the time the $3 billion in funding was exhausted in August, nearly 700,000 old vehicles had been traded in and new ones purchased [13]. The program was expected to provide economic benefits to consumers and the struggling economy, and to benefit the environment by removing some of the least fuel efficient vehicles from the road [14].

2.1.2. Accounting for emissions benefits in the existing literature

2.1.2.1. Literature on CARS. Public communication about CARS frequently emphasized the program's expected environmental benefits. President Obama released a statement after the program's first week, lauding its "environmental benefits well beyond what was originally anticipated" [15]. Estimates of the program's environmental impact, and in particular the effect on fuel consumption and greenhouse gas (GHG) emissions, have been made prior to and since its conclusion. Abrams and Parsons [2, 3] and Sachs [9] used the average fuel economy of scrapped and new vehicles to estimate savings of about 280 gallons of gasoline per vehicle per year it would have remained on the road in the absence of CARS. Abrams and Parsons estimated scrapped vehicles would have been driven an additional three years, and Sachs assumed five years, implying total savings ranging from 840 to 1,400 gallons per vehicle, or about 570 to 950 million gallons total. Knittel [5] similarly analyzed the program's effect on GHG emissions, and he also considered the benefits from reduction of criteria pollutants. For its report to Congress on the results of CARS, the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) [1] estimated total savings of 823 million gallons of gasoline, or just under 9.5 million metric tons of CO_2-equivalent (CO_2-e) emissions (including those from gasoline combustion and upstream impacts from fuel extraction, processing, and distribution). The net effect of CARS on GHG emissions, however, is also influenced by factors other than the improvements in fuel economy. The program encouraged early retirement of functional vehicles, and by extension, moved forward in time the production of new vehicles; both the disposal and manufacture of vehicles contributes to GHG emissions. We believe that a life cycle assessment, which takes this fact into account, would provide a more accurate accounting of the GHG emissions impact of CARS.

2.1.2.2. Literature on accelerated vehicle retirement programs. Accelerated vehicle retirement programs (also known as scrappage programs) like CARS have been used for several decades. Most of the literature on the environmental impacts of such programs focuses mainly on the reduced emissions during vehicle operation (e.g., [16-19]), however, these studies potentially overestimate the net emissions reductions. Some of the recent literature has acknowledged the importance of a full life cycle perspective. Kim et al [20] addressed this issue and developed a model to calculate a vehicle lifetime that is optimal in terms of minimizing life cycle energy use and various vehicular emissions; Spitzley et al [21] built upon this work by also exploring the optimal lifetime from an economic standpoint, including the consumer's ownership costs and societal pollution costs. These two studies concluded that, depending on the pollutant or economic effect being prioritized and a vehicle's annual miles traveled, optimal lifetime could range from 2 to 19 years.

Van Wee et al [22] similarly suggested that assessments of scrappage programs need to include full vehicle life cycle effects. Using fuel efficiency data from vehicles in the

Netherlands, they estimated an optimal vehicle lifetime that balanced the energy use from operation with the energy use from production and disposal. They concluded that encouragement of accelerated vehicle retirement in the Netherlands might not actually reduce overall energy use or resulting emissions. Allan et al [23] reviewed characteristics of many vehicle scrappage programs from North America and Europe, demonstrating how program design could affect GHG emission reductions. They also advocated for the use of a life cycle framework, and proposed a formula to evaluate the minimum improvement in fuel economy between trade-in and replacement vehicles necessary to result in a net emissions reduction after taking into account the emissions from new vehicle production.

Despite the recognition that analyses of vehicle retirement programs should account for vehicle life cycle emissions, there has not yet been a study of CARS which fully includes this effect. In fact, the U.S. Government Accountability Office [11] has criticized NHTSA for its failure to account for life cycle effects in its assessment of the program. We have developed a more comprehensive model to fill this gap in the literature by assessing the greenhouse gas impact of CARS across the full vehicle life cycle.

2.2. Methodology

2.2.1. Life cycle system definition

The life cycle GHG emissions impact of vehicles can be analyzed by separately considering the fuel cycle and the vehicle production and disposal cycle (figure 1). The fuel cycle is made up of an upstream “well-to-tank” portion, which includes feedstock recovery and transportation, and fuel production and transportation; and the “tank-to-wheel” portion, which accounts for the combustion of the fuel in the vehicle during use [24]. The “tank-to-wheel” or combustion phase accounts for approximately 80% of total fuel cycle GHG emissions from gasoline [25]. The vehicle production and disposal cycle includes material extraction, processing, and fabrication; component production; vehicle assembly; end-of-life management; and the transportation of goods between these phases

[24]. The vehicle production and disposal cycle contributes about 10% to 20% of the total vehicle life cycle greenhouse gas emissions [24, 26, 27].

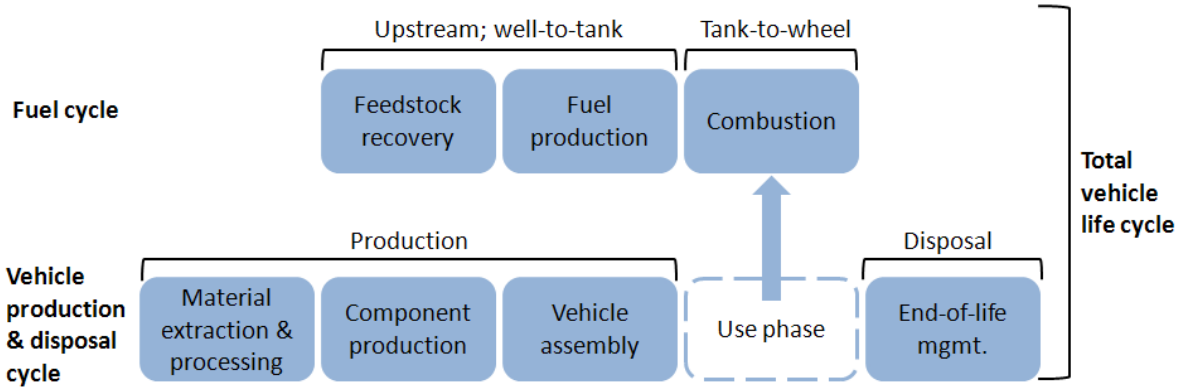

Figure 1. Separate fuel and vehicle production & disposal cycles are used to evaluate the total vehicle life cycle impact.

2.2.2. Modeling the effects of CARS on the life cycle system

The greenhouse gas impact of CARS is modeled in a two-step process. First, the impact of the program on the vehicle life cycle system is determined, so that the system may be compared with and without the program; next, those differences are used to calculate the emissions attributable to CARS.

2.2.2.1. Life cycle system with CARS. The schematic in figure 2a represents the life cycle of three successive vehicles, owned by one consumer, under the CARS scenario. The horizontal axis represents the number of vehicle miles traveled (VMT). The uppermost line represents the life cycle of Vehicle 1, owned by the consumer prior to announcement of the CARS program. The circles represent the greenhouse gas emissions from production and disposal of that vehicle, p_1 and d_1. The length of the bar represents the miles driven by that vehicle, at fuel economy m_1.

Under this scenario, the consumer drives x_1 miles on the original vehicle, and then trades it in through CARS, using the rebate to purchase a new vehicle, Vehicle 2_{CARS}. Over its

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lifetime, Vehicle 2_{CARS} produces emissions associated with production and disposal, p_{2CARS} and d_{2CARS}, and is driven x_2 miles at fuel economy m_{2CARS} before its own end of life. (We assume that, without an incentive such as CARS to retire a vehicle early, the end of a vehicle life is determined by miles traveled, x_2.) At that time, the consumer would purchase the next vehicle, and so on.

Only the retirement of Vehicle 1 and the purchase of Vehicle 2_{CARS} are affected by CARS, due to the short-term nature of this program. Therefore, the scope of analysis for this system is from mile zero on Vehicle 1 to the end of the life of Vehicle 2_{CARS}, which occurs at mile x_1+x_2. This area is shaded in figure 2.

2.2.2.2. Life cycle system without CARS. Figure 2b represents the life cycle of three successive vehicles *without* the CARS incentive program, the business-as-usual (BAU) scenario from which we calculate the differential impact of CARS.

Vehicle 1 in this scenario is the same as Vehicle 1 under the scenario with CARS. Its production, disposal, and fuel economy (p_1, d_1, and m_1) are the same as described above. The lack of an incentive to retire the vehicle early, however, means that Vehicle 1 is driven for x_2 miles, the expected life of a vehicle, before it is retired and replaced with Vehicle 2_{BAU}.

Vehicle 2_{BAU} may or may not be the same model vehicle as the consumer purchases under the CARS incentive, Vehicle 2_{CARS}. Because of the requirement to purchase a vehicle that meets certain fuel economy standards under CARS, Vehicle 2_{BAU} may be a less fuel efficient model than Vehicle 2_{CARS}. Vehicle 2_{BAU} is driven for an expected lifetime of x_2 miles before being retired and replaced with a third vehicle, and so on through the consumer's life. Once again, the scope of our analysis goes only through x_1+x_2 miles, represented by the shaded area in figure 2b.

