Greenhouse Gas Emission Impacts of Carsharing in North America

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***Abstract*—This paper evaluates the greenhouse gas (GHG) emission impacts that result from individuals participating in carsharing organizations within North America. The authors conducted an online survey with members of major carsharing organizations and evaluated the change in annual household emissions (e.g., impact) of respondents that joined carsharing. The results show that a majority of households joining carsharing are increasing their emissions by gaining access to automobiles. However, individually, these increases are small. In contrast, the remaining households are decreasing their emissions by shedding vehicles and driving less. The collective emission reductions outweigh the collective emission increases, which implies that carsharing reduces GHG emissions as a whole. The results are reported in the form of an observed impact, which strictly evaluates the changes in emissions that physically occur, and a full impact, which also considers emissions that would have happened but were avoided due to carsharing. The mean observed impact is −0.58 t GHG/year per household, whereas the mean full impact is −0.84 t GHG/year per household. Both means are statistically significant. We present a sensitivity analysis to evaluate the robustness of the results and find that the overall results hold across a variety of assumptions. The average observed vehicle kilometers traveled (VKT) per year was found to decline by 27%. We conclude with an evaluation of the annual aggregate impacts of carsharing based on current knowledge of the industry membership population.**

***Index Terms*—Carsharing, greenhouse gas (GHG) emissions, statistical analysis, survey design.**

I. Introduction

MOUNTING evidence of climate change and concerns about energy costs are motivating many state and local governments to explore policy options that can simultaneously reduce petroleum consumption and greenhouse gas (GHG) emissions. Within the United States (U.S.), transportation activity accounts for close to 30% of all GHG emissions and nearly 70% of all petroleum consumption [1]. Roughly 96% of all energy consumed within this sector in the U.S. comprises either gasoline or diesel [1]. Moreover, a well-established reliance on the private automobile for urban transportation has placed the U.S., and to a lesser extent Canada, in uniquely difficult positions to shift travel in ways that lower automotive dependence.

Carsharing (short-term vehicle access) has been continuously operating in North America for about 15 years. Just over ten years ago, carsharing emerged in select cities within the U.S. as a niche market alternative to offer members auto access without the costs of private vehicle ownership. Carsharing organizations operate by placing vehicles throughout urban neighborhoods, metropolitan centers, and colleges/universities. The vehicles are accessible to members through a reservation that is booked in advance by phone or the Internet. Members can pay for carsharing services in a variety of ways, depending on the pricing plan to which they subscribe. Most members pay a monthly or an annual fee in some combination with per-hour and per-mile charges [2].

Since its inception, carsharing has rapidly grown. As of July 1, 2009, there were 16 active programs in Canada and 26 in the U.S., with an estimated 378 000 carsharing members and approximately 9800 vehicles in North America. In the U.S., 8 of the 26 operators in the U.S. were for-profit, accounting for 86% and 88% of the members and vehicles, respectively. In Canada, 6 of the 16 Canadian carsharing operators were for-profit, representing 87% of members and 86% of the vehicle fleet [3], [4].

Research suggests that carsharing may offer considerable environmental and social benefits [3]–[9]. These benefits include GHG emission reductions and greater use of alternative modes such as public transit, walking, and cycling. In the industry today, carsharing vehicles are newer relative to the average personal vehicle and generally have higher average fuel economy [10]. As carsharing satisfies the mobility needs of consumers without the personal automobile, it has been considered a promising demand management tool capable of displacing gasoline consumption that would otherwise occur in its absence.

This paper presents the results of a survey of carsharing members across the North American continent. The survey was conducted online from September to November 2008 with all of the major carsharing organizations in the U.S. and Canada. The survey asked respondents about past and current vehicle holdings, as well as shifts in travel patterns to estimate changes in GHG emissions that result from carsharing.

This paper proceeds with four main sections: First, the authors present a review of earlier studies and surveys assessing the environmental impacts of carsharing, with an emphasis on

Manuscript received September 2, 2009; revised September 8, 2010; accepted March 7, 2011. Date of publication July 14, 2011; date of current version December 5, 2011. This work was supported in part by the Mineta Transportation Institute, San Jose State University, by the Transportation Sustainability Research Center, University of California, Berkeley, and by the Honda Motor Company, through its endowment for new mobility studies at the University of California, Davis. The Associate Editor for this paper was C. C. White.

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Digital Object Identifier 10.1109/TITS.2011.2158539

North America. Second, we provide a methodological framework that characterizes how carsharing can alter member emissions and describe how GHG impacts are measured within this study. Then in the results, we evaluate the distribution of carsharing impacts along with the sample averages, which is supported by a sensitivity analysis to illustrate how these results vary with assumptions on respondent input. We finish with conclusions that outline the critical insights of this paper and their implications for policy.

II. Related Work

Among the most consistent findings of past research is that carsharing reduces car ownership. The first demonstration of carsharing started in San Francisco with the Short-Term Auto Rental (STAR) program. Established in 1983, STAR was a 55-vehicle pilot designed to operate for three years but terminated after 18 months of operation. In the STAR evaluation, Walb and Loudon reported on changes in car ownership and travel among members. They found that 17% of members sold a vehicle, whereas 43% postponed a vehicle purchase. However, their assessment of travel changes raised doubts as to whether carsharing would result in more efficient travel, as member travel was reported to have slightly increased [11]. While the STAR program did not gain traction, lessons learned from that effort were used to inform and improve the launch of CarSharing Portland more than a decade later [12]. Similar to STAR, an early study of CarSharing Portland's impacts found that 26% of members sold a car, whereas 53% avoided a purchase [13]. The study also reported members using public transit, biking, and walking more. However, as with STAR, the early study found no change in vehicle miles traveled (VMT)/vehicle kilometers traveled (VKT) among members [13]. For a more extensive review on the history of the carsharing industry, see Shaheen and Cohen [6] and Shaheen *et al.* [14].

Similar results persisted throughout the early 2000s. Carsharing returned to San Francisco with the launch of City CarShare in March 2001. Cervero initiated a before-and-after study to evaluate the impacts of City CarShare on both member and nonmember travel behavior three months before the launch and nine months after [15]. A profile of the early members indicated that they were in their early 30s, college graduates, and worked in professional fields. Most significantly, two thirds of members came from zero-car households, whereas 20% came from one-car households. This early study found that mean daily VMT/VKT dropped for both members and nonmembers. In addition, shares of walking and biking fell. Cervero's early results of City CarShare were broadly consistent with past work in North America; they found similar demographics among members and that changes in VMT/VKT were not substantial. The early carsharing adopters were those who were primarily carless and used carsharing as a means to augment their mobility [15].

Lane evaluated the first-year impacts of PhillyCarShare, a nonprofit organization operating in Philadelphia as of November 2002. One year after PhillyCarShare's launch, Lane administered a 500-member online and mail-in survey in November 2003. Roughly 60% of members who joined were from households with zero cars. Members were otherwise demographically similar to the early adopters of City CarShare. Lane evaluated vehicles sold as a result of membership, as well as vehicles not acquired. He reported that each PhillyCarShare vehicle removed roughly 23 cars from the road. Finally, Lane discussed VMT/VKT drops among members while acknowledging uncertainty in his estimate. He concluded that a typical reduction would amount to a couple hundred miles per month for members who gave up a car, but that there was considerable variance in his estimate [9].

