CARSHARING'S LIFE-CYCLE IMPACTS ON ENERGY USE AND GREENHOUSE GAS EMISSIONS

T. Donna Chen
Assistant Professor
University of Virginia
Thornton Hall D203
351 McCormick Rd, Box 400742
Charlottesville, VA 22904-4742
tdchen@virgina.edu
Phone: 434-924-7464

Kara M. Kockelman
(Corresponding author)
E.P. Schoch Professor of Engineering
Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin
kkockelm@mail.utexas.edu
Phone: 512-471-0210

The following paper is a pre-print, the final publication can be found in *Transportation Research Part D: Transport and Environment*, 47: 276-284, 2016.

ABSTRACT

This paper examines the life-cycle inventory impacts on energy use and greenhouse gas (GHG) emissions as a result of candidate travelers adopting carsharing in US settings. Here, households residing in relatively dense urban neighborhoods with good access to transit and traveling relatively few miles in private vehicles (roughly 10 percent of the U.S. population) are considered candidates for carsharing. This analysis recognizes cradle-to-grave impacts of carsharing on vehicle ownership levels, travel distances, fleet fuel economy (partly due to faster turnover), parking demand (and associated infrastructure), and alternative modes. Results suggest that current carsharing members reduce their average individual transportation energy use and GHG emissions by approximately 51% upon joining a carsharing organization. Collectively, these individual-level effects translate to roughly 5% savings in all household transport-related energy use and GHG emissions in the U.S. These energy and emissions savings can be primarily attributed to mode shifts and avoided travel, followed by savings in parking infrastructure demands and fuel consumption. When indirect rebound effects are accounted for (assuming travel-cost savings is then spent on other goods and services), these savings fall to as little as 3% across all U.S. households.

KEYWORDS

Carsharing, life-cycle analysis, greenhouse gas emissions, energy.

INTRODUCTION

In 2009, for the first time since World War II, the U.S. vehicle fleet diminished in size, as 14 million vehicles were scrapped and 10 million new vehicles were sold (Brown 2010). Alongside a U.S. trend toward lower private-vehicle ownership (Cohen 2012) and a growing popularity of the shared-use economy (Botsman and Rogers 2010), carsharing is emerging as an alternative travel "mode" that is both more flexible than transit and less expensive than traditional ownership. Both peer-to-peer carsharing (through organizations like Getaround and Relayrides) and business-to-consumer carsharing (through operations like Car2Go and Zipcar) are gaining ground in urban areas. Worldwide, carsharing organizations operate in over 1,100 cities across at least 27 countries (Shaheen and Cohen 2013).

In North America alone, carsharing systems exist in more than 20 metropolitan areas (Martin and Shaheen 2011b) and membership levels are over 1 million persons (Shaheen and Cohen 2013). Shared mobility innovations are rapidly growing, and policymakers may want to incentivize this special mode far more than we have seen to date. Carsharing generally reduces automobile dependence and lowers emissions while benefitting its users via lowered travel costs (Litman 2000). For decision makers to better appreciate carsharing's contributions, it is useful to quantify the life-cycle implications of a shift toward shared-car use. A life-cycle inventory (LCI) analysis quantifies the complete energy and atmospheric emissions for the lifetime effects of a product, process, or activity (USEPA 1995), allowing decision makers to compare alternative activities and products via common metrics.

This paper quantifies life-cycle energy and greenhouse gas (GHG) emissions for the carsharing mode as compared to one equivalent person-kilometer traveled (PKT) under the traditional (private vehicle ownership) approach. The calculations recognize the vehicle replacement rate changes that come with sharing, as well as the fuel efficiency improvements from faster fleet turnover, travel distances changes, reduced parking demands, and shifts in the use of alternative modes.

PRIOR RESEARCH

Existing studies have examined the environmental impact of carsharing operations to various extents, but few consider life-cycle impacts, which include upstream infrastructure and supply chains (like vehicle manufacture and fuel production). Those that examine life-cycle impacts of carsharing operations exclude key behavioral impacts, such as members' reduced travel distances, as discussed in this section.

Martin and Shaheen (2011a) estimated GHG reductions at the household level via an analysis of 11 carsharing organizations in North America and found that, while some carsharing members increase and others decrease their annual emissions, the net impact is an estimated annual reduction of -0.58 tons of GHG emissions (CO_2-equivalent, per member household, per year) due to observed changes in household driving for North American member households and -0.84 tons of GHG emissions in full impacts per member household per year (including foregone vehicle purchases). This reduction roughly translates to 11% to 16% of the average American household's transport-related GHG emissions per year (USDOT 2009). Using stated preference survey data from Bremen, Germany and Brussels, Belgium, Ryden and Morin (2005) estimated emissions savings per new member to be 54% in the former and 39% in the latter, based on lower vehicle travel distances (vehicle-kilometers traveled, or VKT), increased fleet fuel economies, and increases in public transit use.

Martin and Shaheen's (2011a) and Ryden and Morin (2005)'s emissions reductions estimates did not reflect any land use impacts of carsharing. Using stated preference data from Car2go members in Ulm, Germany, Finkhorn and Muller (2011) examined both mobile emissions impacts and changes in parking and roadway infrastructure requirements. They estimated a reduction of 146 to 312 kg of CO_2 per member per year, taking into account reduced vehicle ownership and VKT. Switzerland's Mobility Carsharing operation has developed an environmental inventory tool to assess their fleet's consequences - from vehicle manufacturing and maintenance, to road use, infrastructure provision, and land use effects. As compared to the average Swiss passenger car, they estimate that the Mobility Carsharing fleet reduces overall environmental burdens (including exhaust emissions, fuel consumption, material use for car and road infrastructure, health damages from road noise, and motor vehicle accidents) by 39% per vehicle-kilometer travelled (VKT), on a vehicle-to-vehicle comparison, thus ignoring additional savings from members' reduced VKT (Doka and Ziegler 2001). For modern cars with low emissions, carsharing did not provide significant reductions of NO_x, HC, CO, and PM10 (as compared to clear benefits in CO_2, noise, accidents, and fuel production. The authors noted that as vehicles become more fuel efficient, land use aspects (e.g., transportation infrastructure requirements) become a more significant share of the total environmental burden reduction.

