Environ. Res. Lett. 5 (2010) 044003 (8pp) doi:10.1088/1748-9326/5/4/044003

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

Shoshannah M Lenski, Gregory A Keoleian and Kevin M Bolon

Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan, Dana Building, 440 Church Street, Ann Arbor MI 48109, USA

E-mail: gregak@umich.edu

Received 16 July 2010
Accepted for publication 11 October 2010
Published 4 November 2010
Online at stacks.iop.org/ERL/5/044003

Abstract

One of the goals of the US Consumer Assistance to Recycle and Save (CARS) Act of 2009, more commonly known as 'Cash for Clunkers', was to improve the US vehicle fleet fuel efficiency. Previous studies of the program's environmental impact have focused mainly on the effect of improved fuel economy, and the resulting reductions in fuel use and emissions during the vehicle use phase. We propose and apply a method for analyzing the net effect of CARS on greenhouse gas emissions from a full vehicle life cycle perspective, including the impact of premature production and retirement of vehicles. We find that CARS had a one-time effect of preventing 4.4 million metric tons of CO_2-equivalent emissions, about 0.4% of US annual light-duty vehicle emissions. Of these, 3.7 million metric tons are avoided during the period of the expected remaining life of the inefficient 'clunkers'. 1.5 million metric tons are avoided as consumers purchase vehicles that are more efficient than their next replacement vehicle would otherwise have been. An additional 0.8 million metric tons are emitted as a result of premature manufacturing and disposal of vehicles. These results are sensitive to the remaining lifetime of the 'clunkers' and to the fuel economy of new vehicles in the absence of CARS, suggesting important considerations for policymakers deliberating on the use of accelerated vehicle retirement programs as a part of the greenhouse gas emissions policy.

Keywords: greenhouse gases, accelerated vehicle retirement, life cycle analysis, car allowance rebate system

1. Introduction

1.1. Cash for Clunkers program overview

In June 2009, the US 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 \$3500 or \$4500 rebate toward the purchase of a new, more fuel-efficient vehicle. Retired vehicles were then destroyed, permanently removing them from the US 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 [1]. 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 [2].

1.2. Accounting for emissions benefits in the existing literature

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

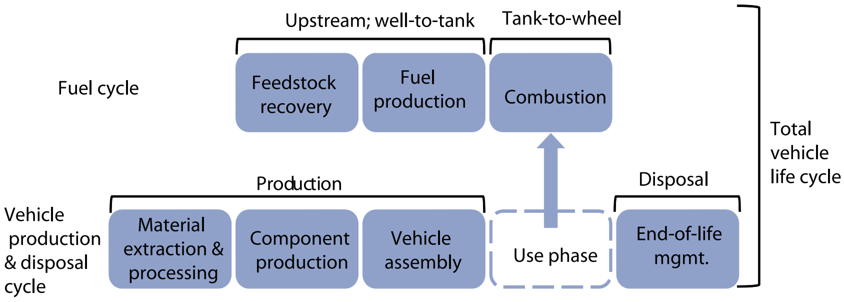

Figure 1. Separate fuel and vehicle production and disposal cycles are used to evaluate the total vehicle life cycle impact.

benefits well beyond what was originally anticipated' [3]. 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 [4, 5] and Sachs [6] 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 1400 gallons per vehicle, or about 570–950 million gallons total. Knittel [7] 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) [8] 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.