As carsharing evolved, researchers began to discern more pronounced effects on VMT/VKT. Cervero and Tsai [10] and Cervero *et al.* [5] revisited City CarShare impacts in 2004 and 2007, respectively. With the third study, VMT/VKT reductions attributable to carsharing were becoming more evident as member VMT/VKT was found to decrease relative to nonmember VMT/VKT. VMT/VKT reductions among carsharing members appeared to occur during the first two years, but large variations existed within the group. Overall, mean mode-adjusted VMT/VKT, which accounted for occupancy levels, dropped by 67% for carsharing members in contrast to a 23% increase among nonmembers [5].

III. Methodological Approach

The scope of this paper is defined as the GHG impacts resulting from changes in travel behavior among active carsharing users. The unit of analysis in the survey is the household, as an individual's carsharing use can affect the travel decisions of all household members. The operating statistic of our analysis is the *change in annual emissions* of the household's travel activity before and after carsharing. This measure was selected because it illustrates the change in the "state of household travel" facilitated by carsharing. The state of household travel can be thought of as the travel routines that are adopted by carsharing households. These new routines may result in lower vehicle ownership and driving, or in the case of carless households, the new routines could lead to an increase in driving at the expense of public transit and nonmotorized travel.

A. *Classifications of Carsharing Impacts*

To evaluate the full breadth of emission change that carsharing can facilitate, we define two classifications of impact. These classifications are separated by the degree to which they consider unseen emissions that would have occurred in the absence of carsharing. One impact is defined as the "observed impact" and includes the emission change that result from an observable change in household driving. The observed impact constitutes changes that actually happen and are physically measurable.

However, carsharing also provides an alternative to households that may substitute for actions that would otherwise occur in its absence. For example, a car-owning household may join carsharing rather than acquire an additional car. The forgone vehicle would have been driven some distance had it been acquired. However, carsharing prevents this from happening, and those emissions never occur in the private vehicle. Instead, travel is shifted to carsharing vehicles and alternative modes to achieve the same purpose. These emissions are not manifested and, when taken in sum with the observed impact, comprise the “full impact.” Hence, the full impact assesses what physically happened with carsharing, as well as “what would have happened otherwise” in the absence of carsharing.

To measure the full impact, respondents were asked to provide an approximation of the number of vehicles that they would have acquired and the distance that they would have driven those vehicles. While the full impact is real, there is an elevated level of uncertainty associated with such responses. For this reason, the observed and full impacts are always separately considered, as there will always be a larger degree of uncertainty with respect to the measurement and precision of the full impact. The observed impact is also subject to its own measurement error as respondents report actual annual personal VMT (PVMT)/personal VKT (PVKT). To evaluate the impact of the actual distance measurement error, we perform a sensitivity analysis that illustrates how results would have differed had respondents reported overestimations of PVMT/PVKT values.

B. Treatment of Different Travel Modes

The net change in total household VMT/VKT is the primary metric used to assess a difference in member travel patterns that impact GHG emissions. The overall net change in VMT/VKT from carsharing is a result of the balance of impacts across all members. Carsharing is beneficial from a VMT/VKT perspective if the reductions in private auto use exceed the overall carsharing use.

As joining carsharing can change travel behavior, it is important to consider how shifts to other modes would impact emissions. Some cases are simple. For instance, shifts to nonmotorized modes such as walking and biking exhibit no increase in GHG emissions. With respect to public transit, we treat this effect as close to the same, as most fixed rail and bus routes operate regardless of capacity utilization. Energy conservation does dictate that an additional person switching to public transit has to increase GHG emissions by some marginal amount. As a person steps onto a bus or train, the vehicle must exert more energy to move that person to his or her destination. However, because public transportation travels regardless of the presence of the additional passenger, a carsharing member who rides transit is only responsible for the marginal emissions caused by his or her presence. These emissions are smaller than the marginal emissions of a personal vehicle or taxi trip. Hence, if a trip has to be made within an urban region (e.g., for work) and nonmotorized travel is infeasible for such a trip, traveling by public transit on an established network is the most efficient decision an individual can make from an energy and emission perspective.

Within the scope of this paper, the evaluation of GHG emission impacts attributable to carsharing is predominantly a function of the change in distance traveled by personal and carsharing vehicles. However, local use of rental cars and taxis can also make a small contribution. After joining carsharing, motor vehicle use consists of personal autos that still remain in the household (if any), carsharing vehicles, local rental vehicles, and local taxi trips.

C. Survey Design and Data Collected

The respondents completed a single survey, and the questionnaire was designed to yield “before-and-after” data to assess impacts. Respondents were first asked questions about their household travel lifestyle during the year before they joined carsharing. They were then asked to evaluate the same parameters “at present” as this permitted simpler recollection and prevented respondents from self-assessing the “after” time frame in which they may have shifted travel patterns.

The survey collected the make, model, and year of each vehicle within the household both before joining carsharing and at the time of the survey. In addition, the annual PVMT/PVKT driven during the year before the member joined and at the time of the survey was solicited for each vehicle. Respondents were given guidelines to make a “best estimate” of annual PVMT/PVKT. To remove the influence of very high distance drivers, any respondent listing a PVMT/PVKT for any vehicle that was over 48 000 km (30 000 mi) was not included in the analysis. The make, model, and year of each vehicle were used to determine the vehicle’s fuel economy. Each vehicle dating back to 1978 was linked to an appropriate entry in the U.S. Environmental Protection Agency (EPA) fuel economy database. Vehicles manufactured prior to 1978 were not listed in the database; these vehicles were given a standard combined fuel economy of 15 mi/gal (15.7 L/100 km). The forgone distances driven in vehicles not acquired (as per the full impact) were all assigned a conservative 42 mi/gal (5.6 L/100 km). The GHG emissions of all vehicle travel are computed using the standard methodology published by the EPA [16].

Respondents were asked to indicate the carsharing vehicle that they used most often and the approximate monthly miles that they drove it. They were not expected to know the model year; thus, a 2007 model year was generally assumed. In addition, respondents were asked whether they would purchase a vehicle in the absence of carsharing. If they indicated that they “Maybe would,” “Probably would,” or “Definitely would,” then they were asked to indicate how many vehicles would be purchased and to provide a range estimate of the distance that would be driven on the vehicle(s). This information was used to compute the full impact.

A subsample of respondents was asked about their use of rental vehicles and taxis before and after carsharing. The subsample was used due to concerns of respondent fatigue and the challenges of providing recollections of rental and taxi use, which are not routine. About 20% of each subsample opted out of the questions, indicating that they could not recall. The emission change of those that could recall was evaluated, and the average change of both was very small. Average emissions from taxi use were slightly reduced, whereas the average emission change of rental cars was not statistically different from zero [17].

There are a variety of confounding factors that could interfere with the analysis. Questions were asked to search for these factors across each respondent. If one was found, then the respondent was removed. For instance, moving residential or employment locations is common and corresponds with many life events. Some moves are local, but others cause notable travel shifts.