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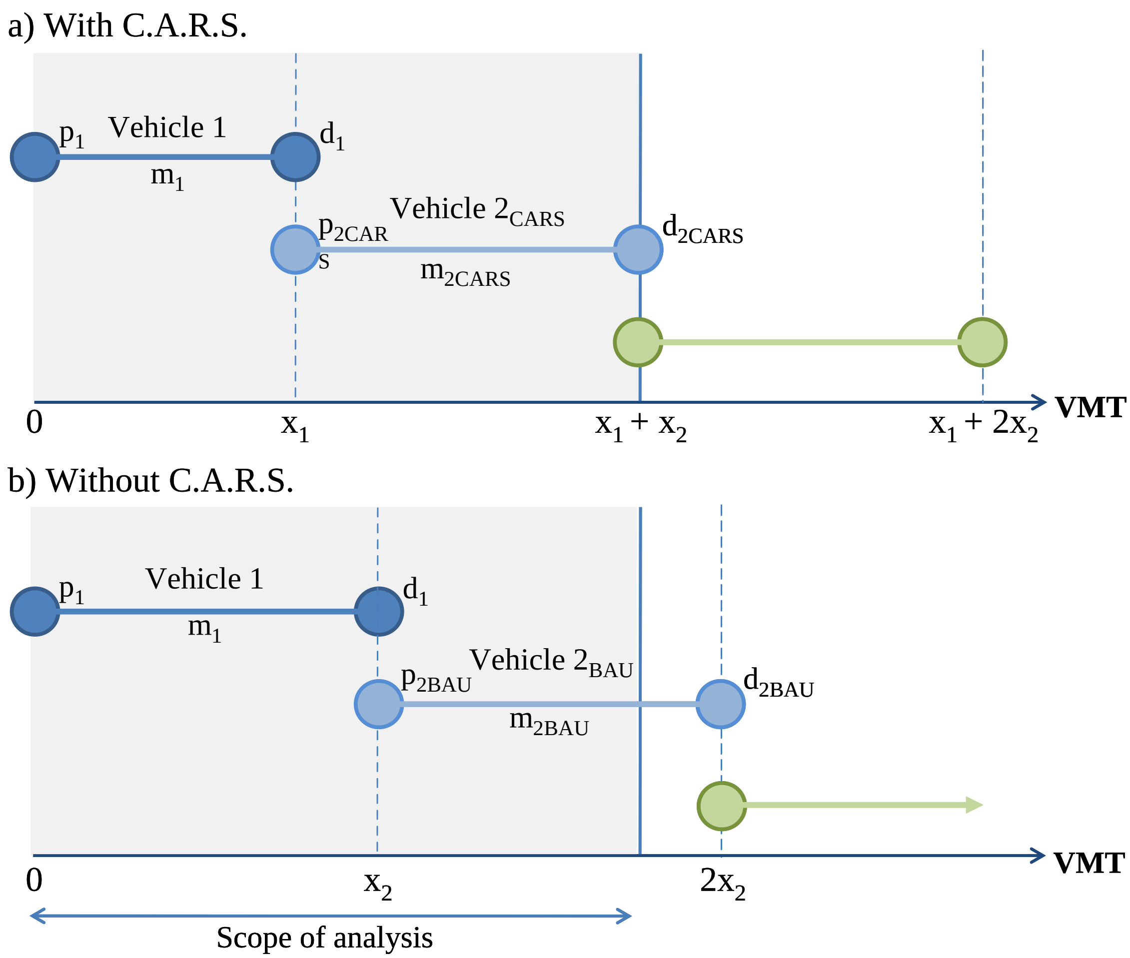

Figure 2. Vehicle replacement schedules with and without CARS, across a fixed "time" period as measured in vehicle miles traveled (VMT). Circles represent production and disposal of vehicles. Our analysis is limited in scope to the emissions attributable during the lifespan of Vehicle 1 and Vehicle 2_{CARS}, through mile x_1+x_2.

2.2.2.3. Characterizing system differences with and without CARS. The systems characterized in figure 2 suggest three sources of emissions differences with and without CARS (table 1). First, between miles x_1 and x_2, the vehicle driven by a consumer who participates in CARS (Vehicle 2_{CARS}) is more fuel-efficient than the vehicle driven in the absence of CARS (Vehicle 1). This is the fuel economy effect modeled in most previous analyses. Second, Vehicle 2_{CARS} may be more fuel-efficient than Vehicle 2_{BAU}, a benefit that accrues for all miles driven between x_2 and x_1+x_2. Third, within our time scope, the consumer who participates in CARS has been responsible for the production and disposal

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of two full vehicles. Without CARS, that consumer would have only been responsible for the production and disposal of Vehicle 1, and a *portion* of the production and disposal of Vehicle 2_{BAU} (we allocate production and disposal impacts by VMT.) The first two effects described above relate to emissions from the fuel cycle, whereas the third effect takes place in the vehicle production and disposal cycle.

The extra vehicle-cycle emissions created through CARS occur because of somewhat earlier production and purchase of the second vehicle. Importantly, though, those emissions as modeled here are *not* simply inevitable emissions shifted in time. A portion of the emissions from the production and disposal are incremental emissions that would not have occurred without CARS. If figure 2 were extended out indefinitely, the consumer who participated in CARS would always be responsible for the production of a partial additional vehicle compared to a consumer who did not participate in CARS. Those emissions are the ones we model here.

Table 1. Key sources of emissions differences with and without CARS.

Effect	**Part of**	**Description**
1	Fuel cycle	"Clunker" retired early, and miles remaining in its natural life instead driven in new, more fuel-efficient vehicle.
2	Fuel cycle	New vehicle purchased under CARS more fuel-efficient than consumer's next new vehicle would have been.
3	Vehicle production & disposal cycle	Premature retirement of "clunker" and manufacture of new vehicle under CARS cause additional production and disposal emissions.

Defining the following variables, we model the impact of each effect for a single vehicle:

p_i = GHG emissions resulting from production of Vehicle i, for i =1, 2_{CARS}, 2_{BAU}
d_i = GHG emissions resulting from disposal of Vehicle i, for i =1, 2_{CARS}, 2_{BAU}

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m_i = fuel economy (mpg) of Vehicle i, for i =1, 2_{CARS}, 2_{BAU}

E = GHG emissions (upstream and combustion) per gallon of fuel

x_1 = lifetime VMT of vehicle retired early due to CARS program

x_2 = lifetime VMT of vehicle retired at end of natural life

The emissions savings attributable to *Effect 1* can be expressed as:

$$\left(x_2 - x_1\right)\left(\frac{E}{m_1} - \frac{E}{m_{2CARS}}\right)(1)$$

The emissions savings attributable to *Effect 2* can be expressed as:

$$x_1\left(\frac{E}{m_{2BAU}} - \frac{E}{m_{2CARS}}\right)(2)$$

The incremental emissions attributable to *Effect 3* can be expressed as:

$$p_{2CARS} + d_{2CARS} - \frac{x_1}{x_2}\left(p_{2BAU} + d_{2BAU}\right)(3)$$

The sum of *Effect 1* and *Effect 2*, minus *Effect 3*, equals the total per-vehicle emissions savings attributable to CARS:

$$\left(x_2 - x_1\right)\left(\frac{E}{m_1} - \frac{E}{m_{2CARS}}\right) + x_1\left(\frac{E}{m_{2BAU}} - \frac{E}{m_{2CARS}}\right) - \left(p_{2CARS} + d_{2CARS} - \frac{x_1}{x_2}\left(p_{2BAU} + d_{2BAU}\right)\right)$$

(4)

We calculate the program's total GHG emissions impact based on the average vehicle in CARS, multiplied by 677,081, the total number of participating vehicles.

2.2.3. Data sources and assumptions for empirical analysis

2.2.3.1. Official statistics on CARS. The Department of Transportation (DOT) published data for the vehicles that were traded in and purchased through CARS. These data (tables 2 and 3) include number of vehicles by type (passenger car and three categories of light trucks), odometer reading and age of traded-in vehicles, and fuel economy. Average fuel economy (m_1) and odometer reading (x_1) of traded-in vehicles were 15.7 mpg and 160,167 miles, respectively. Average fuel economy of new vehicles (m_{2CARS}) was 24.2 mpg. As tables 2 and 3 show, in addition to fuel economy improvements in each vehicle category, some improvement can also be attributed to a substantial number of participants trading in light trucks for passenger cars.

Table 2. Summary characteristics of vehicles traded-in through CARS. (Note. Source: [13]. Average fuel economy is calculated as fleet harmonic mean. Average odometer reading and average age are weighted averages by number of vehicles per category.)

Vehicle category	**Number traded-in**	**Average fuel economy (mpg)**	**Average odometer reading (miles)**	**Average age (years)**
Passenger car	102,638	17.5	152,401	16.6
Category 1 light truck	447,505	15.9	158,339	14.0
Category 2 light truck	119,394	14.1	172,068	16.2
Category 3 light truck	7,544	14.1[a]	185,948	16.3
Total / average	677,081	15.7	160,167	14.8

[a] Not available. Assumed same as category 2 light trucks.

Table 3. Summary characteristics of new vehicles purchased through CARS. (Note. Source: [13]. Average fuel economy is calculated as fleet harmonic mean.)