Briceno et al. (2004) have extended the scope of life-cycle analysis (LCA) for shared-vehicle systems by anticipating rebound (in consumption) effects, via the use of input-output analysis (to derive emissions from added non-transport consumption that comes from the average member's travel cost savings). They found that if car-sharers in Norway spread their transportation savings uniformly across non-transport items, the overall rebound effects are small. However, if the travel-cost savings were spent on air travel, the added (rebound) GHG emissions are high, demonstrating how moves towards ostensibly more sustainable consumption patterns can have rather unintended consequences. As Hertwich (2005) notes, carsharing typically reduces local travel expenditures, but use of those savings in other expenditure categories can have negative environmental impacts.

CARSHARING'S IMPACTS ON ENERGY USE AND GHG EMISSIONS

Life-cycle analysis offers a systematic approach to evaluating the environmental consequences of carsharing, painting a complete picture of this emerging mode's environmental impacts - as measured in an equivalent PKT. This "cradle-to-grave" process recognizes resource extraction to produce the vehicles and fuels, and resource depletion through the vehicle use and disposal phases. Environmental impacts are numerous along the way: First, vehicle "ownership" (in terms of vehicles per person) generally falls with carsharing membership, offering environmental benefits from vehicle production and parking infrastructure savings. Second, carsharing has impacts on VKT and vehicle utilization rates (and thereby fleet replacement rates), which tends to reduce fuel consumption (as well as, arguably, road infrastructure needs, though this potential savings is generally not assessed). Lastly, carsharing shifts many trips previously carried out by private automobile to transit and non-motorized modes (as well as some trips previously carried out by non-auto modes to shared cars). As pointed out above, in this paper's literature review, prior studies have examined the environmental impact of carsharing to different extents, but no study has examined the overall impact of all these behavioral changes associated with carsharing concurrently (ownership impacts on vehicle production and transportation infrastructure, vehicle utilization and fleet replacement, and modal shift). This study applies an LCA framework to comprehensively examine the combined effects on energy use and GHG emissions accounting for all of these potential traveler behavior shifts.

Candidate Households for Carsharing

However, carsharing is not a reasonable option for every traveler. Carsharing membership is more appealing for those who travel fewer kilometers and reside in higher-density neighborhoods with good walking, cycling, and transit options (Litman 2000). Thus, carsharing programs tend to concentrate in metropolitan cores, well served by other modes, where travelers can and do rely less on private car use than the average traveler (Stillwater et al. 2009). In an analysis of 13 U.S. regions with carsharing programs, Celsor and Millard-Ball (2007) found that carsharing neighborhoods are more likely to have higher shares of one-person households and residents with Bachelor's degrees, more workers commuting by transit and non-motorized modes, lower vehicle ownership levels, higher density, and more walkable environments than non-carsharing neighborhoods. Furthermore, carsharing trips are more like to be used for shopping, personal business, and recreation trips versus commute trips (see, e.g. Millard-Ball et al. 2005 and Cervero et al. 2007), and members' average trip distances are shorter than those of non-members (Cervero et al. 2007).

Thus, while carsharing is not an omnipresent and universally feasible travel option, it does appeal to various populations. Frost and Sullivan (2010) estimated that car owners who drive 12,000 miles (7,460 km) per year at an average speed of 30 mi/hr can save $1,834 by switching to a carsharing service (with those driving less than 12,000 miles reaping even greater savings). Looking specifically at the San Francisco Bay Area, Duncan (2011) estimates that as much as one-third of those households have vehicle usage patterns that would save money via carsharing. Others are not as optimistic: Schuster et al. (2005) estimate that in Baltimore, Maryland, 4.2% to 14.8% of vehicles would be less expensive to share than to. If estimates from the Bay Area and Baltimore are applied to urban areas throughout the US (taking into account that 80% of the US population now resides in urban areas (Census 2010), the range of potential carsharing members nationwide covers a wide spectrum: from 3% up to 26% of persons. Surveying 26 existing organizations in North America, Shaheen et al. (2006) estimate that market potential for carsharing is 10% of adults 21 and older. In addition to existing neighborhood infrastructure and household demographics, policy can also affect the adoption of carsharing. Using stated preference survey from Palermo, Italy, Catalano et al. (2008) developed a multinomial logit (MNL) model which simulated that carsharing activity could increase up to 10% with policies which increase parking fees, add reserved parking careas for carsharing and carpooling users, and closing off specific traffic zones for high-emissions vehicles.

For members who actively participate in carsharing, the adoption of carsharing behavior has quantifiable effects on vehicle ownership rates, VKT, and modal shift to and from transit and non-motorized modes. The energy and GHG impacts of these vehicle ownership and travel behavior shifts are discussed in detail below.

Vehicle Ownership Impacts

Within carsharing households, early studies estimate that vehicle ownership can be reduced by about 40% to 44% (Whitelegg and Britton 1999, Meijkamp 1998). Zhou and Kockelman (2011) surveyed Austin, Texas households in 2008 and found that 21% of those surveyed (following population correction) would expect to give up/release at least one of their private held vehicles upon joining a carsharing organization. A 2008 nationwide survey found that after carsharing, US households reduced their overall vehicle ownership by 49%, with most of this shift from one-car households to no-car households (Martin and Shaheen 2011b). In the San Francisco Bay Area, Cervero et al. (2007) looked at the longer term effects of membership in City Carshare and found that vehicle shedding effects level off with length of membership. A survey 4 years following the program's establishment found that the net vehicle shedding effects (as compared to non-member households) is about 10 vehicles per 100 households. Martin et al. (2010) also concluded that the combined effect of vehicles shed and vehicles avoided translates to each carsharing vehicle serving in lieu of 9 to 13 privately owned vehicles. A first-year look in Philadelphia estimates that each PhillyCarShare vehicle replaced, on average, 23 private vehicles (Lane 2005). Other North American studies have estimated the vehicle replacement rate closer to one carsharing vehicle per 15 privately owned vehicles (Millard-Ball et al. 2005, Econsult 2010, Frost & Sullivan 2010, Stasko et al. 2013).

Impacts on Vehicle-Kilometers Traveled (VKT)

Upon joining a carsharing operation, households typically travel by car less than prior to joining carsharing. When use of a vehicle involves reserving a vehicle in advance and the costs of operating a vehicle are made more apparent (generally with a by the minute charge in most car-share operations), households tend to decrease their use of vehicles. Comparing similar households in Montreal, Sioui et al. (2012) found that households who subscribe to and active use a carsharing organization utilize a car 3.7 times less than neighbors who do not subscribe to these services.