Respondents were asked whether they had moved their home or work since joining carsharing. If either had changed, respondents were asked to assess whether their travel had changed more due to the move or carsharing. If a respondent stated that the move had an equal or a dominant impact on their driving, they were removed from the analysis. In addition, two key carsharing submarkets were not included in the analysis, namely, college and exclusive business/government use (6% and 2% of the sample, respectively). Respondents that identified themselves as part of these submarkets were removed because the survey design was focused on assessing the impacts of the neighborhood or residential carsharing model.

Finally, carsharing contains a subset of people who are members of the organization but otherwise do not regularly use carsharing. These members, termed "inactive members," exist for several reasons. One reason is that some carsharing organizations have had zero cost membership plans. Low or no fixed-cost membership plans make it easier for a person to be a carsharing member and not use it. Because members of this cohort do not use the service, we consider the impact of their membership to be zero. Any observed changes in travel behavior are not considered facilitated by a service that is effectively not used. The impact of the inactive membership share on aggregate emissions is discussed later in the results.

D. Participating Organizations

The survey was administered to organizations across the U.S. and Canada. Canadians and Americans received separate surveys due to their different distances and currency units. The participating organizations included were as follows: 1) AutoShare; 2) City Carshare; 3) CityWheels; 4) Community Car Share of Bellingham; 5) CommunAuto; 6) Community Car; 7) Co-operative Auto Network; 8) IGo; 9) PhillyCarShare; 10) VrtuCar; and 11) Zipcar (in North America). The organizations distributed solicitations to their members, which included a link to the survey. The survey opened at the start of September 2008 and closed on November 7, 2008. To encourage participation, two reminders were sent in addition to the original survey solicitation. The survey did start before a major financial crisis. However, a majority of respondents were members of carsharing for a year or longer. A forthcoming sensitivity analysis will illustrate how results vary across respondents by membership duration.

Most organizations, which were located in a single city, distributed survey solicitations to all of their members. Because of Zipcar's size and geographic distribution, the sample was capped at 30 000 members within specific markets. This included 5000 each within New York City; Boston; Washington, D.C.; Portland; and Seattle. An additional 2500 each in Vancouver and Toronto also received survey solicitations. Based on this and the size of the other participating organizations, we estimate that nearly 100 000 carsharing members received the survey solicitation. In total, 9635 surveys were completed, constituting a response rate of approximately 10%.

Based on the coverage, size, and selection of this population, we consider the sample to be representative of the active carsharing population within North America. As with all surveys, respondents must consent to being surveyed, and this does inject some self-selection into the sample. However, this self-selection mostly applies to the propensity of the respondent to take an online survey among active users. However, the inactive cohort would be less likely to take a survey about a service that they use infrequently and is thus subject to a nonresponse bias. Because this cohort is outside of the targeted population of this study, they do not influence the mean impacts. However, they do influence the assessment of aggregate carsharing impacts, as the exact size of the inactive cohort is uncertain and likely a lower bound of the share observed in the sample. The implications of this issue will be discussed further in the results.

IV. Results

The survey results illustrate how carsharing interacts with different households in different ways. Across all respondents, carsharing facilitates both increases and decreases in annual emissions among members. However, on balance, carsharing facilitates a net reduction in emissions for both the observed and full impacts. However, it is important that the "how and why" of this result is understood in the context of the broad diversity of emission change. While carsharing does facilitate lower emissions, this result is not generalizable across all or even a majority of members. Rather, carsharing facilitates large decreases in the annual emissions of some households, which more than compensate for the collective small emission increases of other households.

A. Demographics

Of the total 9635 surveys, the U.S. had 6895, whereas Canada had 2740. The complete data set consists of all respondents. As respondents were filtered for confounding factors, the final data set ($N_{\text{final}} = 6281$) includes only those respondents who remained after all filters were applied. Table I illustrates the sample distribution of age, education, and income. The table presents both the complete and final data sets to illustrate that the filtering induced very minor departures from the complete sample. The main differences include a slight shift toward older populations and slightly higher incomes.

While the distribution shows that carsharing members are skewed toward the young adult demographic, there is considerable representation among older respondents. Both data sets show that at least a third of respondents are over 40 years old. The income and education of respondents illustrate a similar level of diversity. Carsharing members tend to be well educated, with more than 80% holding at least a bachelor's degree. In addition, a majority of households ($\sim$60%) had 2007 household incomes less than \$80 000, whereas more than 20% of households had incomes greater than 100 000. Females outnumber males (55%/45%), whereas the size of the households is smaller than average. The average household sizes in the U.S. and Canada are 2.6 and 2.5, respectively, whereas the average among all respondents was 1.9 persons [18], [19].

TABLE I
DEMOGRAPHICS

Age Category	Complete N = 9482	Final N = 6197	Education	Complete N = 9591	Final N = 6263	Income (HH, $ US)	Complete N = 9536	Final N = 6281
Less than 20	0.6%	0.1%	Grade School	0%	0%	Under $20,000	8%	6%
20 to 30	39.3%	35.3%	Graduated High School	2%	2%	$20,000 - $40,000	18%	17%
30 to 40	29.1%	31.0%	Some College	12%	12%	$40,000 - $60,000	19%	20%
40 to 50	15.8%	16.9%	Associate's Degree	4%	4%	$60,000 - $80,000	14%	15%
50 to 60	10.4%	11.1%	Bachelor's Degree	42%	42%	$80,000 - $100,000	11%	11%
60 to 70	4.1%	4.8%	Master's Degree	27%	27%	$100,000 - $120,000	7%	7%
70 to 80	0.6%	0.6%	Juris Doctorate Degree	4%	4%	$120,000 - $140,000	4%	4%
80 to 90	0.1%	0.1%	Doctorate	8%	8%	More than $140,000	9%	10%
			Other	2%	2%	Decline to Respond	10%	9%

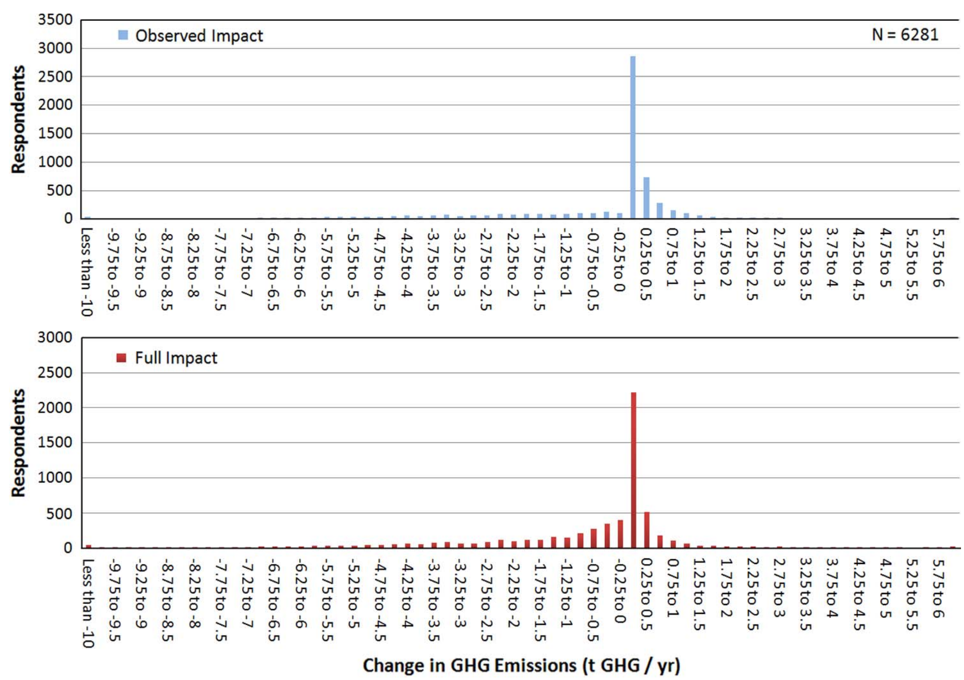

Fig. 1. Distribution of the annual household GHG emission impact.