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., [9–12]), 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* [13] 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* [14] 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* [15] 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* [16] 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 US Government Accountability Office [17] 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. Methodology

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 [18]. The 'tank-to-wheel' or combustion phase accounts for approximately 80% of total fuel cycle GHG emissions from gasoline [19]. The vehicle production and

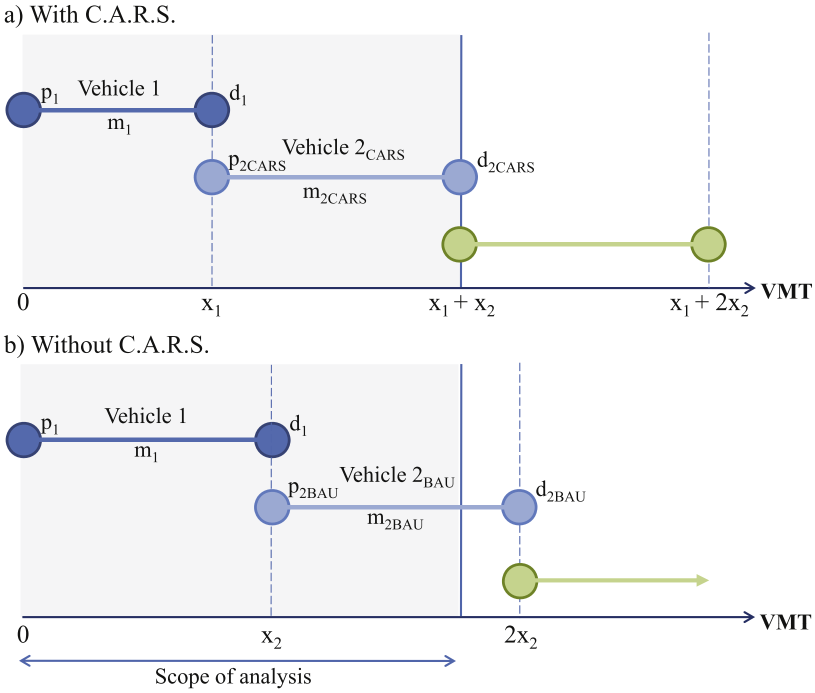

Figure 2. Vehicle replacement schedules with and without CARS, across a fixed 'time' period as measured in vehicle miles traveled (VMT). Circles represent production and disposal of vehicles. Our analysis is limited in scope to the emissions attributable during the lifespan of vehicle 1 and vehicle 2_{CARS},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

disposal cycle includes material extraction, processing, and fabrication; component production; vehicle assembly; end-of-life management; and the transportation of goods between these phases [18]. The vehicle production and disposal cycle contributes about 10%–20% of the total vehicle life cycle greenhouse gas emissions [18, 20, 21].

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.

2.2.1. Life cycle system with CARS. The schematic in figure 2(a) 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 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. Life cycle system without CARS. Figure 2(b) 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,

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 and disposal cycle	Premature retirement of 'clunker' and manufacture of new vehicle under CARS cause additional production and disposal emissions.

Table 2. Summary characteristics of vehicles traded in through CARS. (Note. Source: [1]. 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.

the scope of our analysis goes only through $x_1 + x_2$ miles, represented by the shaded area in figure 2(b).

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 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.

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 $i = 1, 2_{\mathrm{CARS}}, 2_{\mathrm{BAU}}$; d_i = GHG emissions resulting from disposal of vehicle i, for $i = 1, 2_{\mathrm{CARS}}, 2_{\mathrm{BAU}}$; m_i = fuel economy (mpg) of vehicle i, for $i = 1, 2_{\mathrm{CARS}}, 2_{\mathrm{BAU}}$; 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:

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

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

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

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

$$p_{2\mathrm{CARS}} + d_{2\mathrm{CARS}} - \frac{x_1}{x_2}(p_{2\mathrm{BAU}} + d_{2\mathrm{BAU}}). \tag{3}$$

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

$$(x_2 - x_1)\left(\frac{E}{m_1} - \frac{E}{m_{2\mathrm{CARS}}}\right) + x_1\left(\frac{E}{m_{2\mathrm{BAU}}} - \frac{E}{m_{2\mathrm{CARS}}}\right) - \left(p_{2\mathrm{CARS}} + d_{2\mathrm{CARS}} - \frac{x_1}{x_2}(p_{2\mathrm{BAU}} + d_{2\mathrm{BAU}})\right). \tag{4}$$

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.