However, estimates of how much households reduce their auto travel distances vary greatly. Sperling et al. (2000) estimate carsharing reduces VKT by 30-60%. Frost and Sullivan (2010) estimate carsharing members drive 31% fewer kilometers upon joining a carsharing service. Cervero et al. (2007) looked at members of City CarShare in San Francisco and found that in the long term, carsharing members reduced their annual VKT by 67%. Martin and Shaheen (2011b) found through a North American survey that the average VKT by respondents decreased 27% after joining carsharing (from 6468 km/year to 4729 km/year). In Europe, these impacts seem to be even greater as Muheim (1998) estimates that members of Mobility Carsharing Switzerland drove 72% fewer kilometers after their first year of joining the program and Meijkamp (1998) reports that members of carsharing organizations in The Netherlands drove 33% fewer miles after becoming car-sharers. Ryden and Morin (2005) used stated preference surveys and found that, on average, carsharing members in Bremen, Germany and Brussels, Belgium reduced their VKT by 45 and 28%, respectively.

Impacts on Energy Consumption During Use Phase

In addition to reducing use phase energy demand by reducing VKT, members of car-share operations also tend to drive more fuel efficient vehicles than non-car-share members. Meijkamp (1998) estimate that shared cars are approximately 24% more fuel efficient than the average car in the Netherlands. Martin and Shaheen (2011a) also found that carsharing vehicles are more fuel efficient than the vehicles they replaced, with the carsharing fleet averaging 13.9 km per liter (32.8 mpg) and the vehicles they replaced averaging 9.8 km per liter (23.3 mpg). Using stated preference data from Germany and Belgium, Ryden and Morin (2005) estimated that the average carsharing vehicle is 17% more fuel efficient than the average privately owned vehicle. This phenomenon can probably be attributed to the faster replacement rate of car-share vehicles since they have higher utilization rates. The average privately owned new vehicle in the U.S. is owned for 71.4 months (or approximately 6 years) before being "replaced", which may be via sale as a used vehicle, trade-in (when acquiring a newer or different vehicle), shedding an unneeded vehicle, or a serious crash (Seng 2012). On the other hand, due to more VKT and faster wear and tear, the commercial car-share operations replace cars every 2 to 3 years (Mont 2004). With government mandates like CAFE standards and increasing fuel prices, newer vehicles, on average, are more fuel efficient (and smaller) than older fleets, contributing to a more fuel efficient shared fleet compared to a privately owned fleet.

Impacts on Parking Infrastructure Demand

Reduced car ownership has potential impacts on infrastructure requirements, particularly parking. Most governing authorities' interest in promoting carsharing is motivated by parking demand reduction (Millard-Ball et al. 2005). While numerous studies qualitatively link reduced vehicle ownership and parking demand (see, e.g., Millard-Ball et al. [2005] and Martin et al. [2010]), few studies have quantified the magnitude of that impact. The 1-to-15 shared-vehicle-to-private-vehicle replacement rate discussed earlier does not directly translate to a parking impact in high-demand areas, since many car-share participants use transit and other non-auto modes for commute trips (Celsor and Millard Ball 2007), and hence much of the parking reduction would occur in private garages and parking lots. A 2004 study in the U.K. surveyed employers and found that spaces fell from 0.79 spaces per staff member to 0.42 spaces per staff member after starting a carsharing program (Department for Transport 2004). Looking at carsharing and parking at the building scale in Toronto, Engel-Yan and Passmore (2013) found that buildings with dedicated carshare vehicles required 50% fewer parking spaces than those without such dedications. Using survey data from Ithaca Carshare, Stasko et al. (2013) estimated that program participants' on-street parking needs or demands fall by 26 to 30%, depending on day of week and time of the day.

Impacts on Other Modes of Transportation

So how do car-share members pursue trips while reducing vehicle ownership and cutting VKT? Overwhelming, studies point to increase use in non-motorized modes and transit. In the Netherlands, Meijkamp (1998) reports 14% increase in bicycling, 36% increase in rail transit use, and 34% increase in bus transit use among carsharing members. In Germany and Belgium, Ryden and Morin (2005) estimate that carsharing members use public transportation 35 to 47% more during weekdays. In Montreal, Canada, households who subscribe to carsharing services use public transportation 55% more often than neighbors who own one private vehicle (Sioui et al. 2012). In the US, a second year evaluation of CarSharing Portland found members reporting

25% increase in walking, 10% increase in bicycling, and a 14% increase in public transit use (Cooper et al. 2000). Similar results can be seen in Philadelphia after one year of joining Philly CarShare, 19% of members reported more walking, 8% reported more cycling, and 18% reported more transit use (Lane 2005). In a survey of 13 car sharing operations in North America, Martin and Shaheen (2011c) found the impact on transit use was statistically insignificant after joining car sharing programs but net use of walking, biking, and carpooling modes increased 2%, 7%, and 3%, respectively.

ANALYSIS AND RESULTS

The total impact of carsharing on energy use and GHG emissions as compared to an equivalent PKT in a private automobile (the functional unit in this study) is the combined effect from all of these different dimensions of travel behavior, vehicle technology, and infrastructure change. This analysis presents three different scenarios to examine the sensitivity of reduction in total life-cycle energy and GHG emissions for a candidate household member (one who travels shorter total distances and resides in higher-density urban neighborhoods, with good walking, cycling, and transit services) upon joining a carsharing organization. Table 1's results for low-impact (pessimistic), medium-impact (likely), and high-impact (optimistic) scenarios are based on multiple input factors (as shown in Table 1's first column). The values and ranges of these inputs come from the studies discussed earlier, in this paper's Impacts section, where the low-impact scenario represents results from the most pessimistic estimate from prior studies, the high-impact scenario represents the most optimistic estimate, and the medium-impact scenario reflects a commonly agreed-upon estimate from multiple previous studies (in the better-studied impact categories) or a single study's value lying between the low- and high-impact estimates.