B. Overall Impacts of Carsharing

The distribution of the change in annual household GHG emissions shows the wide diversity of GHG impacts exhibited by carsharing members. The distribution shows that a majority of carsharing members are increasing their annual emissions, but those increases are individually small. Fig. 1 shows the distribution of annual emission change by respondent frequency for both the observed and full impacts. The horizontal axis define "bins" of annual GHG change in metric tons of GHG per year (t GHG/year), whereas the vertical axis defines the count of respondents within each bin.

A striking feature of the distribution is the high number of respondents that exhibit an increase in annualized emissions within the bounds of 0 and 0.25 t GHG/year. The spike is evident within both the observed and full impacts. Members increasing their annual emissions by some amount under 0.25 t GHG/year outnumber the frequency of any other bin along the horizontal axis. Another notable feature of the distribution is the exponential decline of respondent frequency as the rate of annual emissions increases from zero. This decline is far faster to the right of zero than it is to the left. In total, 4456 (71%) of respondents have a positive observed impact (emission increase), whereas 1825 (29%) have a negative observed impact (emission reduction). For the full impact, the balance is more evenly distributed, as 3281 respondents (53%) have a positive full impact (emission increase), whereas 2953 respondents (47%) have a negative full impact (emission reduction).

The difference between the number of respondents decreasing their emissions in the observed and full impacts highlights the importance of considering avoided emissions. When the full impact is considered, 1175 respondents (∼19%) that appear to be increasing observed emissions were in fact reducing emissions when accounting for avoided travel.

The exponential drop in annual emissions to the right of zero suggests that those joining carsharing for access to automotive mobility do not drive much. To illustrate in more detail, Fig. 2

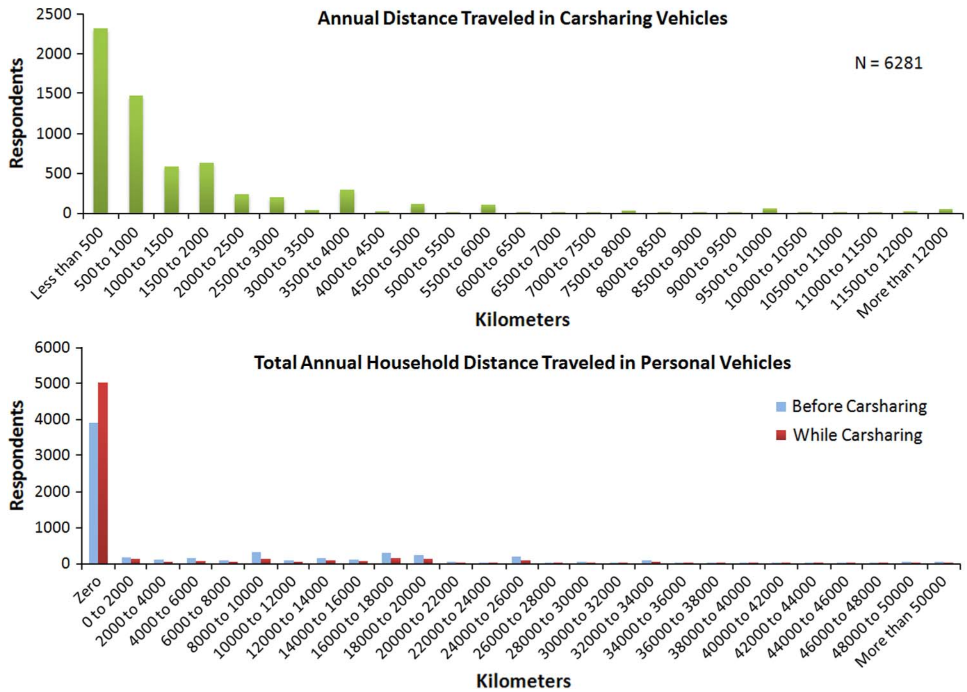

Fig. 2. Distribution of the carsharing distance driven and the personal vehicle distance driven.

shows the distribution of the annual distance driven by carsharing members and the distribution of PVMT/PVKT both before and after the survey.

The top graph in Fig. 2 shows that most households drove very low annual distances on carsharing vehicles. Thirty-seven percent of all households drove less than 500 km ($\sim$300 mi) per year on carsharing vehicles. An additional 24% reported driving between 500 and 1000 km ($\sim$620 mi). In total, nearly 80% of all households drove less than 2000 km ($\sim$1250 mi) per year on carsharing vehicles.

In addition to carsharing miles, the change in the distribution of PVMT/PVKT illustrates simultaneous shifts in the overall driving of private vehicles. The bottom graph in Fig. 2 shows the distribution of the annual distance driven on all personal vehicles held by households before joining carsharing and at the time of the survey.

It shows that the majority of households joining carsharing drove zero distance in personal vehicles. These are essentially carless households, and the only distance they drive is on carsharing vehicles. The "before-and-after" shift in the PVMT/PVKT distribution shows a significant gain in the number of carless households, an increase of nearly 30%. The distribution of annual household PVMT/PVKT distances shows a general decline of households driving all distances. This does not mean that there were no households reporting an increase in household PVMT/PVKT; some did. However, most households that reduced their driving did so by eliminating at least one vehicle.

Although the majority of respondents are increasing their emissions in the observed and full impacts, the net carsharing impact remains unclear from the information presented thus far. The long tail of respondents in Fig. 1 reducing their emissions exhibits greater reductions with greater distance from zero. Fig. 3 shows the same overall distribution, but weighted by the annual emission change of respondents. Each categorical bin of the horizontal axis contains the summation of the annual change in respondent emissions. The result is a distribution that illustrates the cumulative net annual change in emissions for all survey respondents. The top graph in Fig. 3 shows this distribution for the observed impact, whereas the bottom graph shows the full impact.