2.3. Data sources and assumptions for empirical analysis

2.3.1. Official statistics on CARS. The Department of Transportation (DOT) published data for the vehicles that were

Table 3. Summary characteristics of new vehicles purchased through CARS. (Note. Source: [1]. 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.

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 ($m_{2\mathrm{CARS}}$) 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.

2.3.2. Fuel economy in absence of CARS. Sivak and Schoettle [22] 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 presumably be attributed to CARS' incentives. Therefore, $m_{2\mathrm{BAU}}$ is calculated as $m_{2\mathrm{CARS}} - 0.7$, 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 US fleet. Without CARS, the consumer selling a used vehicle would have purchased a new replacement, so *that* new vehicle (though it is not actually purchased by the same consumer) is the one we compare to the new vehicle purchased through CARS.

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 [4, 6, 7]; added to the odometer reading at the time of trade-in, this would imply total vehicle lifetimes of about 196 000–220 000 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 [23].

Second, although a typical US vehicle is driven about 12 000 miles per year [24], 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 9412 miles in the year prior to CARS [8], close to what standard VMT schedules would predict for 14–16 year old cars and trucks (table 4). Further, VMT decreases at 4.33% per year, on average, for 15–20 year old vehicles (table 4).

Assuming 9412 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.

2.3.4. Calculating greenhouse gas emissions. Emissions factors from GREET models 1.8c.0 and 2.7 [18] were used to calculate fuel cycle and vehicle cycle emissions, respectively. The fuel cycle model provided an estimate for our emissions factor, E, of 0.011 17 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, $p_{2\mathrm{CARS}} = p_{2\mathrm{BAU}}$ and $d_{2\mathrm{CARS}} = d_{2\mathrm{BAU}}$.

Table 4. VMT schedule used to estimate miles remaining for CARS trade-in vehicles. (Note. Source: [25].)

Vehicle age	Passenger cars VMT	Δ	Light trucks VMT	Δ
14	9633	—	10 396	—
15	9249	−3.99%	9 924	−4.54%
16	8871	−4.09%	9 468	−4.59%
17	8502	−4.16%	9 032	−4.60%
18	8144	−4.21%	8 619	−4.57%
19	7799	−4.24%	8 234	−4.47%
20	7469	−4.23%	7 881	−4.29%
	Average Δ across cars and light trucks: −4.33%			

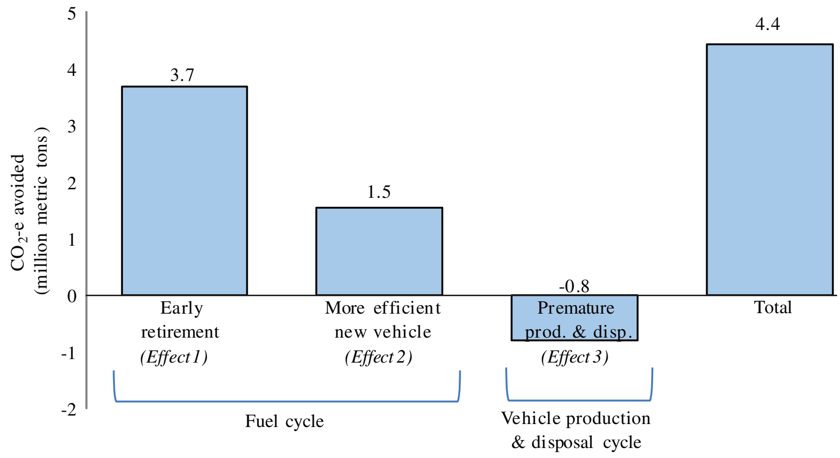

Figure 3. Reduction in CO_2-e emissions as a result of CARS. *Effects 1, 2*, and *3* are as defined in table 1.

3. Results

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%).

