UNDERSTANDING MODES OF CARSHARING: DIFFERENTIATIONS BETWEEN ONE-WAY AND TWO-WAY MEMBER ADOPTION AND UTILIZATION

by

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Abstract

In post-industrial economies, 40% of all GHG emissions are from transport services while three-quarters of the population live in urban centers. Provision of more efficient transportation services is a key to reducing GHG emissions, urban air pollution, and traffic congestion. Carsharing is often viewed as an environmentally efficient alternative to private car ownership. Many municipal governments have adopted this belief and support carsharing through various accommodations and subsidies. These policies often apply equally to all services that fall under the carsharing umbrella, including one-way, or free-floating carshare and two-way, or round-trip carshare. This thesis attempts to differentiate these two modes of travel with the goal of informing nuanced transportation policy. Results from a survey in Vancouver, Canada showed that one-way and two-way carsharing members have different motivations for carsharing and travel patterns. One-way members self-report that they carshare for convenience, using shared vehicles twice as frequently and private vehicles three times as frequently as two-way members. Two-way members choose carsharing for financial savings and a more efficient lifestyle. They tend to walk and bike more often than one-way members and the overall Vancouver population. Overall, two-way members are more likely to seek efficiency and frugality in their transportation habits and are superior planners. Analysis of trip data in Metro Vancouver leads to further differentiations. One-way vehicles are used for commuting, having highest utilization during morning and afternoon commute hours. A dominant spatiotemporal flow of one-way vehicle is observed, with vehicles leaving residential neighborhoods towards business-oriented neighborhoods during morning commute hours then reversing the trip during evening commute hours. A preliminary framework is introduced to determine whether a one-way trip is a replacement or first mile/last mile complement to other forms of transportation, in particular
transit. Two-way vehicles are most utilized on weekends and show no geographic biases in neighborhood idle times Metro Vancouver. Municipalities may consider these differences between one-way and two-way carsharing of relevance for policy construction.
Lay Summary

Carsharing is a service where members have access to a fleet of shared vehicles distributed across a city. Members can book a vehicle when needed, allowing for the convenience of vehicle ownership while reducing the need to own private vehicles. The two leading forms of carsharing are a free-floating or one-way model, where users can pick up and drop off vehicles anywhere inside a service area, and a round-trip or two-way model, where members pick up the vehicle at a specific location and later return it to that starting location. Despite these operational differences, municipal policies regulating one-way and two-way carsharing are often identical. This thesis analyzes one-way and two-way travel patterns and member motivations for carsharing, finding two-way carsharing members prioritize efficiency while one-way carsharing members prioritize convenience. One-way carsharing, unlike two-way, is used to commute to work. To meet goals of reducing greenhouse gas, vehicle kilometers traveled, and traffic congestion, municipal policies and subsidies should preferentially support two-way carsharing.
Preface

In both chapters my contributions include: a) identification of research questions, b) research design, c) performance of research activities, d) data analysis, and e) manuscript preparation.

Chapter 2: Distinct Motivations and Travel Patterns of One-Way and Two-Way Carsharing Members in Vancouver, Canada

- Survey was designed by Hadi Dowlatabadi and Jiaying Zhao, with funding and distribution help from Vancity.
- Data analysis was by Rainer Lempert with guidance from Jiaying Zhao.
- Data visualizations were by Rainer Lempert with guidance from Hadi Dowlatabadi.
- Write up was by Rainer Lempert with minor edits from Jiaying Zhao and Hadi Dowlatabadi and feedback from editors and reviewers at Transportation Research Part D.

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Chapter 3: Spatiotemporal Patterns of Carsharing Vehicle Usage

- One-way data scraped by Michiko Namazu. Two-way data provided by Modo.
- Data cleaning and analysis was done by Rainer Lempert with guidance from Hadi Dowlatabadi.
- Data visualizations were by Rainer Lempert with guidance from Hadi Dowlatabadi.
- Write up was by Rainer Lempert with minor edits from Hadi Dowlatabadi.
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1. Introduction

1.1 Carsharing and Environmental Sustainability

Carsharing (also known as “car clubs” in the UK) is defined as “a membership program intended to offer an alternative to car ownership under which persons or entities that become members are permitted to use vehicles from a fleet on an hourly basis.” (Millard-Ball et al., 2005). The first carsharing initiative was established in Switzerland in the late 1940s. However, it wasn’t until the late 1980s that carsharing popularity grew in Europe. In the late 1990s and early 2000s carsharing began to spread to North America and Asia (Shaheen et al., 1999). Throughout the 2000s carsharing membership grew rapidly, aided by advances in Information Communication Technologies (ICTs). Smartphones lowered transactional costs associated with carsharing, making the service more convenient and affordable (Namazu, 2017).

Carsharing was, for five decades, restricted to a “two-way” (a.k.a. round-trip) system where members pick up the car at a specific location and later return it to that starting location. Globally, two-way carsharing has over 10 million members. In the late 2000s, advances in ICTs led to a new model of carsharing, “one-way” (a.k.a. free-floating) where users can pick up and drop off vehicles anywhere within a service area. Over the short span of a decade one-way carsharing has garnered nearly 5 million members and is growing rapidly. Today Car2go is the most popular one-way carsharing service with over 2.5 million members globally, while Zipcar is the most popular two-way service with 750,000 members. Since 2007, carsharing in North America has grown at a rate of 23% per year, from over to 200,000 members to nearly 2 million members (Shaheen, 2017).
Historically, carsharing has not been used for commuting purposes. Instead it serves as a supplement to other modes of transportation. Because of this it best serves cities that have robust public transportation networks. Carsharing is most often used for moderate-length trips that require flexibility, such as making multiple stops or transporting goods (Bonsall et al., 2002). However, new research (Rooke, 2019, Wang et al., 2017 and Sprei et al., 2019) suggests that one-way carsharing may be increasingly used during commuting times, as either a replacement for transit or a first mile/last mile supplement to transit.