The horizontal axis in Fig. 3 is in the same units as in Fig. 1, and the respondents represented within each bin are exactly the same for both figures. The difference between Figs. 1 and 3 is that the vertical axis is the sum of the annual emission change (in t GHG/year) of each respondent within each bin. Fig. 4 shows a clearer perspective on the overall net change in annual emissions observed among all respondents. For both the observed and full impacts, it is visually apparent that the area constituting emission reductions is larger than the area constituting increases. Thus, the results show that while the majority of respondents are increasing annual emissions, the cumulative carsharing emission change is negative. It follows that the average emission change across all respondents is also negative. The distribution of the sample population is not normal and is negatively skewed with high kurtosis. However, the central limit theorem and the large sample size establish the appropriate conditions for a paired t-test, as shown in Table II, to evaluate the statistical significance of the overall mean impacts.

The observed impact across all respondents is an average of -0.58 t GHG/year per household and is statistically significant. The observed impact is contained within a 99% confidence interval -0.50 to -0.65 t GHG/year per household, whereas the full impact, with a mean of -0.84, is contained between -0.76 and -0.91 t GHG/year per household. Thus, the cumulative emission change indicates that carsharing has facilitated a net reduction in the annual rate of GHG emissions of members across North America. In terms of VKT, the average observed VKT of respondents before joining carsharing was

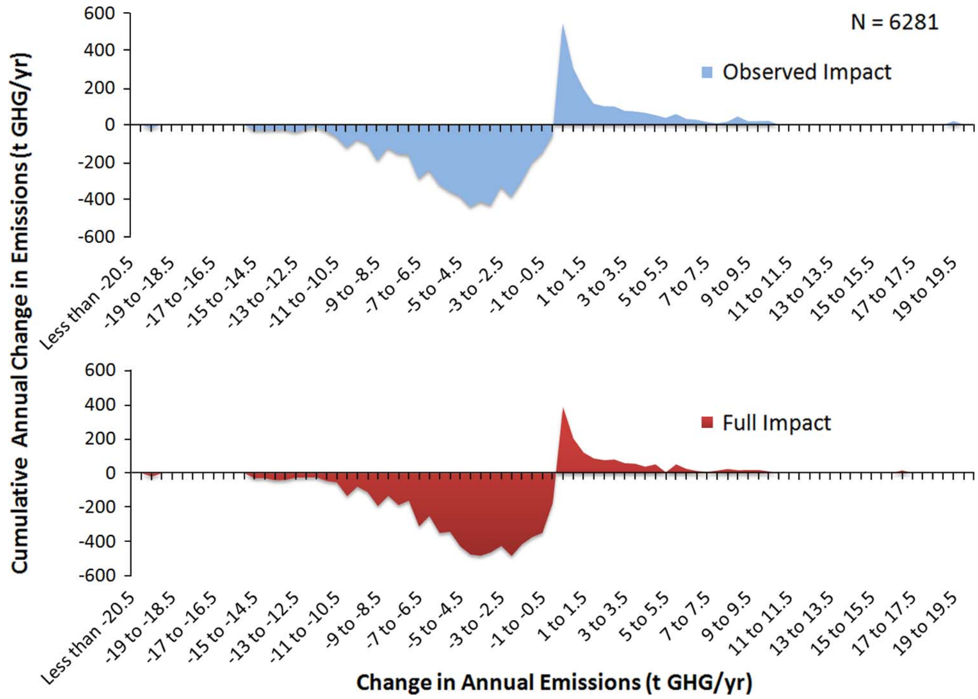

Fig. 3. Profile of the cumulative annual change in GHG emissions by respondents.

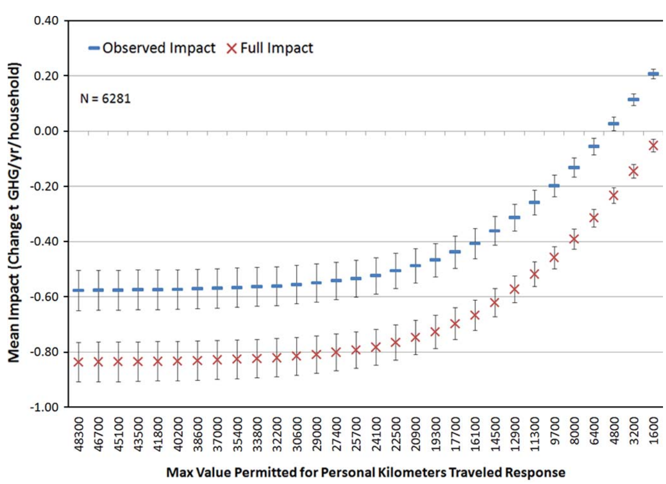

Fig. 4. Sensitivity analysis of carsharing impacts given PVMT/PVKT ceiling.

6468 km/year, whereas the average observed VKT after joining carsharing was 4729 km/year (as calculated by the observed impact). This reduction of 1740 km/year constitutes a decline of 27% in the before-and-after mean driving distance. When the miles that would have been driven in the absence of carsharing are considered, the percentage decline of the mean annual VKT is 43%.

C. *Sensitivity Analysis of Emission Change*

The results of the analysis are striking in that the mean observed and full impacts of carsharing are negative and statistically significant in spite of the fact that a majority of respondents are technically increasing their emissions through carsharing. It is natural to wonder whether this result depends on the presence of households reporting very significant emission decreases and how the result varies given assumptions about the measurement error and the filtered respondents. To elucidate these issues, we present a sensitivity analysis to show how the mean and statistical significance of impacts vary when the most influential observations are adjusted according to certain criteria.

The first analysis illustrates how the results change if the upper bound on PVMT/PVKT responses is gradually lowered such that no PVMT/PVKT response could be greater than the stated upper bound. That is, if the hypothetical upper bound is 32 000 km (20 000 mi), then all responses within the final data set containing PVMT/PVKT values higher than 32 000 km are subsequently reset to 32 000 km. The analysis computes the mean impacts and the associated confidence interval for each upper bound as it is lowered to zero. The results for all values are shown in Fig. 4.

The shallow slope from 48 000 km (30 000 mi) to 32 000 km (20 000 mi) indicates that the respondents stating PVMT/PVKT distances above 32 000 km (20 000 mi) are not influential on the magnitude of the aggregate impacts. The mean aggregate impacts only gradually increase, and the confidence intervals overlap. If the upper bound were reduced further to 16 000 km PVMT/PVKT, the mean observed impact would be −0.41 t GHG/year per household and statistically significant. In the extreme case, where the upper bound is 3200 km (2000 mi) per year or less, those joining carsharing from carless households begin to dominate, and the observed impact is an increase in emissions.