Overall, through the lifetime of vehicle 1 and vehicle 2_{CARS} (the shaded area in figure 2(a)), 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 2(b) 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.

3.2. Modeling limitations and sensitivities

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 [26], 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 three years [23], 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) [26, 27]. 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.

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 (9412) 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 consumers were planning to 'trade-in, sell or dispose of' their vehicle [28]; 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.

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 [29–31] 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 [26]. 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.

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.

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.

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 [32], however, more research on the behavioral impact of CARS is needed [33].

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 US light-duty vehicle emissions [34]. 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 [4, 5] 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 [7] 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 [6] 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 [8] 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 section 2. Most other studies assumed, without justification, substantially longer remaining lives—as much as 60 000 miles, for example, in Sachs [6]—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 [8] estimated that CARS provided for the creation of more than 38 000 direct jobs and many more indirect jobs, and that it contributed \$4–\$8 billion to the gross domestic product (GDP). However, if we consider CARS simply for its GHG emission reductions, setting aside those economic 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 [35].

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.

Acknowledgments

This research was supported through the National Science Foundation (CMMI 0628162), Alcoa Foundation Conservation and Sustainability Fellowship Program, and University of Michigan Transportation Research Institute Doctoral Studies Program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

We thank Alex Andrus, Adam Bennett, and Mike Sintetos for their ideas in the early stages of this research, and John DeCicco and the external advisory board of the Center for Sustainable Systems at the University of Michigan for helpful feedback on early drafts.