All modern carsharing services have several unique characteristics: 1) the user must be a member of the service organization, sometimes needing to pay a membership fee; 2) the user must make payments online via credit card; 3) self-service, meaning no interaction with another human in picking up or dropping off vehicle; 4) payment rates are done by minutes per hour. These first two features serve as barriers of entry for parts of the population who don’t have enough money to pay a deposit or don’t have a debit or credit card (Namazu, 2017).

These barriers to entry, while somewhat exclusionary, are less costly than barriers to car ownership. In order to own a car payment is required for purchase cost, insurance, fuel, and parking. The price of yearly car ownership in British Columbia is estimated by the Canadian Automobile Association to be around $10,000 a year. Carsharing empowers people to forgo this hefty expense while still enjoying the convenience and flexibility of private vehicle ownership.

Car ownership now poses a long list of challenges to municipalities (e.g., congestion, air pollution, greenhouse gas (GHG) emissions, urban sprawl and suppression of other modes of transport). In response, governments have been keen to support transport alternatives that can lead to lower vehicle ownership, greater use of public transit, biking and walking. Carsharing is viewed as a viable alternative as it reduces car ownership, private vehicle usage and GHG
emissions. Carsharing vehicles are generally efficient. The average vehicle in a carsharing fleet is 10 miles per gallon more efficient than the average vehicle sold by members after joining the carsharing organization. An analysis by Martin et al. (2010) determined that the average carsharing vehicle removes between nine and 13 privately held vehicles from the road. This removes cars from traffic patterns and, perhaps more importantly, decreases parking demand. Many studies have estimated that, on average, privately owned vehicles are parked at least 95% of the time. With fewer cars to account for cities can redesign spaces currently occupied by parking lots and garages to better serve street life and improve cities. Martin and Shaheen (2011) found that households participating in carsharing can be expected to reduce their carbon footprint by 0.84 t GHG/year and their vehicle kilometers traveled (VKT) by 27%. Namazu and Dowlatabadi (2015) estimated that households participating in two-way carsharing could reduce their annual GHG emissions by up to 54%, determining that carsharing can positively impact environmental outcomes due to five factors: transportation mode change, fleet vintage, vehicle optimization, more efficient drive trains per vehicle type, and trip aggregation.

There are several factors that could negate these environmental and social benefits. Carsharing makes driving accessible to some people who do not own a vehicle. If the increased number of trips by former non-car owners is greater than the decreased number of trips by former car owners, there could be an increase in net traffic congestion and emissions. Carsharing may also act as a stepping-stone towards car ownership, which would add to the numbers of cars on the road. People with access to carsharing may migrate away from local businesses, perhaps shopping at larger chains located in suburban strips. This could contribute to a form of suburbanization, where people live in areas of high population density but commute frequently outside of that zone, increasing congestion and emissions and negatively impacting street life.
One-way carshare vehicles also have the tendency to “cluster” around popular drop-off destinations, such as major employment, educational, or recreational centers. In extreme cases, carshare vehicles can occupy the majorities of entire streets for extended periods of time, blocking other vehicles, including local residents, from parking.

The growing prevalence of carsharing has prompted many cities’ planning, transportation, and sustainability departments to examine its emerging role and utility as a transportation demand management tool to decrease car ownership and its associated negative impacts (Filosa 2006; Millard-Ball et al., 2005). Well-crafted municipal carshare policy should both account for and aid in the proliferation of the service and its associated positive social and environmental effects while simultaneously limiting its potential negative effects.

1.2 Area of Study

The study area is the Vancouver Metropolitan region of British Columbia, Canada, population 2.5 million. The city of Vancouver is the most populous and dense municipality of the Metro Region with a population approaching 650,000. Vancouver has more carsharing vehicles per capita than any other in North America, with 47.5 vehicles per 10,000 people (Vancity, 2018). In comparison, as of 2016 Vancouver has approximately 5,500 private vehicles per 10,000 people (Metro Vancouver, 2016). The percentage of Vancouver residents over 18 with at least one carshare membership has grown steadily, from 13% in 2013 to 20% in 2014 to 26% in 2015 to 29% in 2016, the last year data was available (City of Vancouver Transportation Panel Survey).

However, carsharing is not evenly distributed across the entire population. People in different income brackets spend substantially different amounts on transportation. In 2016, the
lowest income quintile of the British Columbia population spent, on average, $3,753 on private transportation while the highest quintile spent $18,375 (Stat Canada, 2016). These figures include private vehicle purchases, insurance, maintenance, gasoline, and other miscellaneous fees associated with private car ownership.

Metro Vancouver is currently served by 4 different carshare operators providing two-way (Modo and Zipcar) and one-way (Car2go and Evo) carsharing options to their members. Data for Section 2 was collected from members of all four carshare operators, while data from Section 3 was collected from only Modo, via correspondence with their office, and Car2go and Evo, from their respective open APIs.

1.3 Need for Differentiation between Carsharing Modes

Despite both having the “carsharing” moniker, one-way and two-way services differ greatly operationally. These operational differences lead to differences in outcomes with respect to car ownership, VKT and GHG emissions. Namazu and Dowlatabadi (2018) show that households that primarily use two-way carsharing had fewer cars before they joined the program (0.7 cars/household) but reduced car ownership by a further 50%. However, one-way members started with 1.1 cars/household and after joining the carsharing program reduced their average car ownership by a mere 10%. In addition to this, the barrier to entry for two-way membership is usually much higher (e.g., a large one-time deposit to join the program). Clearly, one-way and two-way members belong to different types of households even before joining carsharing services.