Vehicle category	**Number purchased**	**Average fuel economy (mpg)**
Passenger car	397,182	27.9
Category 1 light truck	230,220	21.6
Category 2 light truck	47,425	16.2
Category 3 light truck	2,254	16.2[a]
Total / average	677,081	24.2

[a] Not available. Assumed same as category 2 light trucks.

2.2.3.2. Fuel economy in absence of CARS. Sivak and Schoettle [10] found that fuel economy of new purchased vehicles during CARS was up to 0.7 mpg greater than would be predicted by their regression model based on historical trends, and this effect can

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presumably be attributed to CARS' incentives. Therefore, m_{2BAU} is calculated as m_{2CARS} – 0.7, or 23.5 mpg.

In the absence of CARS, many consumers would likely have replaced their trade-in vehicle with a used vehicle, instead of a new one. Those used vehicles may have had substantially lower fuel economy than those purchased through CARS, which would suggest a larger benefit than the 0.7 mpg differential we use to model *Effect 2*. However, we assume that all vehicle purchases "flow through" the U.S. fleet. Without CARS, the consumer selling a used vehicle would have purchased a new replacement, so *that* new vehicle (though it isn't actually purchased by the same consumer) is the one we compare to the new vehicle purchased through CARS.

2.2.3.3. VMT in absence of CARS. Data for x_2, the expected life of a vehicle in the absence of an incentive to retire it early, is not readily available. In previous studies, traded-in vehicles have been estimated to have roughly three to five years of life remaining, at an average of 12,000 miles per year [2, 5, 9]; added to the odometer reading at the time of trade-in, this would imply total vehicle lifetimes of about 196,000 to 220,000 miles. For two reasons discussed below, we suspect these estimates are too high, and therefore overestimate the avoided GHG emissions.

First, three to five years of additional use remaining on the "clunkers" may be an overestimate. According to a DOT survey, participants would have kept their vehicles for, on average, another 2.52 years without CARS, and half intended to keep them for less than two years [28].

Second, although a typical U.S. vehicle is driven about 12,000 miles per year [29], annual VMT tends to decrease with vehicle age, so CARS trade-ins should have been driven less than the average. In the DOT survey, participants indicated they drove their vehicles on average 9,412 miles in the year prior to CARS [1], close to what standard VMT schedules would predict for 14 to 16 year old cars and trucks (table 4). Further, VMT decreases at 4.33% per year, on average, for 15 to 20 year old vehicles (table 4).

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Table 4. VMT schedule used to estimate miles remaining for CARS trade-in vehicles. (Note. Source: [30].)

Vehicle age	Passenger cars VMT	Δ	Light trucks VMT	Δ
14	9,633	-	10,396	-
15	9,249	-3.99%	9,924	-4.54%
16	8,871	-4.09%	9,468	-4.59%
17	8,502	-4.16%	9,032	-4.60%
18	8,144	-4.21%	8,619	-4.57%
19	7,799	-4.24%	8,234	-4.47%
20	7,469	-4.23%	7,881	-4.29%
Average Δ across cars and light trucks: -4.33%				

Assuming 9,412 VMT per year, decreasing at 4.33% per year for 2.52 years, vehicles had about 21,904 miles remaining at the time of trade-in. This implies a total expected lifetime of 174,305 miles for passenger cars; 180,243 miles for category 1 light trucks; 193,972 miles for category 2 light trucks; and 207,852 miles for category 3 light trucks. We used the weighted average lifetime VMT (x_2) of 182,071 miles.

2.2.3.4. Calculating greenhouse gas emissions. Emissions factors from GREET models 1.8c.0 and 2.7 [24] were used to calculate fuel cycle and vehicle cycle emissions, respectively. The fuel cycle model provided an estimate for our emissions factor, E, of 0.01117 metric tons CO_2-e per gallon of fuel. The vehicle cycle model provided data for CO_2-e emissions from vehicle production and disposal for passenger cars (7.8 metric tons) and light trucks (10.1 metric tons). Weighted by the number of vehicles in each category, we used a value of 9.76 metric tons for the sum of our variables p_2 and d_2. For simplicity and lack of data, we assume that a consumer who wanted a light truck in the absence of CARS would not have purchased a passenger car as a result of CARS and vice versa, so that broad vehicle class is the same between Vehicle 2 under either scenario. Therefore, in our modeling, $p_{2CARS} = p_{2BAU}$ and $d_{2CARS} = d_{2BAU}$.

2.3. Results

2.3.1 Findings

Using equation (4), we calculate that CARS reduced greenhouse gas emissions by 4.4 million metric tons CO_2-e. As shown in figure 3, the improved fuel economy of CARS replacement vehicles compared to the "clunkers" (*Effect 1*) reduced emissions by about 3.7 million metric tons (83% of net emissions reductions); the improved fuel economy of CARS replacement vehicles compared to non-CARS replacement vehicles (*Effect 2*) reduced emissions by about 1.5 million metric tons (35%); and the premature production and disposal of vehicles (*Effect 3*) increased emissions by about 800,000 metric tons (-18%).

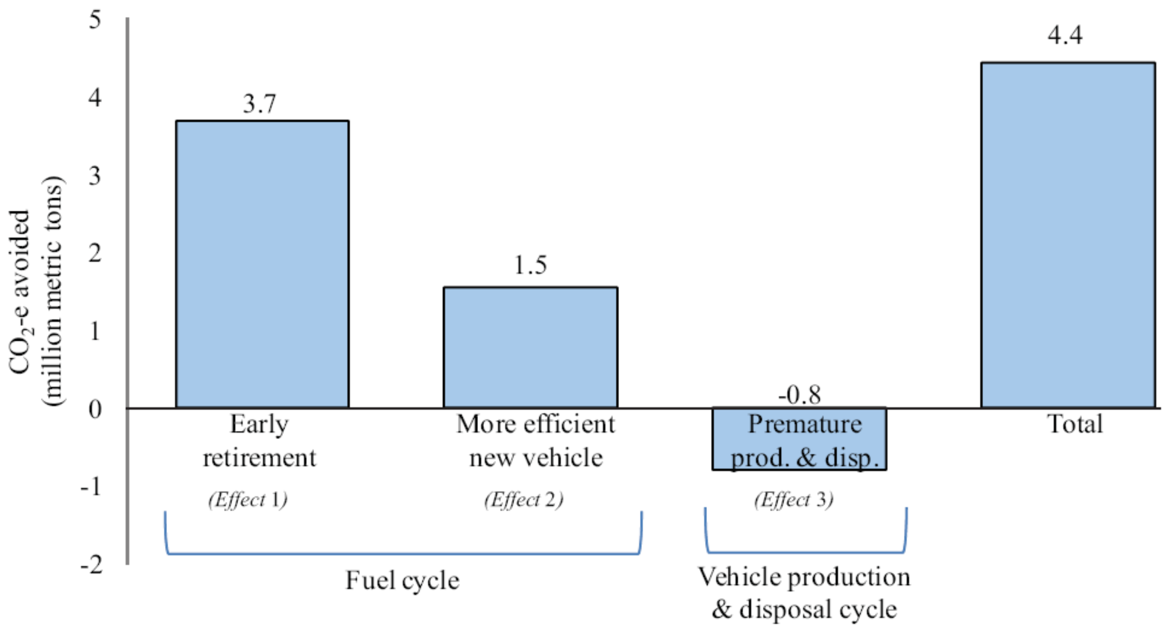

Figure 3. Reduction in CO_2-e emissions as a result of CARS. *Effects 1*, *2*, and *3* are as defined in table 1.

Overall, through the lifetime of Vehicle 1 and Vehicle 2_{CARS} (the shaded area in figure 2a), the 677,081 "clunkers" and new vehicles participating in CARS were responsible for just over 146 million metric tons of CO_2-e emissions. Without CARS, under the scenario modeled in figure 2b for the same number of miles (in the shaded area), those vehicles would have produced nearly 151 million metric tons of emissions. The 4.4 million metric tons of CO_2-e avoided through CARS, therefore, represent a 2.9% savings over the business-as-usual emissions without the program.

2.3.2. Modeling limitations and sensitivities

2.3.2.1. CAFE standards. The modeling of *Effect 2* is based on a study comparing new vehicle purchases in July and August to what they would have been, in those months, without the program. However, most Vehicle 2_{BAU} purchases would have actually occurred several months to several years later. But new, stricter Corporate Average Fuel Economy (CAFE) standards take effect in model year 2012 [31], consequently, any vehicle purchases that were moved forward from model year 2012 to the summer of 2009 may have had a net negative impact on the vehicle's fuel economy.

According to the DOT consumer survey, 31% of consumers planned to keep their vehicles for at least another 3 years [28], at which point the replacement vehicle would have been subject to the new CAFE standards. 2012 standards are 5.8 mpg higher than 2009 standards for passenger cars (33.3 versus 27.5), and 2.3 mpg higher for light trucks (25.4 versus 23.1) [31, 32]. We modeled the impact if 31% of passenger cars and light trucks purchased through CARS (Vehicle 2_{CARS}) were, respectively, 5.8 and 2.3 mpg less fuel efficient than Vehicle 2_{BAU}. Under this scenario, CARS prevents only about 750,000 metric tons of CO_2-e emissions in total.