Table 1. Effect of Carsharing on Travel Behavior, Infrastructure Demand, and Other Modes

Input	Low Impact	Source(s)	Med Impact	Source(s)	High Impact	Source(s)
Carsharing Market Potential (% of US adult population)	3.0%	Schuster et al. (2005)	10.0%	Shaheen et al. (2006)	26.0%	Duncan (2011)
% Reduction in Private Vehicles Owned	10.0%	Cervero et al. (2007)	21.0%	Zhou and Kockelman (2011)	49.0%	Martin and Shaheen (2011b)
Private Vehicle Replacement Rate for Each Car-Sharing Vehicle	9	Martin et al. (2010)	15	Millard-Ball et al. (2005), Econsult (2010), Frost and Sullivan (2010), Stasko et al. (2013)	23	Lane (2005)
% Reduction in VKT	27.0%	Martin and Shaheen (2011b)	31.0%	Frost and Sullivan (2010)	67.0%	Cervero et al. (2007)
% Fuel	17.0%	Ryden and	24.0%	Meijkamp	43.5%	Martin and

Efficiency Improvement		Morin (2005)		(1998)		Shaheen (2011a)
% Reduction in Public Parking Demand	26.0%	Stasko et al. (2013)	38.0%	Department for Transport (2004)	50.0%	Engel-Yan and Passmore (2013)
% Increase in Rail Transit Use	0.0%	Martin and Shaheen (2011c)	8.0%	Cooper et al. (2000), Lane (2005)	36.0%	Meijkamp (1998)
% Increase in Bus Transit Use	0.0%	Martin and Shaheen (2011c)	8.0%	Cooper et al. (2000), Lane (2005)	34.0%	Meijkamp (1998)
% Increase in Bicycling	7.0%	Martin and Shaheen (2011c)	9.0%	Cooper et al. (2000), Lane (2005)	14.0%	Meijkamp (1998)
% Increase in Walking	2.0%	Martin and Shaheen (2011c)	19.0%	Lane (2005)	25.0%	Cooper et al. (2000)

The energy use and GHG emissions impacts are estimated relative to the base case ("Before" scenario) of private vehicle ownership (prior to joining a car-share organization). As discussed previously, potential carsharing participants exhibit different travel behaviors than the average motorist. The calculations on energy and emissions impacts as a result of mode shift are based on initial mode shares of "likely" candidates for carsharing membership, based on findings in Celsor and Millard-Ball (2007) and Cervero et al. (2007).

Table 2. Base Mode Split for Candidate Carsharing Members

	Mode Split
Private Car	33.6%
Rail Transit	19.4%
Bus Transit	11.6%
Bike	3.8%
Walk	31.6%

The impacts of vehicle operation changes are estimated as a result of reduction in VKT in Table 1 and are based on per PKT estimates of a conventional sedan (2005 Toyota Camry with a combined fuel economy of 25 mpg) from Chester and Horvath (2009). As discussed in the Impacts on Energy Consumption During Use Phase section, the average private vehicle replaced by a carsharing vehicle averages 23.3 mpg (Martin and Shaheen 2011a), making this estimate slightly conservative. The impacts of vehicle manufacturing and maintenance changes are a result of the private vehicle replacement rate in Table 1 and are based on per PKT estimates of a 2005 Toyota Camry from Chester and Horvath (2009). The impacts of parking infrastructure demand decrease is a result of percent reduction in public parking demand in Table 1 and are based on the per PKT estimates of a total inventory of 820 million parking spaces in the US including for-pay parking spaces, commercial spaces, and on-street parking from Chester et al. (2010). The impacts of decreased fuel production are a result of the percent fuel efficiency improvement in Table 1 and are based on per PKT estimates for a 2005 Toyota Camry in Chester and Horvath (2009). The energy and GHG emissions impacts from increased rail transit use are based on an average of San Francisco Muni operations in the Bay Area and Green Line operations in Boston (since carsharing members living in the city core are more likely to use light rail over heavy commuter rail). Those for bus transit use are based on operations of a typical 40 ft diesel bus (with combined fuel economy of 4.3 mpg) during peak congestion hours as reported in Chester and Horvath (2009). Lastly, the impacts of increased use of walk and bike (assumed non-electric) modes are from per PKT estimates in Dave (2010).

Table 3. Energy and GHG Emissions per Equivalent Private Vehicle PKT

	Energy (MJ)					**GHG (g CO_2 equiv)**				
	Per PKT	**Before**	**After-Low**	**After-Med**	**After-High**	**Per PKT**	**Before**	**After-Low**	**After-Med**	**After-High**
Vehicle Operation	2.1	2.1	1.53	1.06	0.35	144.15	144.15	105.23	72.61	23.96
Vehicle Manufact. & Maintenance	0.37	0.37	0.04	2.74E-03	1.19E-04	29.76	29.76	3.31	0.22	0.01
Parking Infrastructure	0.5	0.5	0.37	0.23	0.11	46.6	46.6	34.48	21.38	10.69
Fuel Production	0.24	0.24	0.20	0.15	0.09	24.18	24.18	20.07	15.25	8.62
Increased Rail Transit Use	1.61	0	0.00	0.07	0.33	122.33	0	0.00	5.65	25.44
Increased Bus Transit Use	0.67	0	0.00	0.02	0.08	51.56	0	0.00	1.43	6.08
Increased Bike Mode Use	0.2	0	0.00	0.00	0.00	20.63	0	0.16	0.21	0.33
Increased Walk Mode Use	0.06	0	0.00	0.01	0.01	20.63	0	0.39	3.68	4.84
Totals		*3.21*	*2.15*	*1.55*	*0.98*		*244.69*	*163.64*	*120.44*	*79.96*
Total % Reduction			*33.2%*	*51.8%*	*69.5%*			*33.1%*	*50.8%*	*67.3%*

As seen in Table 3, for a traveler who drives relatively few miles each year and lives in a denser urban neighborhood with good access to transit and non-motorized modes, joining a carsharing organization can reduce his/her energy use and GHG emissions 33 to 70%. In the most likely scenario, both inventories are reduced about 51% after a candidate traveler joins a carsharing organization. It is apparent that the energy use and GHG reductions are dominated by changes in vehicle operations, which is a result of reduced trips and travel distances in an automobile. In other words, the most important contributor to carsharing's lowered impacts is avoided travel and travel shifted to non-auto modes. While carsharing can increase the service of underutilized vehicles (with more vehicles replaced due to miles driven, rather than age-related factors - like rust or outdated design), the primary driver behind environmental benefits seem to arise out of a traveler's need to plan for travel and awareness of the cost of automobile travel, since most carsharing services require reservations and operate on a pay-by-the-minute basis.