Despite these differences, carsharing is often treated as a monolith by municipalities, where policies for one-way and two-way carsharing are often undifferentiated. For example, in
Vancouver both one-way and two-way car sharing organizations pay the same subsidized yearly fee to obtain on-street vehicle parking permits (City of Vancouver, 2017). New York City’s Carshare Pilot Program, which applies to both one-way and two-way services, aims to use carsharing to increase mobility options for lower income neighborhoods. Participating carshare organizations are required to have at least 20% of their designated on-street spaces located in low-income neighborhoods (NYC DOT, 2017). However, this is operationally more difficult to achieve and regulate with one-way organizations than two-way, since one-way vehicles do not need to park at designated locations.

Municipal governments need to understand the differences between one-way and two-way carsharing in order to leverage these features through policy initiatives towards achieving their transportation goals. This research aims to enable policy makers by providing further distinctions between these two modes. Towards that end, there are two primary goals in this thesis:

- Differentiate demographics, stated motivations for carsharing, and modal transportation patterns within one-way and two-way membership groups;
- Analyze differences in spatiotemporal utilization patterns for one-way and two-way carsharing trips, in particular reconciling these trips with public transit options.

This thesis has four sections. Section 2 contains the result of survey data analysis describing differences in motivations for carshare and travel modes between one-way and two-way user populations. Section 3 presents an analysis of one-way and two-way trip data, showing findings related to spatiotemporal trip patterns. Section five is a discussion and summary of findings, their implications, and recommendations for policy and future research.
The findings in this thesis provide further evidence of differences in member makeup and utilization patterns between one-way and two-way carsharing. These findings pertain most directly to the city of Vancouver and the surrounding Metro Vancouver. We hope that municipalities will consider the implications of this research when constructing or revising carsharing policy.
2. Distinct Motivations and Travel Patterns of One-Way and Two-Way Carsharing Members

Abstract

Carshare membership in North America has grown approximately 25% per year over the past decade. Some have attributed this to pro-environmental values and low-impact lifestyles of millennials, the primary users of carsharing. Many municipal governments have adopted this belief and support carsharing through various accommodations and subsidies. Results from a survey in Vancouver, Canada (which has the highest level of carsharing in North America) showed that one-way and two-way carsharing members have different motivations for carsharing and travel patterns. One-way members, primarily millennials, self-report that they carshare for convenience, using shared vehicles twice as frequently and private vehicles three times as frequently as two-way members. Two-way members choose carsharing for financial savings and a more efficient lifestyle. They tend to walk and bike more often than one-way members and the overall Vancouver population. These trip mode and frequency differences are consistent across age, gender, income, and geography. Perhaps as a consequence of the above, we also found that while one-way members are on average younger and wealthier, two-way members self-report as having more affordable lifestyles. These findings point to two-way carsharing members adhering to more efficient, sustainable lifestyles. Municipalities may consider these differences in motivations and trip patterns between one-way and two-way members of relevance in their carsharing policies.
2.1 Introduction

One-way and two-way carsharing differ in operational constraints, member profiles and outcomes with respect to car ownership, VKT and GHG emissions. Municipal governments should understand these differences in order to leverage these features through policy initiatives towards achieving their transportation goals. For example, Namazu and Dowlatabadi (2018) show that households that primarily use two-way carsharing had fewer cars before they joined the program (0.7 cars/household) but reduced car ownership by a further 50% -- i.e. most gave up their only vehicle. However, one-way members started with 1.1 cars/household and after joining the carsharing program reduced their average car ownership by a mere 10%. Thus, promotion of one-way and two-way carsharing would be targeting different types of households and achieving different levels of car ownership reduction. In addition to this, the barrier to entry for two-way membership is usually much higher (e.g., a large one-time deposit to join the program). Clearly, one-way and two-way members belong to different types of households even before joining carsharing services.

With the exception of Schaefers (2012) and Kashani & Trépanier (2018) much of the literature on carsharing has focused on service side logistics and optimization rather than user demographics and mobility needs. Our paper builds on their foundation and differentiates characteristics of one-way and two-way carsharing households and their trip frequencies and transportation mode choices.

To our knowledge, there are no studies detailing demographic characteristics of one-way and two-way carshare use in relation to other transportations modes. However, previous studies have examined effects of the introduction of ridehailing on other modes of transportation, with different analyses reaching different conclusions. Hall et al. (2018) found that the introduction of
Uber to metropolitan areas leads to an increase of public transit, with increasing effects over time. Sadowsky and Nelson (2017) found that after an initial spike, the introduction of ridehailing to a city leads to decreased transit use, a function of the convenience and cost-effectiveness of ride-hailing. Clewlow and Mishra (2017) surveyed users, asking ridehailing members if their travel patterns changed after joining Uber or Lyft. Among respondents who reported change in travel patterns, use of buses, light rail, and bicycle decreased while use of heavy rail and walking increased. We hope that our paper may provide some insight into the discrepancies between the results of these studies.