An additional sensitivity analysis illustrates how results would have varied if the PVMT/PVKT values given by respondents were systematically overestimated by respondents. Here, we assume that the original PVMT/PVKT value given by each respondent is an overestimation by some percentage. The PVMT/PVKT value applied in the emission calculation is adjusted down to reflect the actual value implied by the

TABLE II
PAIRED SAMPLE t-TEST OF THE MEAN HOUSEHOLD EMISSION CHANGE

	Paired Sample t-test - Paired Differences							
	Mean	Std. Deviation	Std. Error Mean	99% Confidence Interval Lower	99% Confidence Interval Upper	t	df	Sig. (2-tailed)
Observed Change in Emissions	-.58	2.23	.03	-.65	-.50	-20.5	6280	.000
Full Change in Emission	-.84	2.20	.03	-.91	-.76	-30.0	6280	.000

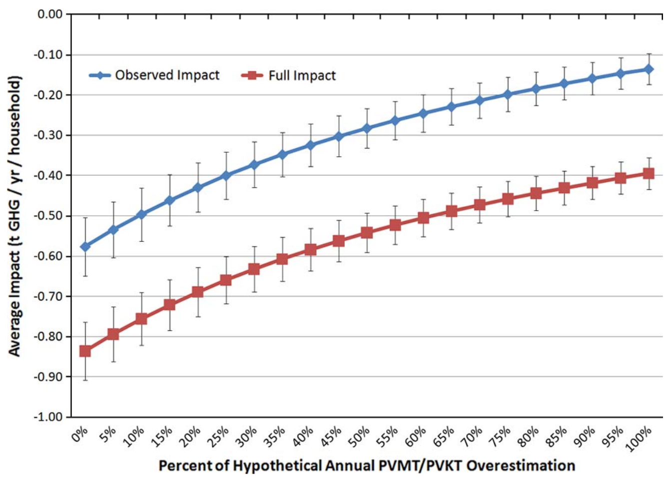

Fig. 5. Sensitivity of impacts to PVMT/PVKT overestimation.

overestimation. Fig. 5 shows the mean and confidence interval at each percentage of overestimation.

Fig. 5 shows that, even if the assumed overestimation of PVMT/PVKT by respondents was systematically as high as 100% across the entire sample, both the observed and full impacts would still have means and confidence intervals that are negative and statistically significant.

To evaluate whether the duration of membership influenced the overall carsharing impact, we divide the respondents into subgroups as categorized by the time that they have been in their organization. The results in Fig. 6 show that the average observed and full impacts are rather stable across different membership durations.

Fig. 6 demonstrates two points. First, it raises the possibility that near-term changes after joining comprise a large share of the impact. However, a longitudinal analysis of members would better corroborate this conclusion. Second, it suggests that the circumstantial timing of the survey during the financial crisis of 2008 did not impose any large effect on the results as respondents that joined far earlier exhibit similar average impacts, all of which are statistically significant.

Finally, the filtering of respondents to eliminate the influence of confounding factors on the results yields a reduced sample of 6281. However, it also introduces the possibility that a bias was inserted if those filtered were systematically skewed toward either negative or positive emission changes. Fig. 7 shows how Fig. 4 would have appeared if all respondents with calculable emissions were included without any data filter.

Fig. 7 shows that the profile of the cumulative emissions of all respondents fits the same shape as Fig. 4 but exhibits a wider distribution of impacts with larger annual changes. This result is expected as Fig. 7 reintroduces respondents that had emission changes resulting from other factors. Across all 9506 respondents, the average observed impact was statistically significant at -0.53 t GHG/year per household with a confidence interval of (-0.59, -0.46), overlapping the filtered mean. For the full impact, it was -0.8 t GHG/year per household with an interval of (-0.86, -0.73). The results in Fig. 7 also suggest that although the number of respondents filtered due to confounding factors was sizable, their removal did not introduce a significant systematic bias that altered the general direction or magnitude of the carsharing impact.

D. Distributions of Subsamples by Membership Circumstance

The impact of carsharing is the composition of a complex and diverse set of relationships pertaining to how individual households incorporate carsharing into their lifestyle. The nuances within the aggregate distributions in Figs. 1 and 3 become more apparent with an analysis of selected subpopulations. At the beginning of the survey, respondents were asked to characterize the circumstances in which their household joined carsharing. These circumstantial categories, as shown in Table III, offer insights as to which subgroups comprise the population.

These circumstances are reflective of the lifestyle that the respondent was leading prior to joining carsharing as they are succinct sentences describing a specific situation. Table III includes information on the share of each circumstantial category within the complete and final sample. For most circumstantial categories, the balance of respondents changes very little. The largest change consists of people who did not have a car and joined carsharing to gain additional personal freedom. This shift is unfavorable to carsharing because the category consists of people who can only increase their observed emissions, as they were not driving prior to joining carsharing.

Fig. 8 shows graphs of two such influential categories in which households were carless prior to joining. The avoided emissions, which generate the full impact, are applicable for both respondent subsamples.

The change in the distributions of annual GHG emissions illustrates the importance of capturing latent effects. Among members that joined carsharing for greater mobility, 26% suggest that carsharing results in lower emissions than would otherwise occur. Likewise, nearly 35% of respondents using carsharing as a substitute for vehicle acquisition suggested that higher emissions would occur if carsharing was not available. Another key distinction of both distributions is the range of

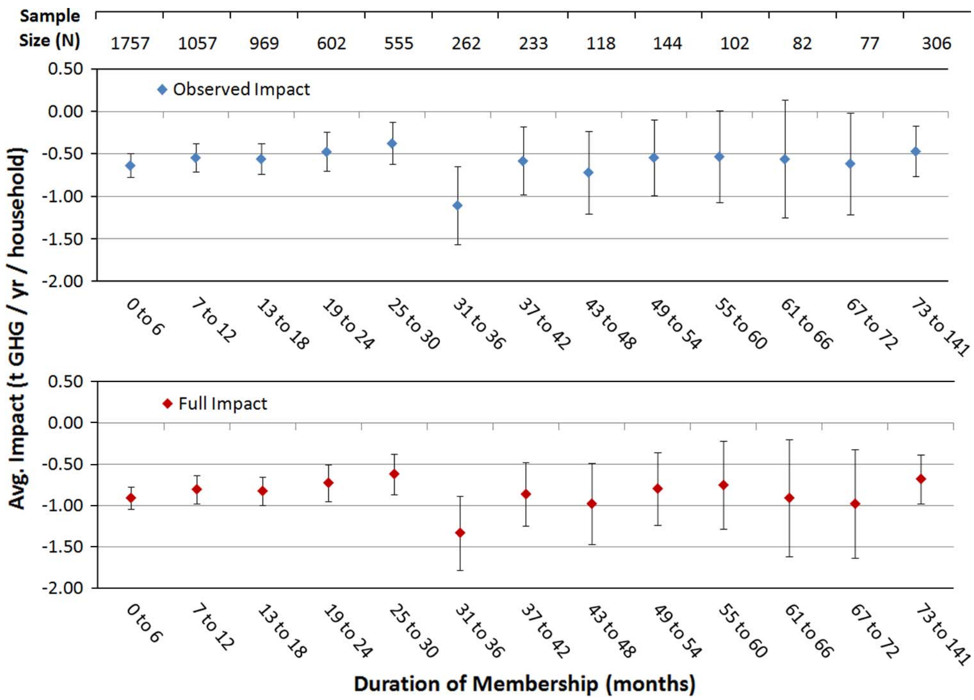

Fig. 6. Analysis of impact by membership duration.