Following vehicle operations, the biggest energy and GHG emissions reductions can be seen in parking infrastructure demand, followed by fuel use decreases, which come from reduced auto ownership, shifted modes, and vehicle technology improvements. Even if one considers only impacts to public parking infrastructure, carsharing's life-cycle energy and emissions savings are substantial. Despite the literature's emphasis on vehicle ownership reduction and vehicle replacement ratios, vehicle manufacture and maintenance have a relatively small impact on total energy use and GHG emissions per equivalent private vehicle PKT.

The biggest inventory changes from trips shifting to non-automobile modes emerge from transit use changes, particularly to the rail mode. In the most likely (medium-impact) scenario, the estimated increase in energy and GHG emissions from increased use of all other modes (rail, bus, bike, and walk) is less than savings from lowered parking demands. However, transit impacts are quite sensitive to occupancy assumptions. As noted earlier, environmental impact estimates from increased rail use are based on San Francisco's Muni (light-rail) and Boston's Green Line (light rail) operations, and bus use impacts are based on peak-hour diesel bus operations. When using the worst-case, low-occupancy assumptions (5 passengers per bus and 25% occupied seats on light rail) from Chester and Horvath (2009), the rise in energy use as a result of increased transit use is estimated to be 0.25 MJ per equivalent private-vehicle PKT and the rise in GHG emissions is estimated to be 20.6 gm CO_{2e} per equivalent private-vehicle PKT. In other words, when transit occupancies are assumed to be low, the corresponding increase in environmental impacts as a result of increased transit trips is comparable to the decrease in environmental impacts from reduced public parking needs, as a result of a candidate household joining a carsharing program, on an equivalent PKT basis.

Potential reductions in energy use and GHG emissions across all US households as a result of all candidate households joining carsharing organizations are in the range of 1 to 18 percent, based on Table 1's nationwide carsharing market potential numbers, with the most likely scenario showing an approximate net 5 percent reduction in energy use and GHG emissions in local household transportation if all candidate households join carsharing organizations (as compared to those households using private, non-shared vehicles). While this analysis assumes that 3.0 to 26.0 percent of US households could be candidate members for carsharing organizations, as of 2013, presently there are just about 800,000 carsharing members in the United States (Steinberg and Vlasic 2013), or less than half of one percent of the nation's 210 million licensed drivers, and their 246 million registered (non-commercial) vehicles (USDOT 2011).

It is important to note that while these calculations include direct rebound effects as a consequence of joining a carsharing organization, in the form of increased transit and nonmotorized trips, they do not account for indirect, economy-wide rebound effects of the avoided and shifted mode trips. From a household perspective, transportation expenditures savings will likely be used to purchase other products and services, which also require energy and have environmental impacts. Since indirect rebound effects are difficult to calculate (as a result of a whole host of second-order effects), estimated impacts from energy and GHG emissions indirect rebound vary widely. Experts estimate these effects to be as little as 5 to 15% (Thomas and Azevedo 2013, Druckman et al. 2011) to as much as 35 to 40% (Sorrell 2007). Thus, with indirect rebound effects considered, the likely total life-cycle inventory energy and GHG emissions savings from all U.S. candidate households joining carsharing organizations is arguably in the range of 3 to 5% of all local household transport-related energy use and emissions.

Of course, each component of travel behavior change, infrastructure demand change, and technology change impacts the total reduction differently, as seen in the tornado graphs shown below. In Figures 1 and 2, the baseline (y-axis) value represents the most likely energy use (1.55 MJ) and GHG emissions (120.44 g CO_{2e}) per equivalent private-vehicle PKT, assuming medium-level impacts (from Table 1) across all impact categories. The bars associated with each impact category show the range of energy use and GHG emissions associated with changing that impact from low to high, while all other impact categories remain at medium levels. These graphs illustrate the sensitivity of results to the estimates in each impact category. As seen in Figures 1 and 2, results are most sensitive to carsharing's assumed impacts on VKT, followed by assumed increases in rail transit use and decreased demand for public parking. It is interesting to note that, while the first two topics are well covered in past literature, the number of studies examining carsharing's parking infrastructure impacts is limited.