This paper was also informed by the rich literature of studies on demand for private car ownership. Dargay (2000) studied the influence of changing incomes on car ownership. He found that there is elasticity with respect to rising income but “stickiness” in response to falling income. Rising income levels allow people to own more cars but falling income levels are less likely to precipitate car shedding, as people become accustomed to their lifestyle and see their cars as necessities. Clark et al. (2016) developed a conceptual framework to determine changes in car ownership. They found that car ownership levels should not be considered as discrete decisions but as the culmination of life processes, influenced by various external stimuli and life events. Nolan (2008) also found that lifecycle events and household composition (such as number of children) are a significant determinant for car ownership. Oakil et al. (2016) determined that increasing urbanization and postponement of parenthood among young adults could reduce future car ownership. Shen et al. (2015) studied factors determining transportation mode choice in a large Chinese city. They found that income, job status, transportation subsidy, motivations related to comfort and safety, and shorter commuting distance all positively
correlated with car ownership and use, while population density and proximity to metro stations has a negligible association with carshare use.

With these considerations in mind, this paper explores differences in travel patterns and motivations for carsharing between one-way and two-way carshare members across multiple demographic dimensions. Toward this goal, there are three objectives:

- Characterize the demographics of one-way and two-way carsharing members;
- Characterize stated motivations for carsharing and modal transportation patterns within one-way and two-way membership groups;
- Determine the relationship between income and affordability and carsharing membership.

This paper is comprised of five sections. Section 2.2 describes the survey context, data, and methods. Section 2.3 uses multiple linear regressions and comparison of means across multiple demographics to describe differences in one-way and two-way user populations. Section 2.4 examines incongruities between income levels and perceived adequacy of incomes to sustain the lifestyles of one-way and two-way members. Section 2.5 is a discussion and summary of findings, their implications, and recommendations for policy and future research. The findings in the study pertain most directly to the city of Vancouver and the surrounding Metro Vancouver.

2.2 Survey Data

We conducted a survey focused on characterizing carshare usage and member motivations. The survey was distributed via an online platform to carsharing members in Metro Vancouver. Participants were recruited by their carsharing provider via monthly newsletter, in-app notification, and social media. A prize draw for carshare credits was given as an incentive by each provider. Survey responses were collected between October 5 and 22, 2017.
In total, 4010 participants completed the survey (54% females, mean age = 35.3 years). Three quarters of respondents reside in the city of Vancouver, while the rest are spread across neighboring municipalities. Of our respondents, 2996 belonged only to one-way carsharing, either Evo, Car2go, or both. 248 of the respondents belonged only to two-way carsharing, either Modo, Zipcar, or both. The remaining 766 respondents belonged to both one-way and two-way carsharing. This group were left out of the analysis because our data precluded differentiation of user motivations by service type.

These respondents are taken to be from a population of ~200,000 one-way carsharing members and ~20,000 members of 2-way carsharing (Modo has 18,000 members, but Zipcar membership data is not public). Our sample of one-way members may not be fully representative because of usage heterogeneity, which is a limitation with our analysis. We are confident in our sample of two-way members being representative (pers. comm. Modo).

Survey questions include information on population demographics, trip patterns by modes of travel, number of cars owned per household, one-way vs two-way membership, income, “subjective affordability index”, Likert-scale ranked attitudes towards car ownership and ride-sharing, and Likert-scale ranked motivations for carshare usage. Questions were strategically ordered to limit response bias due to order effects.

We received information on members geographic location but it was not factored into the analysis. At the time of the survey, approximately 95% of vehicles and utilization for one-way carsharing was located within the city of Vancouver. Two-way carsharing stations and membership extend to other municipalities, with approximately 1/3 of our responses coming from Victoria. However, travel patterns and motivations for two-way carshare members are not
significantly different in Victoria and Vancouver (see Table 8, Appendix B, for a description of two-way travel differences between Victoria and Vancouver residents).

In order to provide context for how one-way and two-way carshare users in Metro Vancouver compare to the broader population, demographic results of the survey have been compared to results from the 2016 Vancouver Metropolitan Area census (Figure 1). One-way and two-way users have similar gender breakdowns to each other and the overall population, with more females than males using both one-way and two-way services. The age breakdown of two-way members is also similar to the general population, skewing slightly younger but still maintaining a fairly even distribution of members across different decades. One-way users, however, skew much younger, with a plurality of surveyed users between 19-30 years old and only 10.6% of surveyed users 51 years or older. More than three quarters of one-way users are 40 years of age or younger, qualifying them as members of the millennial generation.

In the sections to follow, travel patterns and motivations will be analyzed for one-way and two-way users. While many of these analyses treat age as an explanatory variable, it is useful to remember the overall discrepancies in age and income (Figure 2) between one-way and two-way carshare users. One-way users tend to be younger and wealthier than two-way users. While the distinctions between the one-way and two-way members remain constant over different demographic groups, it is useful to note other demographic distinctions between these two groups. One-way users, in our sample, represent a subset of wealthy millennials from the overall Metro Vancouver population, while two-way users are more demographically similar to the overall population.
Figure 1. Age and gender breakdown of Vancouver population (2016 Canada Census), one-way CS users, and two-way CS users.
2.3 Results: Motivations and Travel Modes among One-Way and Two-Way Users

2.3.1 Motivations for CS use

Motivations for carsharing were assessed by four sections in the survey, each with multiple questions, probing various aspects and providing opportunities for gauging respondent consistency (reproduced in full in Appendix A). The first section asked about overall reasons for carsharing, the second contained questions about how carsharing fits into financial decision making, the third had questions related to how people used carsharing to travel, and the fourth asked about how carsharing impacts respondents’ state of mind. Respondents could select “Agree (5)”, “Mildly Agree (4)”, “Neutral (3)”, “Mildly Disagree (2)”, or “Disagree (1)” for each of the statements they were invited to evaluate. Figure 3 presents the mean ratings on each
motivation for one-way and two-way carshare members. Because data were not normally distributed, unpaired two-sample Wilcoxon test was performed on each motivational question to compare the means of both samples.