2.3.2.2. Remaining vehicle lifetime. As in prior studies, the total program impact is sensitive to assumptions about miles remaining. We based our calculation of 21,904 miles remaining per vehicle on the average miles driven in the year prior to CARS (9,412) and the average number of years consumers stated they would have kept their vehicles in the absence of CARS (2.52). There was, however, considerable variability in consumers' responses to these questions, especially the latter, which had a standard deviation of 2.95 years. Moreover, the question about years of use remaining asked when

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consumers were planning to "trade-in, sell or dispose of" their vehicle [33]; vehicles that would have been traded-in or sold may have had more years of use remaining than indicated in the survey. Table 5 shows the sensitivity of emissions avoided through CARS to the assumption about mileage remaining for the average vehicle.

Table 5. Sensitivity of overall program results to assumptions about miles remaining on trade-in in the absence of an early retirement incentive.

Miles remaining	**CO_2-e avoided (million metric tons)**
15,000	3.5
20,000	4.2
21,904[a]	4.4
25,000	4.9
30,000	5.5
33,744[b]	6.1
35,000	6.2

[a] We use 21,904 miles in our calculations, which is based on the average 2.52 years remaining from the DOT consumer survey.
[b] One-half standard deviation above the mean in the survey data would equal 4 years remaining, or 33,744 miles.

2.3.2.3. Replacement vehicle miles traveled. Our analysis assumes that replacement vehicles under CARS are driven the same number of miles, annually, as the vehicles they replace. However, new vehicles might be driven more than their predecessors. First, participants may experience a rebound effect, in which improved fuel economy reduces the per-mile cost of driving, resulting in more miles traveled. Recent literature examining the empirical evidence for the rebound effect [34-36] indicates that up to about 10% of energy savings could be offset by an increase in miles traveled; this value is also utilized by NHTSA [31]. For this study, including a 10% rebound effect would reduce the net avoided emissions of the program from 4.4 to 3.9 million metric tons.

Alternatively, some participants may drive the new CARS vehicle more but conserve total household VMT by reducing driving in another household vehicle. The impact this could have on GHG emissions depends on the characteristics of the household's other vehicles and the number of miles substituted, for which data is not available. However, as long as the new CARS vehicle has better fuel economy than other household vehicles, this substitution would slightly increase the emissions savings attributable to the program.

2.3.2.4. Longer-term behavior change. Our analysis assumes that the short-term incentive provided by CARS results in only short-term behavior change, that is, the purchase of a more fuel-efficient vehicle with the rebate funds. If the program helped to stimulate longer-term environmental consciousness in participating consumers, influencing their choice of vehicle, driving habits, or even non-transportation behaviors after the program ended, the impact in terms of emissions savings could be much larger than calculated here. Previous research has shown that some accelerated retirement programs can help shift consumer vehicle preferences [37], however, more research on the behavioral impact of CARS is needed [38].

2.4. Discussion

CARS had a moderately positive impact on emissions, causing a one-time reduction in life cycle greenhouse gas emissions of about 4.4 million metric tons, or just under 0.4% of total annual U.S. light-duty vehicle emissions [39]. This assessment takes into account the full life cycle impact of the program, from vehicle manufacturing and disposal to use-phase combustion and upstream fuel cycle emissions.

These avoided emissions are lower than those of other authors who have assessed the impact of CARS. Abrams and Parsons [2, 3] expressed findings in terms of gallons of gasoline saved, but using the GREET model emissions factor, we can convert this to an implied 6.4 million metric tons CO_2-e avoided. Knittel [5] estimated per-vehicle CO_2 avoided, but only based on combustion-phase emissions, and without including other GHGs; adjusting his estimates to include upstream fuel cycle (20% of total) and other

GHG (5% of total) emissions, his analysis would suggest 9.0 million metric tons CO_2-e avoided. Similarly, Sachs [9] calculated per-vehicle CO_2 avoided, without upstream fuel or non-CO_2 GHG emissions. A fuller accounting of Sachs' assumptions implies 10.7 million metric tons CO_2-e avoided. Finally, as mentioned above, NHTSA [1] estimated savings of 9.5 million metric tons CO_2-e avoided, including emissions avoided from the upstream fuel cycle, and including the benefit from consumers purchasing more fuel-efficient vehicles under CARS than they otherwise would have.

Our findings of 4.4 million metric tons avoided range from about 30% to 60% lower than these previous studies, for several reasons. The differences are driven in large part by our assumption that traded-in vehicles had about 22,000 miles remaining, for reasons described in our methodology section. Most other studies assumed, without justification, substantially longer remaining lives – as much as 60,000 miles, for example, in Sachs [9] – though some acknowledged they used generous assumptions. Since emissions avoided from *Effect 1* scale with the assumption of miles remaining in the old vehicle's life, these assumptions play a large role in the total impact calculated. Moreover, none of the other studies included the increase in emissions attributable to *Effect 3*, which in our study accounted for an 18% decrease in net emissions avoided.

NHTSA's calculations were based on more detailed consumer survey data than is available to the public at this time, but there appear to be two fundamental differences in methodology. First, NHTSA assumed an increase in VMT on the new vehicle compared to the old one. We discuss this possibility in section 3.2.3. Second, and perhaps most importantly, NHTSA, like all other studies discussed, did not include the negative emissions impact from premature production and disposal of vehicles.

CARS was intended to serve several purposes, not least of which was stimulating the economy (and in particular the automotive sector). NHTSA [1] estimated that CARS provided for the creation of more than 38,000 direct jobs and many more indirect jobs, and that it contributed \$4 to \$8 billion to the gross domestic product (GDP). However, if we consider CARS simply for its GHG emission reductions, setting aside those economic

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stimulus benefits, it would appear to be an extremely expensive way to mitigate GHGs. The program cost about $3 billion in taxpayer money, meaning the public cost for each metric ton of avoided GHGs was well over $600. This is particularly high when compared to the estimated $13 price tag for a metric ton of CO_2-e emissions reduction under the proposed American Clean Energy and Security Act of 2009 [40].

Considering the high cost and moderate GHG emissions reductions from CARS, we believe there is considerable work to be done to ensure that future accelerated vehicle retirement programs provide GHG emissions benefits at a reasonable cost. Our analysis shows that it is important for policymakers to consider the full life cycle impact of programs encouraging early retirement, including the effect of early production and disposal of vehicles. We also believe coordinating the timing of these programs with a regime of increasing fuel economy requirements is critical, as we showed that a program occurring shortly before improved fuel economy standards take effect could negate most of its benefits by encouraging new purchases before stricter standards are in place.

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3. An assessment of environmental and economic costs and benefits of 'Cash for Clunkers'

3.1. Introduction

3.1.1. Program overview

In 2009, the US Congress passed the Consumer Assistance to Recycle and Save (CARS) Act, also known as the Car Allowance Rebate System or, more popularly, 'Cash for Clunkers.' The program encouraged consumers to scrap their fuel-inefficient vehicles ('clunkers') in exchange for a substantial rebate toward the purchase of a new, more fuel-efficient vehicle. Trade-in and new vehicles were required to meet specific fuel economy criteria, and were subject to several other requirements as well. Three billion federal dollars were allotted toward the program, which by all accounts was a popular success, drawing nearly 700,000 participants and exhausting funding in just weeks [13]. The details of the program requirements and participating vehicles are available elsewhere (e.g., [1, 12]). CARS was broadly intended to satisfy two objectives: first, to provide a fiscal stimulus to the US economy in general and to the struggling automotive sector in particular, and second, to benefit the environment by replacing some of the most polluting vehicles on the road with less polluting ones.

3.1.2. Literature review

There is a relatively large body of existing literature on accelerated vehicle retirement or scrappage programs, of which CARS is one example of dozens that have been implemented in the last several decades. Early vehicle scrappage programs in the US were intended primarily to reduce emissions of conventional (criteria) pollutants emitted during vehicle operation [23]. Much of the early literature on these types of programs focused on the economic incentives and decisions that drive participation, and, given projections of participation, the magnitude of pollution reduction achievable. For example, Alberini et al [41] developed a theoretical model of vehicle owners' scrappage

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decisions and used data from a small vehicle retirement program in Delaware to test it. They found that, as expected, owners demand a higher incentive to scrap vehicles with higher market values. Hahn [42] used Los Angeles vehicle fleet data to estimate, at different hypothetical prices, the vehicle scrappage rates and resulting avoided hydrocarbon (HC) and nitrogen oxide (NO_x) pollution. He found that programs are only likely to be cost-effective at reducing criteria pollutants if the price paid for vehicles was relatively low (less than $1,000) and if the programs were implemented in urban areas where the value of abating pollution is typically higher.

In the last decade, with growing understanding of and concern for global climate change, more studies have included an assessment of, or even focused on, the impact of vehicle scrappage programs on energy use and associated greenhouse gas (GHG) emissions (e.g., [20-23]). Studies on CARS' environmental impact have focused primarily on GHG emission reduction (e.g., [2, 5, 6]) though two so far have also briefly examined criteria pollutant reductions [5, 7]. Abrams and Parsons [3] explicitly adopted a cost-benefit approach and used rough estimates of avoided emissions, number of participating vehicles, and scrapped vehicles' market values to conclude that CARS cost $825 million more than the environmental benefits it provided.