Figure 1. Impact of Inputs on Energy Use (MJ) per Equivalent Private Vehicle PKT

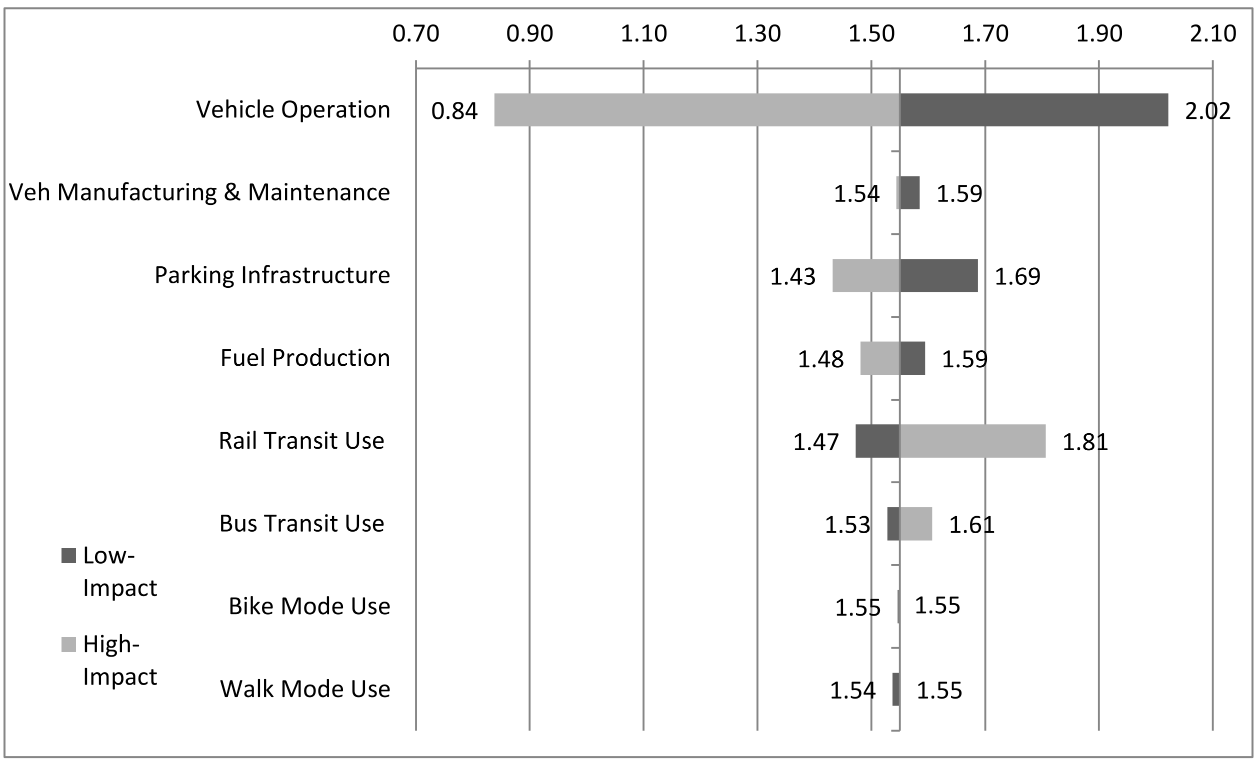
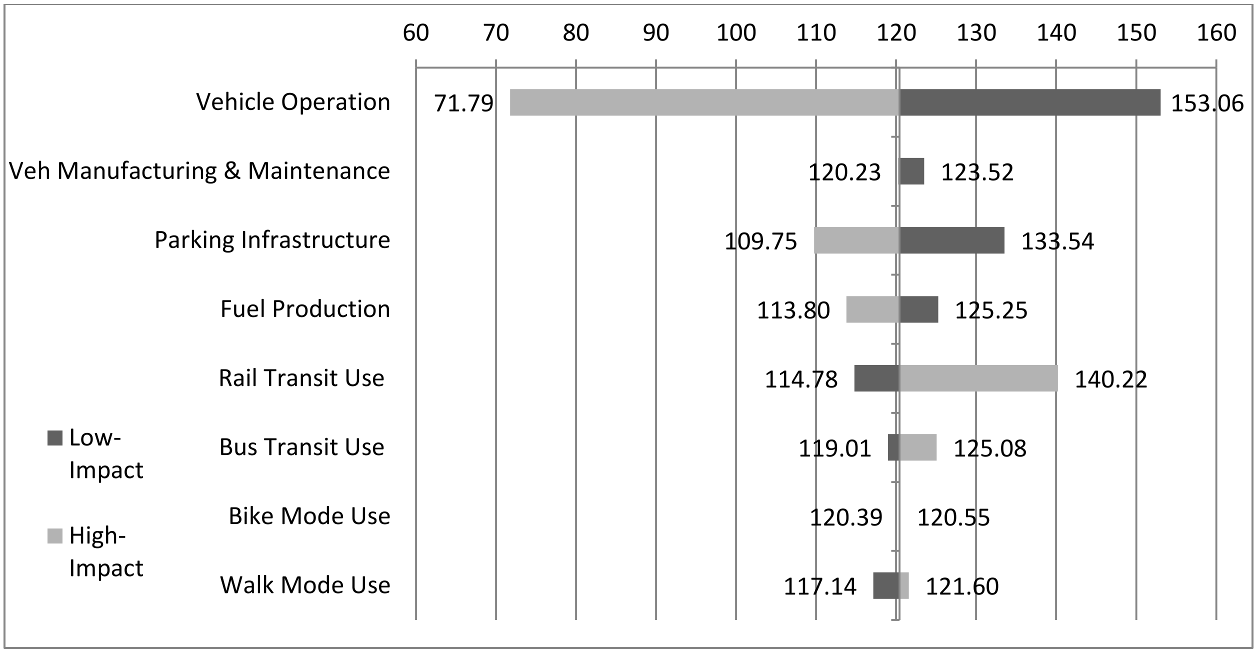


Figure 2. Impact of Inputs on GHG Emissions (g CO_2 equiv) per Equivalent Private Vehicle PKT



CONCLUSIONS AND EXTENSIONS

The benefits of carsharing have been touted in many previous studies, from reductions in vehicle ownership levels to increased transit use. However, few studies have examined the life-cycle impacts of carsharing (including upstream supply chains for vehicles and fuel), and they exclude infrastructure and/or shifted-mode components. Using estimates from a wealth of previous carsharing studies, this study quantifies the life-cycle reductions in energy and GHG emissions of carsharing as compared to an equivalent PKT in a private vehicle, combining the effects of reduced vehicle ownership, reduced vehicle distance traveled, fleet-level fuel efficiency improvements, reduced parking infrastructure demand, and trips shifted to no-auto modes. For a traveler that meets the criteria of a good candidate for carsharing, joining a carsharing organization is predicted to decrease his/her transportation energy use and GHG emissions by 51%, with the biggest reduction coming from decreased vehicle operations as a result of avoided VKT or mode shifts. A decrease in parking infrastructure demand also contributes to significant reductions in energy use and GHG emissions, as recognized through the LCA process employed here but neglected in studies that emphasize vehicle operations. Additional energy and GHG emissions as a result of carsharing members' increased use of transit and non-motorized modes are estimated to be insignificant when compared to the savings from avoided private-vehicle VKT, even under worst-case scenarios, with low transit occupancy rates. Across all US households, this translates to a total energy use and GHG emissions reduction of approximately 5% for local household transportation activities and as little as 3%, once rebound effects (from expenditure of saved funds on other consumer items) are considered.

It is important to note that a comprehensive LCA of the environmental impacts of carsharing generally relies on estimates from prior studies, so any biases or limitations in those prior studies carry forward to this analysis. These biases include the fact that some prior studies rely on stated (rather than revealed) preference data (see, e.g. Zhou and Kockelman 2011, Martin and Shaheen 2011b, Ryden and Morin 2005), in which respondents may over- or under-estimate actual behavioral shifts of carsharing membership. However, by relying on estimates averaged from a wide range of past studies and providing low-, medium-, and high-level scenarios, the aggregate energy and GHG emissions impacts estimated here have sought to minimize any biases of past, individual studies.