Figure 3. Spider diagrams of motivations for carsharing. Each spider diagram represents the mean response of one-way and two-way carsharing members to a) overall motivations, b) trip purpose, c) economic reasoning, and d) attitudinal motivations. In each case, the axis marked with a * displays a difference between the two carsharing categories at the 95% significance level. Highlighted questions signify that the Likert scale scores were significantly explained by demographic variables, including carshare membership type, in a regression model.

As shown in Figure 3, there were differences in motivations between one-way and two-way members for most categories. Two-way members were more motivated by financial and
environmental reasons (i.e., saving money and reducing their carbon footprint) than one-way members. They overwhelmingly agreed that carsharing allows them to reduce their dependence on vehicle ownership and were more motivated to use carsharing as a means to achieve greater life efficiency. On the other hand, one-way members were more motivated by the added convenience and safety of carsharing and didn’t necessarily see the service as a way to reduce their dependence on private vehicles. Instead, they viewed carsharing as a replacement for ridehailing services Uber or Lyft (which are absent in Vancouver), and are more likely to compare the cost of carsharing to using taxis. One-way members are far less likely to attribute carsharing as a means of traveling outside the city, implying that they use their personal vehicles for these longer trips.

It is possible that underlying variables helped determine these transportation pattern differences between one-way and two-way users. To check against this, a series of regressions was performed to assess the explanatory power of demographic features on modal transportation usage. These regressions add to the statistical rigor of this analysis and complement the unpaired two-sample Wilcoxon tests. The regressions follow the formula:

\[
motivation_{ij} = \left[ \beta \ast twoway_i + \sum_{k=1}^{n} \gamma_k \ast d_{ik} \right] j
\]

The dependent variable, \(motivation_{ij}\) is individual i and carsharing motivation j. The explanatory variables are \(twoway_i\), a dummy variable equal to 1 if the user is a two-way member and 0 if the user is a one-way member and \(d_{ik}\), demographic k for individual i. The demographics chosen include age, gender (represented as a dummy variable, with male = 0 and female = 1), number of drivers per household, number of road-worthy vehicles per household,
number of children per household, affordability index (for more information see Section 4) and household income.

Only four of the regressions performed had multiple $R^2$ values greater than 0.10 (Figure 1). The question “do you carshare because of no access to Uber of Lyft?” had a multiple $R^2$ value of 0.11. “Do you compare the cost of carshare to vehicle ownership?” had a multiple $R^2$ value of 0.17. “Does carshare help you live efficiently” had a multiple $R^2$ of 0.12. Finally, “does carshare help you travel outside the city” had a multiple $R^2$ of 0.15. In all cases carshare choice was a significant indicator, with p-values below 0.01. Carshare choice helped explain Likert scale score in the same direction as seen in the comparison of means analysis.

These four questions illustrate the differences between motivations for one-way and two-way carshare membership. One-way members see carsharing as a substitute for ridehailing services such as Uber or Lyft while two-way members view carsharing as a substitute for vehicle ownership. While both one-way and two-way members view carsharing as a means for convenience, only two-way members preferentially view it as a means for living more efficiently. Finally, two-way members view carsharing as a way to travel outside the city.

Table 1. Multivariable linear regression of demographic variables.

For “Carshare Type” dummy variable construction, one-way = 0 and two-way = 1. For “Gender” dummy variable construction, male = 0 and female = 1. * indicates p-value <0.05, ** indicates p-value <0.01.