In a separate body of literature, researchers have examined the economic stimulus impact of CARS, looking at indicators such as number of new vehicle purchases, number of jobs created, and contribution to gross domestic product (GDP). Findings of these studies have varied widely, and researchers have argued over the extent of economic benefits from the program. Li et al [7] found that CARS stimulated about 390,000 new vehicle sales during the program, but that more than a third of those purchases would have occurred by December even in absence of the incentive. They also estimated a short-term increase in auto industry employment by 3,676 job-years, and a longer-term increase of 2,050 job-years. Mian and Sufi [8] suggested that virtually all of the 360,000 new vehicle purchases during the program were pulled forward from June 2010 or earlier, meaning the program did not drive any long-term increase in vehicle purchases. They also found no evidence of an increase in employment due to CARS. Cooper et al [4] found that CARS contributed to nearly 395,000 new vehicle sales through October 2009 (but they did not estimate what portion of this increase was pulled forward from future months). They also estimated that employment increased by about 40,000 job-years as a result of the program. The US Department of Transportation's National Highway Traffic Safety Administration (NHTSA), which administered CARS, estimated that the 346,000 new vehicle purchases during CARS were pulled forward from a six-year period; that the program created or saved 61,960 job-years; and that it contributed about four billion dollars to US GDP [1].

3.1.3. Cost and benefit framework

We propose a framework for assessing a number of the economic and environmental costs and benefits of CARS (figure 4). Costs are separated into two categories: those borne by the federal government (the three billion dollars allotted for rebates) and those borne by participating consumers. Participants' costs provided critical leverage to government funding for the program, and are therefore important to include when assessing the true expenditures allotted toward the goals and benefits of CARS. For every $3,500 or $4,500 rebate provided by government funds, consumers needed to contribute thousands of dollars more (on average nearly $18,250) toward the new vehicle purchase. Because these costs are all measured in dollars, we can relatively simply sum the government and consumer costs to arrive at total expenditures of more than $15 billion.

Benefits of the program fall under three categories: those providing macro-economic stimulus, those contributing to the public good (in this case, through improvements in the environmental impact of the US vehicle fleet), and those accruing to the individual consumers who participated in CARS. Macro-economic stimulus effects include (but are not necessarily limited to) new vehicle sales, job creation, and GDP growth. Public good benefits include any reduction in GHG and criteria pollutant emissions, which can be measured in both magnitude and estimated (non-market) economic value. Benefits to individual consumers include the economic surplus, or "gift," they received in the form of the rebate contribution toward a new vehicle, as well as the utility they get from the new vehicle. The utility should equal or, more likely, exceed the amount paid by consumers for the vehicles, since if it were not at least that large, rational consumers would not have purchased the vehicles. Part of the utility is derived from gasoline savings; with just under 700 gallons saved for the average participating consumer, this component of utility is worth about $1,100 to $2,800 per participant, or $740 million to $1.9 billion in aggregate (assuming gasoline retail costs of $1.59 to $4.05 per gallon, the minimum and maximum US average from January 2005 to the middle of August 2009 [43]). Unlike program costs, benefits are measured with different units. Some are also not summable, as, for example, GDP growth includes the benefits from new vehicle sales. For these reasons, benefits cannot easily be aggregated to arrive at a total value.

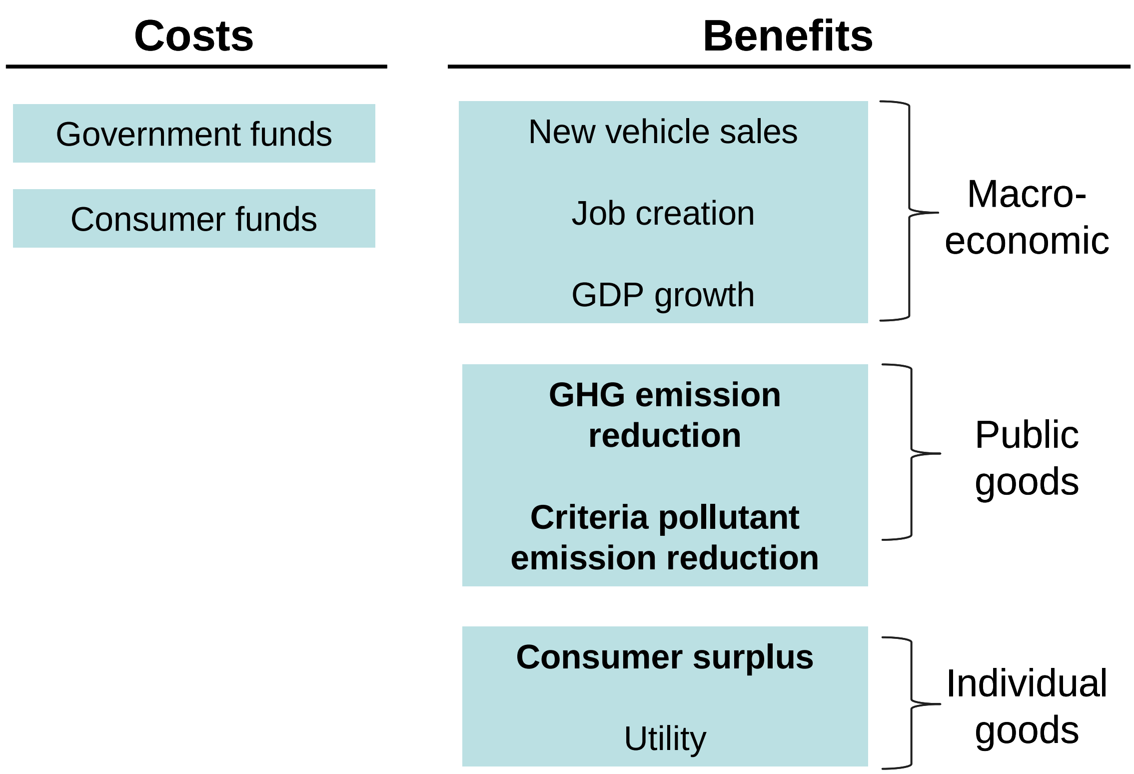

Figure 4. Cost and benefit framework for CARS. (Note: benefits in bold are analyzed in detail in this paper. Others are assessed in the literature review).

It is worth noting that many other second-order economic and environmental impacts of CARS may exist. For example, the decreased supply of used vehicles may have priced some individuals out of the used vehicle market [44], keeping some 'clunkers' on the road that otherwise would have been scrapped. New vehicle sales and new or saved employment may have resulted in increased sales and income tax collection for states and the federal government [4]. On the other hand, for cash-constrained consumers, the new vehicle purchase may have simply shifted spending away from other industries, potentially hurting other retail sectors [45]. CARS may have longer-term or larger-scale behavioral impacts on consumers [38], influencing later choices of vehicles and driving patterns, which are among the household behaviors with the greatest potential for reducing greenhouse gas emissions [46]. This list of additional impacts from CARS is, of course, not exhaustive.

3.1.4. New contributions

Although a few existing studies have examined multiple impacts of the CARS program from both an environmental and economic perspective (e.g. [1, 7]), ours adds several important components. First, we lay out a framework for thinking about the costs (including consumer costs) and benefits, both economic and environmental, resulting from the program, and gather data on some of these values from the literature. Second, we calculate the values of two important benefit components that have been largely neglected in the existing literature. One of these, the economic surplus, or "gift," to consumers, has been popularly assumed to be generous, but has not been calculated in any existing study. The other, the magnitude and value of avoided criteria pollutant emissions, has been roughly estimated in a few existing studies ([1, 5, 7]), but we perform a more rigorous analysis that takes into account the sizeable variation in the impact of pollutants across different geographic regions. These two new calculations and our previous assessment of GHG reductions [6], along with other researchers' estimates of new vehicle sales, job creation, and GDP growth, allow us to more fully account for CARS' costs and benefits according to the framework described above.

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3.2. Surplus value of rebate to participating consumers: the "gift"

In exchange for scrapping their 'clunkers', participating consumers received rebates of either $3,500 or $4,500 toward the purchase of a new vehicle. This option, of course, precluded consumers from selling or trading in vehicles for their market value. Popular literature during CARS widely assumed that the rebate was substantially higher than the market value of vehicles being scrapped (e.g., [47-49]), based on the high participation and faster-than-expected exhaustion of available funds. However, no studies to date have calculated the actual surplus value to consumers. It is important to know whether, in fact, "the government's deal was too good," as reported in the New York Times [50], to help set appropriate rebate levels for future programs of a similar nature.

3.2.1. Methodology

3.2.1.1. Data sources. Data on the rebates provided to consumers is available from NHTSA [51]. For every participating vehicle, NHTSA provided the trade-in vehicle identification number (VIN), odometer reading, dollar value of the rebate, and location of the dealership where the transaction occurred, among other data. Data on the July 2009 trade-in market value of these same vehicles was collected from the National Automobile Dealers Association (NADA), through their e-Valuator® software. See the supplementary materials for a more detailed description of the analysis.

3.2.1.2. Calculations. NADA trade-in market value data is proprietary. We inputted each trade-in vehicle's VIN, odometer reading, and location (state) into the e-Valuator® software, and collected output on the trade-in value. Trade-in value was available under assumptions about the vehicle's condition: "rough," "average," and "clean". Because condition was not known for vehicles scrapped through CARS, we consider a range of values in our results. We calculate the per-vehicle consumer surplus as the difference between the rebate value recorded by NHTSA and the trade-in market value calculated by NADA.