References

[1] US Department of Transportation National Highway Traffic Safety Administration 2009 *CARS Additional Program Statistics* (Washington, DC: US Department of Transportation)
[2] US Department of Transportation Office of Public Affairs 2009 *Transportation Secretary Ray LaHood kicks-off CARS Program, Encourages Consumers to Buy More Fuel Efficient Cars and Trucks* (Washington, DC: US Department of Transportation)
[3] Obama B 2009 *Statement by President Barack Obama on 'Cash for Clunkers'* (Washington, DC: The White House Office of the Press Secretary)
[4] Abrams B A and Parsons G R 2009 Is CARS a clunker? *The Economists' Voice* **6** 4
[5] Abrams B A and Parsons G R 2010 The uneasy case for subsidizing energy efficiency *Milken Inst. Rev.* **12** 63–70
[6] Sachs J D 2009 A clunker of a climate policy *Sci. Am.* **301** 34
[7] Knittel C R 2009 *The Implied Cost of Carbon Dioxide Under the Cash for Clunkers Program* (Davis, CA: University of California)
[8] US Department of Transportation National Highway Traffic Safety Administration 2009 *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* (Washington, DC: US Department of Transportation)
[9] Dill J 2004 Estimating emissions reductions from accelerated vehicle retirement programs *Trans. Res.* D **9** 87
[10] Deysher B and Pickrell D 1997 Emissions reductions from vehicle retirement programs *Trans. Res. Rec.* **1857** 121
[11] Lavee D and Becker N 2009 Cost-benefit analysis of an accelerated vehicle-retirement programme *J. Environ. Plan. Manage.* **52** 777
[12] Alberini A, Harrington W and McConnell V 1996 Estimating an emissions supply function from accelerated vehicle retirement programs *Rev. Econ. Stat.* **78** 251
[13] Kim H C, Keoleian G A, Grande D E and Bean J C 2003 Life cycle optimization of automobile replacement: model and application *Environ. Sci. Technol.* **37** 5407
[14] Spitzley D V, Grande D E, Keoleian G A and Kim H C 2005 Life cycle optimization of ownership costs and emissions reduction in US vehicle retirement decisions *Trans. Res.* D **10** 161
[15] Van Wee B, Moll H C and Dirks J 2000 Environmental impact of scrapping old cars *Transport. Res.* D **5** 137
[16] Allan A, Carpenter R and Morrison G 2009 *Abating Greenhouse Gas Emissions Through Cash-for-Clunkers Programs* UCD-ITS-RR-09-26 (Davis, CA: University of California)
[17] US Government Accountability Office 2010 *Auto Industry: Lessons Learned From Cash for Clunkers Program* GAO-10-486 (Washington, DC: US Government Accountability Office)
[18] Argonne National Laboratory 2009 The greenhouse gases, regulated emissions, and energy use in transportation (GREET) model, available online www.transportation.anl.gov/modeling_simulation_GREET/index.html
[19] US Environmental Protection Agency 2009 *Draft Regulatory Impact Analysis: Changes to Renewable Fuel Standard Program* EPA-420-D-09-001 (Washington, DC: US Environmental Protection Agency)
[20] Keoleian G A, Lewis G M, Coulon R B, Camobreco N J and Teulon H P 1998 *LCI Modeling Challenges and Solutions for a Complex Product System: A Mid-Sized Automobile* 982169 (Warrendale, PA: SAE International)
[21] Sullivan J L and Cobas-Flores E 2001 *Full Vehicle LCAs: A Review* 2001-01-3725 (Warrendale, PA: SAE International)
[22] Sivak M and Schoettle B 2009 *The Effect of the 'Cash for Clunkers' Program on the Overall Fuel Economy of Purchased New Vehicles* UMTRI-2009-34 (Ann Arbor, MI: University of Michigan Transportation Research Institute)
[23] US Department of Transportation National Highway Traffic Safety Administration 2010 *Consumer Survey CSV File* (Washington, DC: US Department of Transportation)
[24] US Environmental Protection Agency Office of Transportation and Air Quality 2005 *Emissions Facts: Greenhouse Gas Emissions From a Typical Passenger Vehicle* EPA-420-F-05-004 (Washington, DC: US Environmental Protection Agency)
[25] Lu S 2006 *Vehicle Survivability and Travel Mileage Schedules* DOT HS 809 952 (Washington, DC: US Department of Transportation)
[26] US Environmental Protection Agency and US Department of Transportation National Highway Traffic Safety Administration 2010 *Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards; Final Rule: Federal Register* (Washington, DC: US Government Printing Office)
[27] US Department of Transportation National Highway Traffic Safety Administration 2009 *Summary of Fuel Economy Performance (Public Version)* (Washington, DC: US Department of Transportation)
[28] US Department of Transportation National Highway Traffic Safety Administration 2010 *CARS Data Dictionary for the Consumer Survey Data File* (Washington, DC: US Department of Transportation)
[29] Sorrell S, Dimitropoulos J and Sommerville M 2009 Empirical estimates of the direct rebound effect: a review *Energy Policy* **37** 1356
[30] Greene D L 2010 Rebound 2007: analysis of US light-duty vehicle travel statistics *Energy Policy* at press
[31] Small K A and Van Dender K 2007 Fuel efficiency and motor vehicle travel: the declining rebound effect *Energy J.* **28** 25
[32] Miravete E J and Moral M J 2009 *Qualitative Effects of Cash-for-Clunkers Programs* (*Discussion Paper Series No. 7517*) (London, UK: Centre for Economic Policy Research)
[33] Conner S 2010 Cash for Clunkers: can cash in the pocket create concerned consumers? *The Annual Mtg of the Assoc. of Collegiate Marketing Educators, 2010 (Dallas, TX)* Abstract
[34] US Environmental Protection Agency Office of Transportation and Air Quality 2006 *Greenhouse Gas Emissions From the US Transportation Sector, 1990–2003* EPA 420-R-06-003 (Washington, DC: US Environmental Protection Agency)
[35] US Environmental Protection Agency Office of Atmospheric Programs 2009 *EPA Analysis of the American Clean Energy and Security Act of 2009: H.R. 2454 in the 111th Congr.* (Washington, DC: US Environmental Protection Agency)