In averaging across studies that do not distinguish between station-based and free-floating carsharing services, this LCA does not differentiate the energy and GHG impacts of these two service types. Previous studies suggest that station-based carsharing services are mostly used for shorter trips, with shorter parking durations (Costain et al, 2012, Barth and Shaheen 2002), while free-floating carsharing services tend to be used for a wider variety of trip purposes and distances (Schmoller et al., 2014). In terms of mode substitution, free-floating carsharing services are generally found to be more substitutable for transit, walking, and cycling modes than are station-based systems (Ciari et al., 2014, Le Vine et al., 2014). Moreover, some potential impacts are not yet quantified here. For example, carsharing may impact roadway construction, lighting, and maintenance demands, and associated technologies are evolving. Improved catalytic converters and electrified shared fleets, possibly reliant on renewable feedstocks for their power, may improve carsharing's contributions to lowered energy demands and emissions. Finally, it should be noted that this study compares a shared fleet of conventional (internal combustion engine) sedans to the average U.S. passenger vehicle's use. With smaller, hybrid and electric vehicles growing in popularity, carsharing's energy and GHG emissions savings will probably grow.

REFERENCES

Barth, M. and S. Shaheen (2002) Shared-Use Vehicle Systems: Framework for Classifying Carsharing, Station Cars, and Combined Approaches. *Transportation Research Record* 1791, pp. 105-112.

Botsman, R. and Rogers, R. (2010) What's Mine is Yours: The Rise of Collaborative Consumption. HarperCollins Publishers, New York, 2010.

Briceno, T., Peters, G., Solli, C., and Hertwich, E. (2004). Using Life Cycle Approaches to Evaluate Sustainable Consumption Programs: Carsharing. Presented at the Norwegian University of Science and Technology Industrial Ecology Programme, Trondheim, Norway, 2004.

Brown, L.R. (2010). U.S. Car Fleet Shrank by .Four Million in 2009 – After a Century of Growth, U.S. Fleet Entering Era of Decline. *Plan B Updates*, Earth Policy Institute, January 6, 2010. http://www.earth-policy.org/plan_b_updates/2010/update87

Catalano, M., Lo Casto, B. and Migliore, M. (2008). Car sharing demand estimation and urban transport demand modelling using stated preference techniques, *European Transport*, 40, 33-50.

Celsor, C. and Millard-Ball, A. (2007) Where Does Car-Sharing Work? Using GIS to Assess Market Potential. *Transportation Research Record* 1992, pp. 61-69.

Cervero, R. Golub, A. and Nee, B. (2007) City CarShare: Longer-Term Travel Demand and Car Ownership Impacts. *Transportation Research Record* 2007, pp. 70-80.

Chester, M.V. and Horvath, A. (2009). Environmental Assessment of Passenger Transportation Should Include Infrastructure and Supply Chains. *Environmental Research Letters* 4, 024008.

Chester, M., Horvath, A., and Madanat, S. (2010) Parking Infrastructure: Energy, Emissions, and Automobile Life Cycle Accounting. *Environmental Research Letters* 5, 034001.

Ciari, F., Bock, B. and M. Balmer (2014) Modeling Station-Based and Free-Floating Carsharing Demand: Test Case for Berlin. *Transportation Research Record* 2416, pp. 37-47.

Cohen, M.J. (2012) The Future of Automobile Society: A Socio-Technical Transitions Perspective. *Technology Analysis & Strategic Management* 24(4), pp.377-390.

Cooper, G., Howes, D., and Mye. P. (2000) The Missing Link: An Evaluation of CarSharing Portland Inc. Oregon Department of Environmental Quality, Portland, Oregon.

Costain, C., C. Andron and K. Habib (2012) Synopsis of User's Behaviour of a Carsharing Program: A Case Study in Toronto. *Transportation Research Part A: Policy and Practice* 46(3), pp. 421-434.

Dave, S. (2010) Life Cycle Assessment of Transportation Options for Commuters. Working paper, Massachusetts Institute of Technology, February 2010. http://www.seeds4green.org/sites/default/files/Pietzo_LCAwhitepaper_0.pdf

Department for Transport (2004) *Making Car Sharing and Car Clubs Work: Final Report.* DfT, London, UK.

Doka, G. and Ziegler, S. (2001) Complete Life Cycle Assessment for Vehicle Models of the Mobility Carsharing Fleet Switzerland. Presented at The 1st Swiss Transport Research Conference, Ascona, Switzerland, 2001. http://www.strc.ch/conferences/2001/doka.pdf

Druckman, A., Chitnis, M., Sorrell, S. and Jackson, T. (2011) Missing Carbon Reductions? Exploring Rebound and Backfire Effects in UK Households. *Energy Policy* 39(2), pp. 3575-3581.

Duncan, M. (2011) The Cost Saving Potential of Carsharing in a US Context. *Transportation* 2011(38), pp. 363-382.

Econsult (2010) *The Economic and Environmental Impact of PhillyCarShare in the Philadelphia Region*. PhillyCarShare by Econsult Corporation, Philadelphia, PA.

Engel-Yan, J. and Passmore, D. (2013) Carsharing and Car Ownership at the Building Scale: Examining Potential for Flexible Parking Requirements. *Journal of the American Planning Association* 79(1), pp. 82-91.

Finkhorn, J. and M. Muller (2011). What Will be the Environmental Effects of New Free-Floating Carsharing Systems? The Case of car2go in Ulm. *Ecological Economics* 70(8), pp. 1519-1528.

Frost & Sullivan Research Service (2010) *Analysis of the Market for Carsharing in North America.* http://www.frost.com/prod/servlet/report-overview.pag?repid=N748-01-00-00-00

Hertwich, E.G. (2005). Consumption and the Rebound Effect: An Industrial Ecology Perspective. *Journal of Industrial Ecology* 9 (1-2), pp. 85-98.

Lane, C. (2005) PhillyCarShare: First-Year Social and Mobility Impacts of Carsharing in Philadelphia, Pennsylvania. *Transportation Research Record* 1927, pp. 158-166.

Le Vine, S., M. Lee-Gosselin, A. Sivakumar and J. Polak (2014). A New Approach to Predict the Market and Impacts of Round-Trip and Point-to-Point Carsharing Systems: Case Study of London. *Transport Research Part D: Transport and Environment* 32, pp. 218-229.