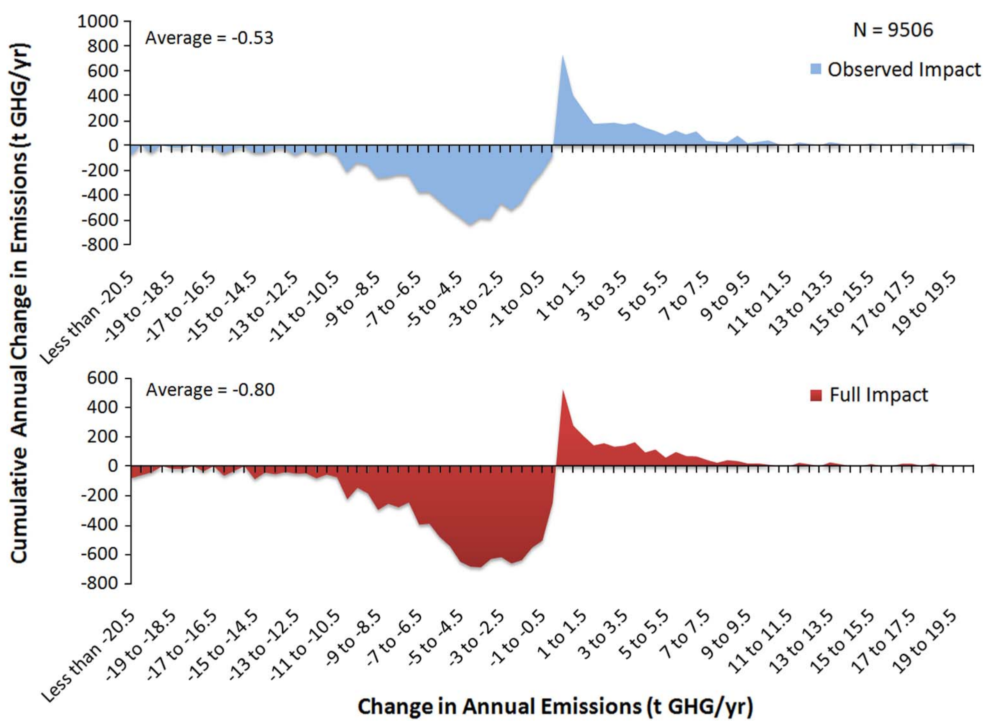

Fig. 7. Cumulative change in annual GHG emission change with the complete data set.

emission change observed on both sides of zero. More than 90% of the observed and full impacts are contained with $+/-2$ t GHG/year, thus emphasizing that emission increments generated by carless households are small.

In contrast to carless households, Fig. 9 shows the distribution of changes in emissions by respondents that entered carsharing with vehicles that they subsequently shed.

Both distributions in Fig. 9 are characterized by a significant majority of respondents reducing annual GHG emissions. Among multivehicle households shedding cars, 88% of respondents reduced emissions. Similarly, among single-vehicle households shedding cars, 93% exhibited an emission reduction. It is important to note that, within Fig. 9, the observed and full impacts are the same. This is a function of the methodological calculation to prevent the full impact from being overstated. As respondents in this category are already shedding vehicles, the application of avoided driving constitutes a replacement of PVMT/PVKT. Thus, the application of avoided emissions

TABLE III
CIRCUMSTANTIAL CATEGORIES OF RESPONDENT MEMBERSHIP

Circumstantial Category	% Respondents in Complete Dataset	% Respondents in Final Dataset
Owned at least one car, but needed an additional car for greater flexibility, and joined carsharing instead of acquiring an additional car.	9%	8%
I am in college, and I joined carsharing to gain access to a vehicle while in college.	6%	0%
Owned one car, but I joined carsharing and got rid of the car.	13%	14%
My household did not have a car, but joined carsharing to gain additional personal freedom.	43%	51%
My household did not have a car, but changes in life required a car and I joined carsharing instead.	6%	7%
My employer joined carsharing, and I joined through my employer.	5%	3%
A car of mine stopped working, and instead of replacing it I joined carsharing.	8%	8%
Owned more than one car. Got rid of at least one car and joined carsharing.	3%	3%
I live in an apartment building with a designated carsharing vehicle, and I joined through its membership arrangement.	0%	0%
I joined carsharing for reasons other than those listed above. Please explain:	9%	7%

Question: Please select the statement that best characterizes the circumstances under which you joined carsharing.

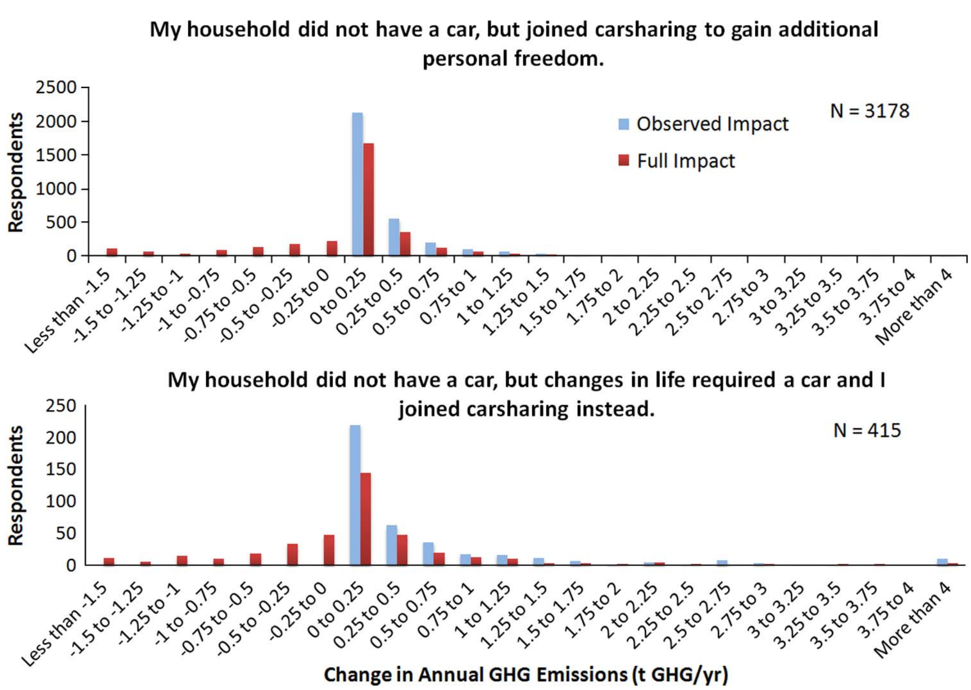

Fig. 8. Respondents entering carsharing without a vehicle.