<table>
<thead>
<tr>
<th>Carshare Motivation</th>
<th>Multiple-$R^2$</th>
<th>Carshare Type P-Value</th>
<th>Estimate</th>
<th>Age P-Value</th>
<th>Estimate</th>
<th>Income P-Value</th>
<th>Estimate</th>
<th>Gender P-Value</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saves money relative to owning a vehicle</td>
<td>0.17</td>
<td>&lt;0.01**</td>
<td>0.37</td>
<td>0.44</td>
<td>0.02</td>
<td>&lt;0.01**</td>
<td>-0.07</td>
<td>0.55</td>
<td>0.01</td>
</tr>
<tr>
<td>Easier to go to more places outside the city?</td>
<td>0.15</td>
<td>&lt;0.01**</td>
<td>0.85</td>
<td>&lt;0.01**</td>
<td>-0.11</td>
<td>&lt;0.01**</td>
<td>-0.16</td>
<td>0.19</td>
<td>-0.02</td>
</tr>
<tr>
<td>Easier to live efficiently?</td>
<td>0.12</td>
<td>0.02*</td>
<td>0.18</td>
<td>&lt;0.01**</td>
<td>-0.06</td>
<td>&lt;0.01**</td>
<td>-0.09</td>
<td>0.58</td>
<td>0.01</td>
</tr>
<tr>
<td>Replace Uber/Lyft Motivations</td>
<td>0.11</td>
<td>&lt;0.01**</td>
<td>-0.49</td>
<td>&lt;0.01**</td>
<td>-0.26</td>
<td>&lt;0.01**</td>
<td>0.06</td>
<td>0.56</td>
<td>-0.01</td>
</tr>
<tr>
<td>Motivation</td>
<td>Value1</td>
<td>Value2</td>
<td>Value3</td>
<td>Value4</td>
<td>Value5</td>
<td>Value6</td>
<td>Value7</td>
<td>Value8</td>
<td>Value9</td>
</tr>
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<td>--------</td>
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<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Easier to see friends/family?</td>
<td>0.08</td>
<td>&lt;0.01**</td>
<td>-0.25</td>
<td>&lt;0.01**</td>
<td>-0.18</td>
<td>0.07</td>
<td>-0.04</td>
<td>&lt;0.01**</td>
<td>0.06</td>
</tr>
<tr>
<td>Like not owning a vehicle</td>
<td>0.07</td>
<td>&lt;0.01**</td>
<td>0.34</td>
<td>0.11</td>
<td>0.03</td>
<td>0.70</td>
<td>-0.008</td>
<td>0.26</td>
<td>0.02</td>
</tr>
<tr>
<td>Easier to go to more places inside the city?</td>
<td>0.06</td>
<td>0.91</td>
<td>-0.009</td>
<td>&lt;0.01**</td>
<td>-0.11</td>
<td>&lt;0.01**</td>
<td>-0.15</td>
<td>0.32</td>
<td>0.02</td>
</tr>
<tr>
<td>Environmental Motivations</td>
<td>0.05</td>
<td>&lt;0.01**</td>
<td>0.28</td>
<td>&lt;0.01**</td>
<td>0.13</td>
<td>0.36</td>
<td>-0.02</td>
<td>&lt;0.01**</td>
<td>0.13</td>
</tr>
<tr>
<td>Compare cost to walking/biking</td>
<td>0.04</td>
<td>0.04*</td>
<td>-0.16</td>
<td>&lt;0.01**</td>
<td>-0.10</td>
<td>0.02*</td>
<td>-0.05</td>
<td>0.91</td>
<td>-0.002</td>
</tr>
<tr>
<td>Enjoy the freedom</td>
<td>0.04</td>
<td>0.93</td>
<td>0.007</td>
<td>&lt;0.01**</td>
<td>-0.06</td>
<td>&lt;0.01**</td>
<td>-0.09</td>
<td>&lt;0.01**</td>
<td>0.07</td>
</tr>
<tr>
<td>Knowing I have personal mobility when needed</td>
<td>0.04</td>
<td>0.04*</td>
<td>0.16</td>
<td>0.04*</td>
<td>-0.04</td>
<td>&lt;0.01**</td>
<td>-0.10</td>
<td>&lt;0.01**</td>
<td>0.05</td>
</tr>
<tr>
<td>Financial Motivations</td>
<td>0.03</td>
<td>&lt;0.01**</td>
<td>0.45</td>
<td>&lt;0.01**</td>
<td>0.07</td>
<td>0.89</td>
<td>0.003</td>
<td>0.06</td>
<td>-0.04</td>
</tr>
<tr>
<td>“In case you need it” Motivations</td>
<td>0.03</td>
<td>&lt;0.01**</td>
<td>-0.26</td>
<td>0.34</td>
<td>0.02</td>
<td>&lt;0.01**</td>
<td>-0.07</td>
<td>0.76</td>
<td>-0.006</td>
</tr>
<tr>
<td>Safety Motivations</td>
<td>0.03</td>
<td>&lt;0.01**</td>
<td>-0.31</td>
<td>0.01*</td>
<td>-0.06</td>
<td>&lt;0.01**</td>
<td>-0.10</td>
<td>&lt;0.01**</td>
<td>0.06</td>
</tr>
<tr>
<td>Saves money relative to taxi</td>
<td>0.03</td>
<td>&lt;0.01**</td>
<td>-0.57</td>
<td>0.99</td>
<td>-0.0003</td>
<td>0.31</td>
<td>0.02</td>
<td>0.03*</td>
<td>0.04</td>
</tr>
<tr>
<td>Convenience Motivations</td>
<td>0.02</td>
<td>&lt;0.01**</td>
<td>-0.47</td>
<td>0.18</td>
<td>-0.03</td>
<td>0.01*</td>
<td>0.05</td>
<td>0.04*</td>
<td>0.03</td>
</tr>
<tr>
<td>Compare cost to public transit</td>
<td>0.03</td>
<td>&lt;0.01**</td>
<td>-0.35</td>
<td>&lt;0.01**</td>
<td>-0.13</td>
<td>0.90</td>
<td>-0.003</td>
<td>0.29</td>
<td>0.02</td>
</tr>
<tr>
<td>Do not evaluate cost</td>
<td>0.02</td>
<td>0.30</td>
<td>-0.08</td>
<td>0.17</td>
<td>0.03</td>
<td>0.53</td>
<td>-0.01</td>
<td>0.05</td>
<td>-0.04</td>
</tr>
<tr>
<td>Not having to rely on others for a ride</td>
<td>0.03</td>
<td>0.95</td>
<td>0.004</td>
<td>0.06</td>
<td>-0.04</td>
<td>&lt;0.01**</td>
<td>-0.07</td>
<td>&lt;0.01**</td>
<td>0.06</td>
</tr>
<tr>
<td>Like having different options for getting around</td>
<td>0.006</td>
<td>0.09</td>
<td>-0.13</td>
<td>0.90</td>
<td>-0.003</td>
<td>0.62</td>
<td>0.01</td>
<td>&lt;0.01**</td>
<td>0.06</td>
</tr>
</tbody>
</table>

While these four models have the most notable multiple-R² values, results of other regressions support the Wilcoxon test results. One-way or two-way carshare membership is a significant explanatory variable within most regressions, and the direction of explanation is similar to the difference of means tests.

To further check against underlying variables causing the discrepancies in motivational responses for one-way and two-way members, results were filtered by demographic levels for age, gender, income, and affordability index. Response patterns remain consistent across levels.
(Table 9 and Table 10, Appendix B). While other demographics do impact answers to the survey questions, as seen in Table 1, the one-way and two-way distinction largely transcends survey measured demographics. This suggests two distinct populations with separate lifestyles and motivations for using carsharing.