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3.2.2. Results

As table 6 shows, the median trade-in market value for scrapped vehicles ranged from $1,075 for a vehicle in rough condition to $2,250 for a vehicle in clean condition. Given the known value of rebates on each vehicle, then, we calculate that CARS provided participating consumers with a median surplus between $1,950 and $3,125, depending on the condition of the scrapped vehicle. For a vehicle in average condition, the median surplus was $2,475. As a whole, then, CARS provided participating consumers with a surplus of approximately $1.3 to $2.1 billion.

Table 6. Market value and consumer surplus for vehicles traded-in under CARS, by vehicle condition. (Note: Market value from NADA e-Valuator® software. Per-vehicle surplus calculated as difference between market value and rebate).

	Rough	**Average**	**Clean**
Median trade-in market value per vehicle	$1,075	$1,713	$2,250
Median surplus (“gift”) per vehicle	$3,125	$2,475	$1,950
Aggregate surplus (“gift”) for program (in billions)	$2.12	$1.68	$1.32

3.3. Value of avoided criteria pollutant and greenhouse gas emissions

Vehicles emit both greenhouse gases (GHGs) and criteria pollutants during use. The process of producing fuels, as well as manufacturing and disposing of vehicles, also contributes to GHG and criteria pollutant emissions. The presence of emissions from upstream fuel production and vehicle manufacturing and disposal suggests that a life cycle methodology is necessary for comprehensively calculating the change in emissions resulting from CARS. Lenski et al [6] developed a life cycle framework to calculate the mass of avoided GHG emissions due to CARS; we employ this methodology here to calculate the mass of avoided criteria pollutants. We then apply economists’ calculations of the marginal benefit of pollution abatement to calculate the value of the avoided emissions. An important new contribution we provide is calculating this value while taking into account the different cost of pollutants in different geographic areas and at different source heights (ground level or stacks), whereas previous studies have simply assumed a national average or median cost from sources of all heights. The difference is significant: we find actual benefits worth two to six times as much as if we had used a simple average or median value for damage costs.

3.3.1. Methodology

3.3.1.1. Data sources. Data on the marginal benefit of pollution abatement for the criteria pollutants NO_x, SO_x, VOCs, $PM_{2.5}$, and PM_{10}, by US county, is sourced from Muller and Mendelsohn [52]. Data on the location of CARS transactions is available from NHTSA [51]. All vehicle transactions are linked to a dealership location, which in turn can be linked to the counties for which marginal pollution damage costs are calculated in [52]. NHTSA data also includes information on the participating trade-in and new vehicles, including vehicle category (passenger car, light truck), make and model, fuel economy, and odometer reading. Argonne National Laboratory's "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation" (GREET) models 1.8c.0 and 2.7 provide emissions data for vehicles of different types, model years, and fuel economy [24]. GREET 1.8c.0 provides greenhouse gas and criteria pollutant emissions, per mile, for the fuel cycle (as defined and described in [6]). GREET 2.7 provides the same emissions data, per vehicle lifetime, for the vehicle production and disposal cycle. See supplementary materials for a more detailed description of assumptions.

3.3.1.2. Calculations. Data on each CARS transaction is grouped by US county (the geographic level at which marginal pollution damage costs are available in [52]). For each county, the following characteristics of the "average" trade-in and new vehicle are determined: fuel economy, model year, vehicle category (passenger car or light truck), and trade-in odometer reading. Using GREET's fuel cycle model, we calculate per-mile emissions of VOCs, NO_x, SO_x, $PM_{2.5}$ and PM_{10} for vehicles of each category, age, and fuel economy.

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Then we calculate the emissions impact in each county, which is based on three effects, described more fully in Lenski et al [6]. In *Effect 1*, emissions are avoided as a result of more fuel-efficient vehicles being driven instead of the less-efficient clunkers they replace, for the 21,904 miles assumed to be remaining in the clunkers' natural lifetime (as calculated in [6]).

In *Effect 2*, emissions are avoided because CARS encouraged consumers to purchase more fuel-efficient vehicles than their next replacement vehicle would have been without the program, under "business as usual" (BAU). We use findings by Sivak and Schoettle [10] that suggest new vehicles under CARS were up to 0.7 mpg more fuel-efficient than new vehicles would have been under BAU.

In *Effect 3*, incremental vehicle cycle emissions are produced as new vehicles are manufactured and old vehicles discarded prematurely. A portion of each new vehicle's production and disposal emissions is attributable to the CARS program. As described in [6], this portion is calculated based on the number of miles remaining in the clunker's natural life at the time it was scrapped under CARS.

The total magnitude of criteria pollutant reductions is calculated as the value of *Effect 1 + Effect 2 – Effect 3*, and the economic benefit of these reductions is calculated by multiplying each county's emissions mass by the marginal benefit of avoided pollution from Muller and Mendelsohn [52]. For fuel cycle emissions – that is, those coming primarily from the combustion of fuel during vehicle use, but also from upstream fuel production – we use the value of abating ground-level emissions. As discussed in [52], the economic benefit of abating ground-level emissions is typically higher (especially in urban areas) than abating those same emissions from high stacks, because people are more directly exposed to the ground-level emissions and therefore suffer worse health consequences. Emissions from the vehicle production and disposal cycle occur not at the location of the vehicle's use, but at the site of its production, as well as all the upstream production processes such as raw material extraction and processing. These activities occur at facilities across the United States and around the world. For simplicity and lack of better data, we assume that 100% of these emissions occur in the United States, and assign them the mean marginal pollution costs of low (<250 meters) and tall (>250 meters) stack emissions in [52]. See supplementary materials for more details on the equations used to model these effects.

We also consider the magnitude of GHG reductions as calculated in Lenski et al [6], and value these at $21 per metric ton, the midpoint social damage cost of CO_2 estimated by the Interagency Working Group on Social Cost of Carbon (SCC) [53].

For simplicity, we ignore the timing of all emissions, and do not discount the value of emissions that are avoided years into the future. Discounting would reduce the dollar value of the benefit from all avoided emissions.

3.3.2. Results

According to our calculations, more than 20,000 metric tons of criteria pollutants were avoided through the CARS program, in addition to the approximately 4.4 million metric tons of CO_2-equivalent GHGs avoided. Nearly 28,000 metric tons of criteria pollutants were avoided through *Effect 1* and *Effect 2*; these were partially offset by nearly 8,000 metric tons of additional criteria pollutants emitted as a result of *Effect 3*.

As table 7 shows, the abatement of criteria pollutants provided economic value of about $17 million, with about $21 million in benefits from *Effect 1* and *Effect 2* partially offset by a cost of $4 million from *Effect 3*. Using our calculated mass of avoided criteria pollutants, but the average (expected) or median nationwide marginal damage costs (across all ground level and stack sources) from [52], as Knittel [5] and Li et al [7] do, results in benefits of just $6.9 and $2.6 million, respectively. This dramatic difference in findings demonstrates the importance of considering the value of abating criteria pollutants with differentiation by geographic location and emissions source height.

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The abatement of GHGs, valued at $21 per metric ton [53], added another $93 million of economic benefit to the program's overall impact. (At SCC's low and high social damage cost estimates of $5 and $35 per metric ton, respectively, GHG abatement is worth $22 million and $155 million). The mass and economic value of avoided GHGs dwarfed those of the criteria pollutants. Valued at $21 per metric ton, GHGs accounted for 99.5% of abated pollution mass and 84.8% of the economic benefit. See supplementary materials for a more detailed discussion of these results.

Table 7. Mass and value of criteria pollutant and GHG emissions reductions from CARS. (Note: Numbers may not sum due to rounding.)

		VOCs	**NO_x**	**$PM_{2.5}$**	**PM_{10}**	**SO_x**	**Total criteria pollutants**	**GHGs (in CO_2-e)**
Mass (1,000 metric tons)	*Effect 1*	14.0	13.7	0.0	0.0	0.1	27.8	3,682.8
	Effect 2	0.0	0.0	0.0	0.0	0.0	0.0	1,541.9
	Effect 3	3.4	1.1	0.5	0.7	2.0	7.7	795.1
	Net reduction (1+2-3)	**10.5**	**12.7**	**(0.4)**	**(0.7)**	**(1.9)**	**20.2**	**4,429.6**
Value ($M)	*Effect 1*	16.5	3.4	0.9	0.0	0.2	21.0	77.3
	Effect 2	0.0	0.0	0.0	0.0	0.1	0.1	32.4
	Effect 3	0.9	0.3	0.9	0.2	2.2	4.4	16.7
	Net benefit (1+2-3)	**15.6**	**3.1**	**0.0**	**(0.2)**	**(1.9)**	**16.6**	**93.0**

3.4. Discussion

We calculated two new measures of the benefits of CARS. First, we found that participants were given, on average, "gifts" of nearly $2,500 above the market value of their trade-in vehicles. This value is critical because it can help inform whether the rebate amount offered was reasonable or too high, as many speculated. Most scrappage programs to date have offered (and most literature has assumed) per-vehicle rebates of $500 to $1,000 [42], implying a maximum "gift" of that much as well, even if vehicles had zero market value. Similarly, in a survey of potential participants in a Delaware scrappage program, Alberini et al [19] found that about half of respondents would have scrapped their vehicles for $1,000 (which the researchers also estimated was approximately the average market value of the eligible vehicles). However, these programs are substantially different than CARS in vehicle eligibility requirements, geographic scope, and number of participants. Accordingly, we don't have data to support speculation on how much of a "gift" would have been necessary to induce participation in CARS, but we suspect that $2,500 is on the high end. The quick exhaustion of available funds implies there was more demand than was able to be satisfied with the three billion dollars allotted. A lower rebate, or an auction mechanism for setting the rebate value, could very well have achieved higher participation (more vehicles scrapped) for the same government-funded cost, resulting in greater "bang for the buck" in terms of both economic stimulus and environmental benefits.