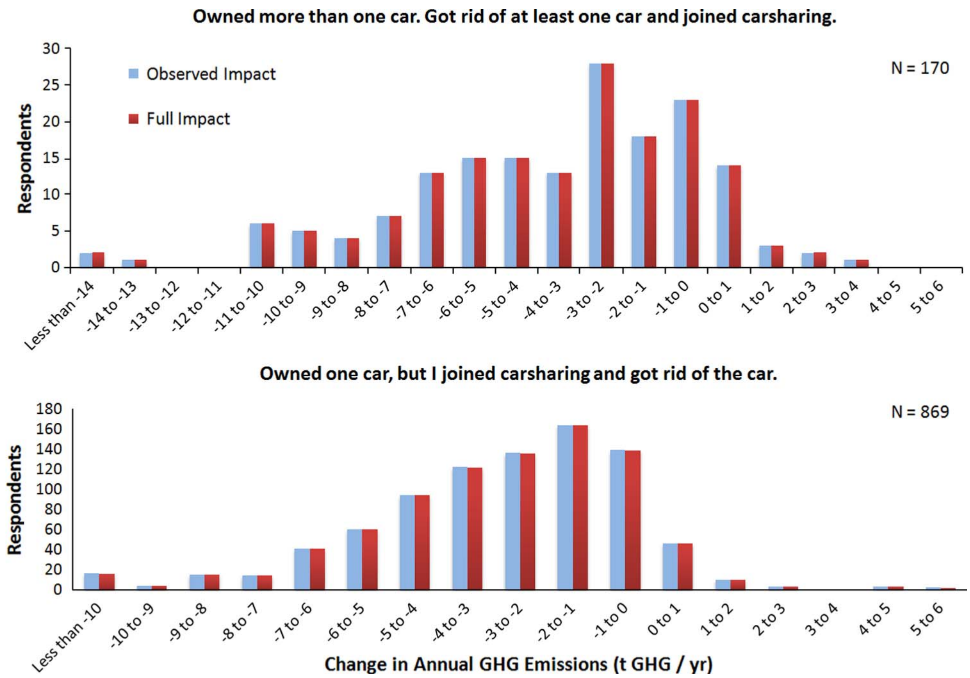

Fig. 9. Joined carsharing and shed vehicles.

would constitute double counting. For this and other categories in which a vehicle was shed, similar rules were followed.

E. Impacts by Organization Type and by Country

Both for-profit and nonprofit organizations have grown to achieve sizable membership rosters within their respective markets. A comparative analysis was done to evaluate the degree to which impacts differ by organization type and by country. The comparison found that the nonprofit organizations exhibited higher reductions per member than for-profit organizations. The analysis also found that the average impact in the U.S. is larger than that in Canada. However, the average observed and full impacts by organization and by county are negative and statistically significant for all categories (for further details, see [17]). While the nonprofits exhibit a higher emission impact per household, the scale of the for-profit impact is likely larger due to the larger membership base. The impact of carsharing in the U.S. is likely larger than that in Canada because Americans drive longer distances and thus have more PVMT/PVKT to reduce. Overall, the data from this study support that both nonprofit and for-profit organizations are reducing emissions. The reason for the apparent discrepancy between organization types remains an open question.

F. Aggregate Carsharing GHG Impacts

The analysis thus far has shown that carsharing members have reduced their emissions. However, until now, the results have presented these impacts in the context of the sample. No information has been presented to translate these impacts to the aggregate carsharing industry.

To do this, we first need to define the population size that is represented by the sample of active carsharing households that use the neighborhood carsharing model. In mid-2009, the carsharing industry had 378 000 members within North America, of which the sample represents a large proportion. From the sample, we estimate that 2% of the population were exclusive business users, whereas 6% were college students. In addition, the survey found that 19% of respondents were members living in households with another carsharing member. The share of respondents with more than two members/household was negligible, and thus, we can estimate a population of 314 390 active households. Finally, we must account for the share of inactive members, which have an impact of zero. From the sample, we know that the share of inactive members is at least 8%, but because there is likely a nonresponse bias with this cohort, we can only assume a range of inactive members within the population. As that share rises, the population to which the average impacts applies shrinks. Table IV illustrates this result across the range of plausible population inactive member shares.

Based on knowledge of the carsharing industry, we consider the share of inactive members to range between 15% and 40% at the time of writing. Given this range, the results suggest that carsharing reduces between 109 000 and 155 000 t GHG/year by the observed impact and between 158 000 and 224 000 t GHG/year by the full impact. It is important to note that this range could shift over time as the industry evolves. This evolution may occur in ways that either increase or decrease the expected share of inactive members, and the average impact could change. For example, if free and low fixed-cost membership plans become less common in the industry, the share of inactive memberships will probably fall.

V. Conclusions

Based on this study, carsharing is reducing net annual GHG emissions in North America. This reduction is not the result of all members universally reducing their emissions. Rather, it is derived from the balance of the distribution of changes

TABLE IV
SENSITIVITY OF AGGREGATE CARSHARING GHG EMISSION IMPACTS

Inactive Share	Active Carsharing Household Population	Observed Impact Total Annual Emissions (t GHG/yr)	Full Impact Total Annual Emissions (t GHG/yr)
0%	314,390	-182,000	-264,000
5%	298,671	-173,000	-251,000
10%	282,951	-164,000	-238,000
15%	267,232	-155,000	-224,000
20%	251,512	-146,000	-211,000
25%	235,793	-137,000	-198,000
30%	220,073	-128,000	-185,000
35%	204,354	-119,000	-172,000
40%	188,634	-109,000	-158,000
45%	172,915	-100,000	-145,000
50%	157,195	-91,000	-132,000

across members. The number of carless households increasing their emissions is comparatively large, constituting more than half of the respondents. However, the degree to which these households are increasing emissions as a result of carsharing is small on an individual basis. The overall emission reduction is driven by the remaining respondents reducing their emissions by larger amounts that compensate for increases of the majority. Carsharing appears to enable members to converge to a shared-vehicle low-mileage lifestyle. Carless households converge to this lifestyle by increasing emissions, and car-holding households converge by decreasing emissions.

The results and scope of this paper have implications for policy design. Carsharing systems provide environmental benefits. However, caution regarding the caveats of this study in any policy design is necessary. It is clear from the data collected that not all members reduce emissions. More importantly, not all members of carsharing organizations are active members. For this reason, a blanket application of emission factors to carsharing membership roles is not recommended as an appropriate method of accounting, as an organization could inadvertently increase casual (inactive) members by initiating zero fixed-cost membership plans. The diversity of impacts by member (and member type), region, and organization type suggests that credits for carsharing impacts should be certifiable.

This paper suggests that carsharing in North America has provided the following results: 1) mobility to thousands of carless households with some increase in emissions and 2) a mobility alternative to urban households that can adapt to a less auto-intensive lifestyle with emission reductions. The net effect of these two trends is an overall reduction in annual emissions. Future studies should continue to evaluate these trends, as they will likely evolve. As long as carsharing continues to economically thrive, its benefits may change as more car-holding households may find carsharing to be an established option for meeting automotive travel needs within North American cities.

ACKNOWLEDGMENT

The authors are grateful to the Mineta Transportation Institute for funding this study. The authors would like to thank the numerous carsharing programs in North America that participated in this survey. The authors would also like to thank C. Rodier, A. Cohen, D. Allen, M. Chung, B. Dix, K. Brown, J. Ma, J. Bato, S. Contreras, and E. Mao of the Transportation Sustainability Research Center, University of California, Berkeley, for assistance with the literature review and survey development, as well as A. Gershenson and A. Zia of San Jose State University, N. Weiss of Arizona State University, D. Brook, C. Lane, and K. McLaughlin for assistance with survey development and report review. The contents of this report reflect the views of the authors and do not necessarily indicate acceptance by the sponsors.

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