2.3.2 Travel Modes

![Spider diagram of weekly transportation use.](image)

The average use of each mode by one-way and two-way carsharing members is plotted. Where the travel patterns differ at a statistically significant level, the label is marked. In each case, the axis marked with a * displays a difference between the two carsharing categories at the 95% significance level. *Private Car (Driver)* is highlighted because it was significantly explained by demographic variables, including carshare membership type, in a regression model.

The previous section showed differences in one-way and two-way members motivations for carsharing. This section aims to see if these motivations are reflected in members transportation choices and patterns. Figure 4 is a visualization of the average travel pattern for one-way and two-way carsharing members. The radial diagram displays the average number of
trips per week for each mode of transportation (from 0 to 12). Because data were not normally distributed, an unpaired two-sample Wilcoxon test was performed on each travel mode to compare the means of both samples. Due to the eight travel modes not being independent, Bonferroni correction was applied to counteract the problem of multiple comparisons. Mean differences in all modes with the exception of public transit and taxi service are considered significant with a p-value less than alpha/n (0.05/8 = 0.00625).

Two-way users tend to walk and bike more frequently than one-way users. On average they walk 1.8 and bike 1.2 more times per week. One-way users travel by private cars more than three times as frequently as two-way users, and they carshare more than twice as frequently. One-way users also averaged 2.27 more total trips per week than two-way users. However, without closely examining household demographic characteristics it is difficult to draw meaningful conclusions from that particular comparison.

It is possible that underlying variables helped determine these transportation pattern differences between one-way and two-way users. To check against this, a series of regressions was performed to assess the explanatory power of demographic features on modal transportation usage. These regressions are similar to the ones performed in the previous section and follow the formula:

\[
mode_{ij} = \beta \cdot twoway_i + \sum_k^{n} \gamma_k \cdot d_{ik}
\]

The dependent variable, \(mode_{ij}\) is individual i and mode use j. The explanatory variables are \(twoway_i\), a dummy variable equal to 1 if the user is a two-way member and 0 if the user is a one-way member, and \(d_{ik}\), demographic k for individual i. The demographics chosen include age, gender (represented as a dummy variable, with male = 0 and female = 1), number of drivers
per household, number of road-worthy vehicles per household, number of children per household, affordability index (for more information see Section 2.4) and household income.

This model was run for all eight modes of transportation. The multiple $R^2$ value was low, with a value less than 0.1, for travel modes other than driving a private vehicle (Table 2), which had a multiple $R^2$ value of 0.25. Due to the construction of the dummy variable for carshare membership, with 0 signifying a one-way membership and 1 signifying a two-way membership, this model shows that one-way membership significantly explains increasing numbers of trips per week in a private vehicle. Other regressions, while having less explanatory multiple-$R^2$ values, had similar results to the Wilcoxon tests. Carshare membership choice significantly explains trip use for walking, biking, carsharing, and operating a private vehicle. Two-way members are more likely to walk and bike, while one-way members are more likely to drive.

Table 2. Multivariable linear regression of transit modes.
Estimates predictive power on number of trips per week via private vehicle. For “Carshare Type” dummy variable construction, one-way = 0 and two-way = 1. For “Gender” dummy variable construction, male = 0 and female = 1. * indicates $p$-value < 0.05, ** indicates $p$-value < 0.01.

<table>
<thead>
<tr>
<th>Transportation Mode</th>
<th>Multiple - $R^2$</th>
<th>Carshare Type</th>
<th>Age</th>
<th>Income</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>0.06</td>
<td>0.03*</td>
<td>0.16</td>
<td>0.02*</td>
<td>0.05</td>
</tr>
<tr>
<td>Biking</td>
<td>0.03</td>
<td>&lt;0.01**</td>
<td>0.24</td>
<td>0.62</td>
<td>0.01</td>
</tr>
<tr>
<td>Transit</td>
<td>0.11</td>
<td>0.66</td>
<td>-0.03</td>
<td>&lt;0.01**</td>
<td>-0.16</td>
</tr>
<tr>
<td>Carpool</td>
<td>0.03</td>
<td>0.25</td>
<td>0.08</td>
<td>&lt;0.01**</td>
<td>-0.11</td>
</tr>
<tr>
<td>Taxi</td>
<td>0.02</td>
<td>0.11</td>
<td>-0.13</td>
<td>&lt;0.01**</td>
<td>-0.07</td>
</tr>
<tr>
<td>Carshare</td>
<td>0.06</td>
<td>&lt;0.01**</td>
<td>-0.40</td>
<td>&lt;0.01**</td>
<td>-0.13</td>
</tr>
<tr>
<td>Private Vehicle (Passenger)</td>
<td>0.06</td>
<td>&lt;0.01**</td>
<td>-0.26</td>
<td>0.15</td>
<td>0.03</td>
</tr>
</tbody>
</table>

22
To complement the regressions and test for the explanatory power of other demographics on trip patterns, further analysis was performed across other demographic levels. Members were separated by their gender, income, self-reported affordability index, and age. Trip patterns were determined for levels within these demographics. While transportation mode use varies across demographics, the same general difference in travel patterns between one-way and two-way members is present at almost every level. Table 7 (Appendix B) shows the difference in weekly trips per mode between one-way and two-way members across demographic levels. In particular, these results show that one-way members take significantly more trips in privately owned vehicles than two-way members, with consistently significant p-values across all demographics.

Differences in private vehicle trips per week can largely be explained by differences in vehicle ownership between one-way and two-way members. 70% of one-way members own at least one private vehicle, compared to only 30% of two-way members. However, even when comparing respondents who own at least one vehicle, one-way members still drive more frequently. One-way respondents who own a vehicle average 5.1 trips per week while two-way members who own a vehicle average 3.8 trips per week.