Second, we found that the value of the avoided criteria pollutant and GHG emissions is approximately $110 million, although significant uncertainty about the value of abating GHG emissions could imply benefits as low as about $40 million or as high as about $170 million. These environmental benefits seem relatively small, given the combined $15 billion spent on the program by participating consumers and the government. The benefits we calculate are already likely somewhat overstated, as we ignore the timing of avoided emissions; if we had discounted the value of avoiding future emissions, the benefits would be somewhat smaller. In particular, we found that including the benefit of avoided criteria pollutant emissions did not do much to increase the economic value of CARS' environmental impact, since most of the benefit came from avoided GHG emissions. This result is particularly interesting given that, in the past, most accelerated vehicle retirement programs have been aimed at reducing criteria pollutant emissions. The findings suggest that, because criteria pollutant emissions from vehicles are quite low compared to a decade or two ago, and because the rate of reduction has slowed, scrappage programs may no longer be appealing mechanisms for abating these pollutants.

We summarized the literature on several other economic benefits of CARS: new vehicle sales, GDP growth, and job creation. There was significant disagreement among some experts about these values, but we can nonetheless use their estimates to help put the emissions reduction and consumer surplus benefits we calculate in the larger context of the impact of CARS (figure 5).

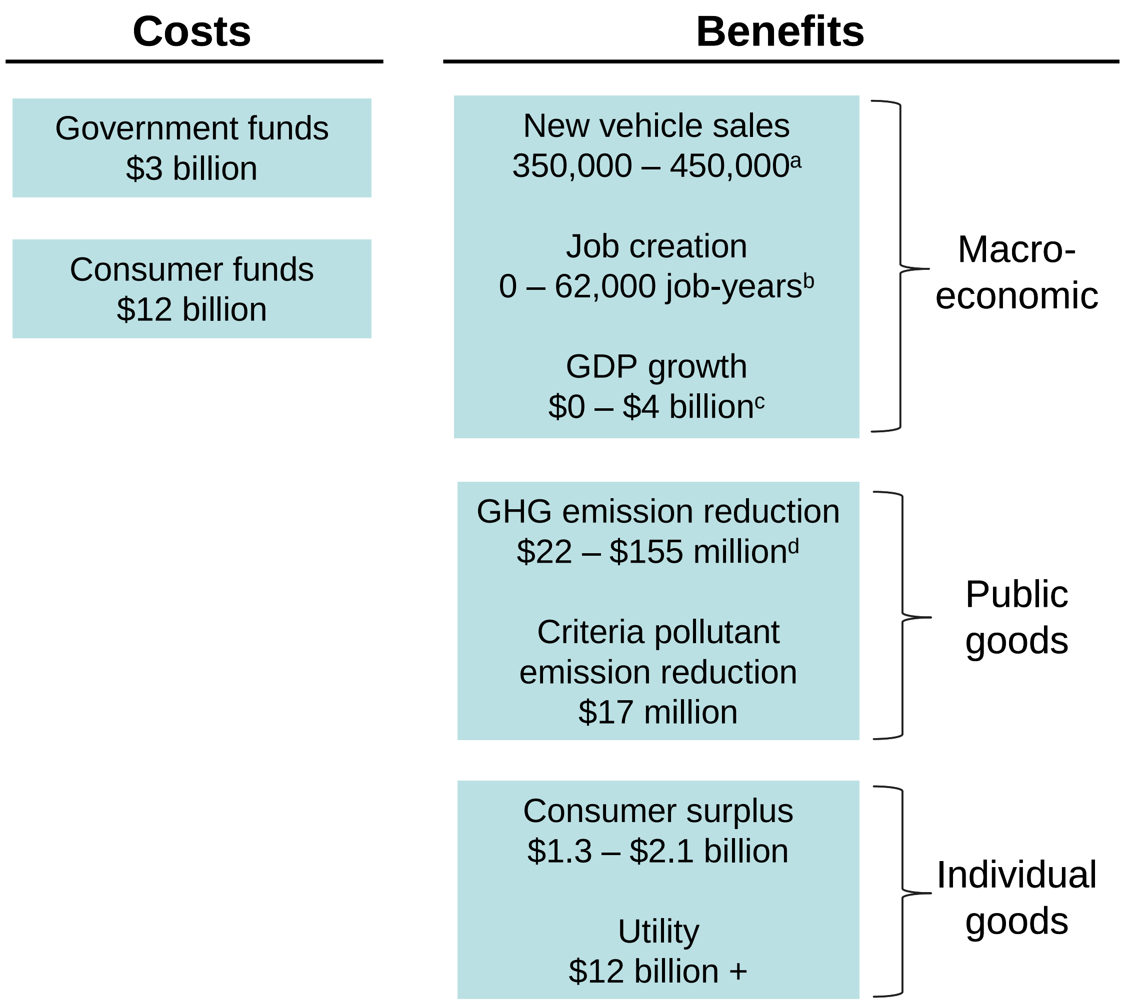

Figure 5. Cost and benefits of CARS. (Notes: a, b: sources are [1, 4, 7, 8]. c: source is [1]. d: range based on 4.4 million metric tons avoided, as calculated in [6], at benefit per metric ton of $5 to $35 as calculated in [53].)

Overall, we suspect that given the high value of the rebates to consumers and the relatively low value of the emission reductions, there was significant opportunity to get more environmental and economic "bang for the buck" with CARS. This could have been achieved with a lower rebate or an alternative rebate mechanism such as an auction, in which consumers bid for the opportunity to trade in their 'clunker' at a particular rebate level. Presumably, more vehicles could have been traded in for the same three billion dollars in government spending under this scheme, or the same number of vehicles could have been traded in for less than three billion dollars. Further, the environmental "bang for the buck" could have been improved with more stringent criteria for the clunkers and/or new vehicles, or, potentially, by targeting the program to geographic areas where the marginal damage cost from emissions is particularly high, and therefore the value of abating them is high as well.

3.5. Supplementary materials

3.5.1. Additional assumptions for calculation of consumer surplus

NADA E-Valuator did not have market value data available for vehicles from before model year 1990. We assumed all these vehicles had market values of $0 if in rough condition, $250 in average condition, and $500 in clean condition. These may be somewhat generous assumptions as they are close to what we found for the 1990 model year vehicles, and some of the pre-1990 model year vehicles were substantially older. In addition to the pre-1990 model year vehicles, there were 14,439 other vehicles for which no trade-in value was available, either because the VIN had an error, the trade-in occurred in a US territory instead of one of the 50 states, or because NADA otherwise couldn't find a value. We assumed that vehicles had no add-ons (for example, sunroofs, premium media systems, etc.) other than those that were automatically selected by NADA E-Valuator when given the VIN (for example, four wheel drive on many vehicles). Most of these add-ons would be valued at about $50-300 on a trade-in, so inclusion of add-ons on some vehicles should not dramatically change our findings about the value of the consumer surplus.

3.5.2. Additional assumptions for calculation of criteria pollutant emissions

Our research assumes that CARS participants drive in the same county where they purchased their new vehicle; this may not always be exactly the case, of course, but no better data on participants' home location or driving habits is available. We also assume for ease that upstream fuel cycle emissions occurred in the county where CARS vehicles were purchased. The transaction location data in [51] needed significant manual cleaning due to typographical errors, and while every effort was made to catch and correct these errors, some may remain.

Missing information and typographical errors were also found for other data in [51]. For vehicles missing fuel economy data, we assume trade-ins got 15.7 miles per gallon (mpg) and new vehicles got 24.2 mpg, the fleet harmonic means found in [6]. Thousands of trade-in vehicles appeared to have incorrect odometer readings (either very low or exceptionally high, with a range from 0 to nearly 10 million). Consequently, all calculations rely on the average odometer reading for the entire passenger car or light truck fleet (152,401 miles and 161,555 miles respectively, as calculated in [6]), rather than the particular odometer reading of any vehicle or subset of vehicles.

Several other assumptions were made for characteristics of the "average" trade-in and new vehicle in each county. Fuel economy is calculated as the fleet harmonic mean for each county, rounded to the nearest whole number. Model year is rounded to the nearest 5 years, the frequency at which GREET calculates pollutant emissions levels. The few counties with an average trade-in vehicle older than 1990 are given a model year of 1990 for emissions calculations purposes, as this is the earliest year available in GREET. New vehicles are all assumed to be 2010 model year for emissions calculations purposes. The vehicle category – passenger car or light truck – is based on which type made up the majority of trade-in or new vehicles in that county.