Litman, T. (2000) Evaluating Carsharing Benefits. *Transportation Research Record* 1702, pp. 31-35.

Martin, E., Shaheen, S.A., and Lidicker, J. (2010). Impact of Carsharing on Household Vehicle Holdings: Results from North American Shared-Use Vehicle Survey. *Transportation Research Record 2143*, pp. 150-158.

Martin, E.W. and Shaheen, S.A. (2011a). Greenhouse Gas Emission Impacts of Carsharing in North America. *IEEE Transactions on Intelligent Transportation Systems* 12(4), pp. 1074-1086.

Martin, E.W. and Shaheen, S.A. (2011b). The Impact of Carsharing on Household Vehicle Ownership. *Access* 38. http://www.uctc.net/access/38/access38_carsharing_ownership.pdf

Martin, E.W. and Shaheen, S.A. (2011c). The Impact of Carsharing on Public Transit and Non-Motorized Travel: An Exploration of North American Carsharing Survey Data. *Energies* 2011(4), pp. 2094-2114.

Meijkamp R. (1998) Changing Consumer Behaviour Through Eco-Efficient Services: An Empirical Study of Carsharing in the Netherlands *Business Strategy and the Environment* 7(4), pp. 234-244.

Millard-Ball, A., Murray, G., Schure, J., Fox, C. and Burkhardt J. (2005). *Carsharing: Where and How It Succeeds.* Transportation Research Board, Washington, DC.

Muheim, P. (1998). *Mobility at Your Convenience: Carsharing, the Key to Combined Mobility*. Berne, Switzerland: Energie 2000, Transport Section.

Mont, O. (2004). Institutinalisation of Sustainable Consumption Patterns Based on Shared Use. *Ecological Economics* 50, pp. 135-153.

Schmoller, S., Weikl, S., Muller, J. and Bogenberger, K. (2014) Empirical Data Analysis of Free-Floating Carsharing Systems, presented at the 93rd Annual Meeting of the Transportation Research Board. Washington, DC, January 2014.

Schuster, T., Byrne, J., Corbett, J., and Schreuder, Y. (2005). Assessing the potential extent of carsharing – A new method and its applications. *Transportation Research Record* 1927, pp. 174-181.

Seng, M. (2012) *Length of U.S. Vehicle Ownership Hits Record High*. Polk View Report, R.L. Polk, February 2012. https://www.polk.com/knowledge/polk_views/length_of_u.s._vehicle_ownership_hits_record_high

Shaheen, S. (2004). *Carlink II: A Commuter Carsharing Pilot Program Final Report.* Technical Report UCD-ITS-RR-40-30, Institute for Transportation Studies, University of California at Davis.

Shaheen, S. and Cohen, A. (2012) Carsharing and personal vehicle services: worldwide market developments and emerging trends. *International Journal of Sustainable Transportation* 7(1), pp. 5-34.

Shaheen, S. and Cohen, A. (2013) *Innovative Mobility Carsharing Outlook: Carsharing Market Overview, Analysis, and Trends – Summer 2013*. Transportation Sustainability Research Center, University of California, Berkeley. http://tsrc.berkeley.edu/sites/tsrc.berkeley.edu/files/Innovative%20Mobility%20Industry%20Outlook_Carsharing_Summer%202013%20FINAL.pdf

Shaheen, S., Cohen, A. and Roberts, J.D. (2006) Carsharing in North America: Market Growth, Current Developments, and Future Potential. *Transportation Research Record* 1986, pp. 116-124.

Sioui, L., Morency, C. and Trepanier, M. (2012). How carsharing affects the travel behavior of households: a case study of Montreal, Canada. *International Journal of Sustainable Transportation* 7(1), pp. 52-69.

Sorrell, S. (2007) The Rebound Effect: An Assessment of the Evidence for Economy-Wide Energy Savings From Improved Energy Efficiency. United Kingdom Energy Research Centre report, October 2007. http://aida.econ.yale.edu/~nordhaus/homepage/documents/UK_ReboundEffectReport.pdf

Sperling, D., Shaheen, S., Wagner, C. (2000) *Carsharing—Niche Market or New Pathway?* University of California, Berkeley, California. http://tsrc.berkeley.edu/node/452

Stasko, T.H., Buck, A.B., Gao, H.O. (2013) "Carsharing in a University Setting: Impacts on Vehicle Ownership, Parking Demand, and Mobility in Ithaca, NY." *Transport Policy* 30, pp. 262-268.

Steinberg, S. and Vlasic B. (2013) Car-Sharing Services Grow, and Expand Options. *New York Times*, January 25, 2013. http://www.nytimes.com/2013/01/26/business/car-sharing-services-grow-and-expand-options.html?ref=technology&_r=1&

Stillwater, T., Mokhtarian, P.L., Shaheen, S.A. (2009) Carsharing and the Built Environment: A GIS-Based Study of One U.S. Operator. *Transportation Research Record* 2110, pp.27-34.

Thomas, B.A. and Azevedo, I.L. (2013) Estimating Direct and Indirect Rebound Effects for U.S. Households with Input-Output Analysis. Part 2: Simulation. *Ecological Economics* 86, pp. 188-198.

USDOT (2009) The "Carbon Footprint" of Daily Travel. NHTS Brief, Federal Highway Administration, US Department of Transportation, March 2009. http://nhts.ornl.gov/briefs/Carbon%20Footprint%20of%20Travel.pdf

USDOT (2011) *Our Nation's Highways 2011*. US Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/policyinformation/pubs/hf/pl11028/onh2011.pdf

USEPA (1995) *Life-Cycle Impact Assessment: A Conceptual Framework, Key Issues, and Sumary of Existing Methods.* EPA-452/R-95-002, United States Environmental Protection Agency, Office of Air Quality Planning and Standards, July 1995.

Whitelegg, J., Britton, E.E. (1999). "Carsharing 2000 – A Hammer for Sustainable Development." *World Transport Policy and Practice* 5(3).

Zhou, B. and Kockelman, K.M. (2011) Opportunities for and Impacts of Carsharing: A Survey of the Austin, Texas Market. *International Journal of Sustainable Transportation* 5(3), pp. 135-152.

LIST OF TABLES

LIST OF FIGURES