Carbon monoxide (CO) is not evaluated in [52], and the damage costs from CO pollution are not as well studied or published as other pollutants. In some studies, CO pollution is assumed to have zero cost, as low ambient concentrations have very limited effects [54]. In one study, CO is estimated to cause health effects worth between \$0.01 and \$0.09 (1991 dollars) per kilogram throughout the United States, and as high as \$0.18 per kilogram in Los Angeles [55]. We exclude CO from most analyses but consider its inclusion as a sensitivity analysis.

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The mass of PM_{10} emissions was calculated as the difference between GREET's PM_{10} and $PM_{2.5}$ emissions, to avoid double-counting $PM_{2.5}$ emissions, and to match the marginal pollution cost calculations in [52].

3.5.3. Formulas for calculation of avoided criteria pollutant emissions

Defining the following variables, we model the magnitude of each effect for each particular pollutant:

n_c = number of vehicles participating in CARS in county c, for c = 1, 2, … , 2276, 2277
E_i = fuel cycle (upstream and combustion) emissions per mile for Vehicle i, for i = 1, 2_{CARS}, 2_{BAU} where 1 is the average trade-in vehicle in a county, 2_{CARS} is the average new vehicle purchased under CARS in a county, and 2_{BAU} is the counterfactual average new vehicle in a county under the "business as usual" scenario
p_i = emissions resulting from production of Vehicle i, for i = 1, 2_{CARS}, 2_{BAU}
d_i = emissions resulting from disposal of Vehicle i, for i = 1, 2_{CARS}, 2_{BAU}
x_1 = lifetime VMT of vehicle retired early due to CARS program
x_2 = lifetime VMT of vehicle retired at end of natural life

The emissions savings attributable to *Effect 1* can be expressed as:

$$\sum_{c=1}^{2,277} n_c\left(x_2 - x_1\right)\left(E_1 - E_{2CARS}\right) \quad (5)$$

The emissions savings attributable to *Effect 2* can be expressed as:

$$\sum_{c=1}^{2,277} n_c\left(x_1\right)\left(E_{2BAU} - E_{2CARS}\right) \quad (6)$$

The incremental emissions attributable to *Effect 3* can be expressed as:

$$\sum_{c=1}^{2,277} n_c\left(1 - \frac{x_1}{x_2}\right)\left(p_{2CARS} + d_{2CARS}\right) \quad (7)$$

The process described above captures just over 669,000 of the more than 677,000 vehicle transactions in CARS. Some were excluded because they occurred in counties for which the marginal cost of pollution was not available, or had other missing values that made them uncountable. We adjust our calculations to include these missing vehicles, assuming they emitted pollutants at our mean rate per vehicle, and valuing their emissions at our mean rate per metric ton.

3.5.4. Additional detail and description of results regarding criteria pollutant emissions

Effect 2 had very little impact on criteria pollutant mass or value (whereas in [6] it was found to play an important role in the program's impact on GHG emissions). This is a result of the fact that criteria pollutant emissions are regulated and measured on a per-mile basis, and therefore have no direct correlation to a vehicle's fuel economy. The reduction in criteria pollutants from *Effect 1* results from improved pollution control between older and new vehicles, rather than from improvements in fuel economy. Since *Effect 2* measures only the benefit of improved fuel economy, the impact is negligible. SO_x is the only exception – since more than 90% of fuel cycle SO_x emissions occur upstream in the fuel production process, rather than during vehicle operation itself, these emissions are correlated to a vehicle's fuel economy.

VOCs contributed more than 50% of the mass of avoided criteria pollutants, and more than 90% of the economic value of criteria pollutant abatement. Per-mile fuel cycle emissions of VOCs have declined dramatically (by more than 80%) from model year 1990 to model year 2010 vehicles , so replacing older vehicles with newer ones creates a substantial reduction in VOCs emitted during the fuel cycle, although this benefit is partially offset by the relatively large VOC emissions from the vehicle production and disposal cycle. And although the mean marginal pollution cost of VOCs in US counties is low, a large number of CARS transactions occurred in regions with extremely high marginal costs. Accordingly, a metric ton of VOC avoided through *Effect 1* delivered nearly $1,200 in value, whereas the incremental VOC emissions from *Effect 3* cost just over $250 per metric ton.

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Similarly, NO_x accounted for a large portion of the avoided criteria pollutants by mass, as per-mile fuel cycle emissions have declined by about 80% in the last 20 years. However, the economic impact of avoided NO_x emissions was quite small at just over $3 million. The mean value of abating a metric ton of NO_x through *Effect 1* was just $246, skewed in part because in several metropolitan areas with a large number of CARS transactions (Los Angeles County, for example), abating NO_x is *costly*, not beneficial. In these locations, where the underlying NO_x concentration is high enough, additional NO_x emissions actually help reduce ozone concentrations [56], providing a net economic benefit.

Emissions of $PM_{2.5}$, PM_{10}, and SO_x all appear to have increased as a result of CARS. These pollutants are emitted at very low rates during the fuel cycle and their emission rates have changed very little since 1990, leading to small savings from *Effect 1* and *Effect 2*. However, the vehicle production and disposal cycle produces substantial emissions of all three of these pollutants, so premature production of new vehicles actually leads to an increase in net emissions. For $PM_{2.5}$, the value of avoided fuel cycle emissions from high-value areas (where many CARS transactions occurred) is high enough to offset the cost of additional vehicle cycle emissions that we assumed were spread throughout the country. For PM_{10} and SO_x, the cost of incremental emissions from *Effect 3* more than offsets the value of abatement from *Effect 1* and *Effect 2*, therefore these pollutants impose a net cost.

3.5.5. Additional sensitivity analysis for criteria pollutant emissions

We also consider the impact of including economic benefit from avoided CO pollution. We assume the marginal benefit of a metric ton of CO avoided to be $62.88 (the average of McCubbin and Delucchi’s “low” and “high” US estimates [55], adjusted for inflation to 2000 dollars to match the rest of the analysis). We find that CARS prevented about 105,445 metric tons of CO pollution, for an economic benefit of $6.6 million.

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4. Conclusion

A life cycle framework was developed to assess the mass of avoided greenhouse gas and criteria pollutant emissions from the CARS program. CARS was found to have prevented approximately 4.4 million metric tons of CO_2-equivalent greenhouse gas emissions, and 20,000 tons of criteria pollutant emissions. Using existing values for the damage costs associated with such emissions, the program is estimated to have created $110 million in (non-market) public-good economic benefits. These benefits are placed in the context of other economic benefits of CARS, including macroeconomic impacts such as new vehicle sales, increase in employment, and GDP growth. The benefits to participating individuals, in the form of the rebate toward the purchase of a new vehicle, are also calculated. This consumer surplus, or “gift”, is found to be worth approximately $1 to $2 billion in aggregate. These benefits are compared to the government and consumer funds used for the purchase of the new vehicles, which totaled more than $15 billion.

CARS was not the first accelerated vehicle retirement program employed to reduce emissions, nor is it the last (since CARS’ conclusion, such programs have been introduced in several European nations, and similar types of programs targeting different energy-consuming devices, such as household appliances, have been considered or implemented across the US). This research offers several important findings from CARS that can help policymakers as they develop these programs in the future. In particular, we have shown how the reduction in greenhouse gas emissions is highly sensitive to vehicles’ remaining lifetime and to the timing of scrappage programs relative to scheduled improvements in vehicle fuel economy. Policymakers can consider how requirements for age, condition, or odometer reading of eligible vehicles might increase pollution reduction benefits, and ensure that programs are offered at times that maximize consumers’ purchases of the most fuel-efficient vehicles likely to be available in the near future. Moreover, we have demonstrated that the economic benefits of criteria pollutant reduction were higher than might otherwise be predicted because many of the vehicle trades occurred in urban areas with a high marginal value of pollution abatement. Future

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policies might take advantage of this by targeting geographic regions where pollution abatement is particularly important or valuable. Finally, we have established that the consumer surplus, or "gift" to participating consumers, was higher than has been offered in previous programs and may have been greater than necessary to induce participation. More environmental and economic "bang for the buck" could be achieved by setting rebates at a more appropriate level, perhaps through an auction mechanism or some other system more closely linked to vehicles' market value.

There is substantial opportunity to continue researching CARS, and we intend to expand upon the analysis presented here. First, it would be interesting to study the geographic relationship between participation rates, consumer surplus, emission reductions, and economic value of emission reductions. Some areas of the US certainly benefited more than others from CARS, and in different ways. Second, it would be useful to explore the timing of accelerated, postponed, and avoided emissions. Particularly with greenhouse gases, the urgent need to mitigate and the potential for tipping-point effects at various (unknown) levels of atmospheric concentration suggest that there may be greater value (even after accounting for discounting of economic benefits, which we did not include here) to more immediate reductions in emissions. Finally, it would be valuable to learn about consumers' willingness to scrap their 'clunkers' at different rebate levels, to help understand how much larger than necessary the CARS rebates really were, and how to set incentive levels more appropriately in the future. A survey of consumers with vehicles eligible for trade-in under CARS (both those who participated and those who chose not to) may be necessary to collect this data.

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