As a comparison to the overall population in Vancouver, Figure 5 shows travel mode percentage for one-way and two-way members, relative to a longitudinal panel survey of 2000 residents from the City of Vancouver (City of Vancouver, 2016). The figure shows that both one-way and two-way carsharing members preferentially use more sustainable modes of transportation, including walking, biking, and public transit, relative to the overall city population. One-way members, however, have a travel pattern that is closer to panel survey population than two-way members.
Figure 5. One-way vs. two-way vs. Vancouver travel modes.

A comparison of how modes of transportation vary across the overall Vancouverites and one-way and two-way carsharing members. Note that the Vancouver Panel Survey did not measure taxi, carpool, and carshare trips. Boxes with heavy borders represent trips taken via an automobile, either private (passenger or driver), taxi, carpool, or carshare.

This analysis shows that there are clear distinctions in travel patterns between one-way and two-way carshare members. Differences exist between demographic levels, but within all levels two-way members preferentially use less expensive and more sustainable travel modes, making fewer trips by private vehicle and carshare. These travel patterns correspond to the motivations for one-way and two-way carshare use analyzed in the previous section.
2.4 Affordability vs. Income for One-Way and Two-Way CS Users

2.4.1 Affordability Index

Studies of private demand for mobility often rely on income as a key independent variable. In this study, we are sensitive to the high cost of living in Vancouver possibly impacting income available for discretionary expenses and impacting demand for carsharing in lieu of car ownership. Therefore, income may not reflect the perceived affordability in our sample. To account for this discrepancy, we constructed the survey to gauge, in addition to income level, respondent’s subjective perception of their lifestyle affordability.

Many household differences, such as the number of dependents, outstanding debts and patterns of discretionary spending can easily render a person with a higher income feeling their lifestyle to be less affordable. Those households which can modify their lifestyles to fit their incomes can be expected to find even the Vancouver region more affordable.

Before asking respondents to select their income bracket, we asked them “With respect to the cost of living in our region, would you say that: (a) I/my household find living here unaffordable or close to unaffordable; (b) I/my household meet our needs but cannot save for the future; (c) I/my household can comfortably meet our present and future needs; or (d) Prefer not to answer. For analysis in an ordinal logistic regression model, respondents who selected (a) were assigned a value of 0, respondents who selected (b) were assigned a value of 1, and respondents who selected (c) were assigned a value of 2 (respondents who answered (d) were filtered out of the analysis). These scores constitute what we refer to as an “affordability index.” We note that the three levels are ordinal rather than interval or ratio. While it is a common practice in psychology to treat ordinal data on a gradient as interval ratio data (see de Winter &
Dodou, 2010), we have used non-parametric analyses (e.g., ordinal logistic regressions) on the affordability index in this section.

To examine the relationship between affordability index and income, ordinal logistic regression was performed. The three levels of the affordability index were predicted by income. After scaling the incomes into standard deviations, the coefficient value was 0.56 with a standard error of 0.04 and a p-value of <0.001. This implies that as income increases by a full standard deviation the odds of observing a higher-ordered affordability response increase by 56%

Although wealthier respondents tended to find Vancouver and its surrounding municipalities more affordable, there were some inconsistencies between the subjective construct of affordability and income levels. For example, approximately 15% of the respondents who found their lives to be “unaffordable or close to unaffordable” lived in households making over $100,000, while approximately 10% of respondents who claimed to be able to meet their “present and future needs” lived in households with a combined income of less than $50,000.

We believe the nexus of affordability and income may provide new insights for understanding carsharing motivations (e.g., whether people carshare out of necessity or convenience). In this section, we examine differences in income and affordability levels for one-way and two-way carshare members across different demographic groups. We hope to introduce further subtleties towards our understanding of one-way and two-way members and provide an example of the explanatory power of this new index.

2.4.2 Discrepancies between Affordability and Income

Because the affordability index and income level were measured by different scales (affordability was measured as an ordinal value, and income brackets ranged from less than $25,000 to greater than $150,000), in order to meaningfully compare the two parameters, the
percent difference of each between one-way and two-users was calculated. For income, percent difference was calculated as the difference in the average income between one-way and two-way users (two-way minus one-way) divided by the mean income of both groups. Since affordability index is an ordinal value, a different approach was taken to calculate the percent difference.

Respondents who selected either (b) and (c), living either fully or partly affordable lives, were combined into the “affordable group”, while respondents who selected (a) were the “unaffordable group”. The percentage of “affordable” participants in one-way and two-way members was computed and their difference was calculated (two-way minus one-way) as the percent difference. For both income and affordability, positive values indicate a higher score for two-way members compared to one-way members. As Figure 6 shows, overall two-way members had 7.3% lower income than one-way members, but there were 1.8% more two-way members in the affordable group.
Figure 6. Percent difference in affordability and income.
Percent differences in the average affordability index (in blue) and average income (in red) between two-way and one-way carsharing members and broken down by age. Positive values reflect high affordability and income differences for two-way members. One-way members, on average, have higher incomes by 7.3%, while two-way members report having a more affordable lifestyle by a margin of 1.8%.

Initially, we thought that age might explain differences in one-way and two-way affordability and income, given the differences in demographic makeup of the two populations (Figure 1). However, this does not appear to be the case. One-way members are wealthier across all age levels. While two-way members do not report more affordable lives than one-way members across all ages, differences in affordability between two-way and one-way members are lower than differences in income for all age groups.

To further understand this discrepancy, we examined affordability, car ownership, and membership size within each income bracket (Table 3). Two-way members had a higher
percentage of respondents in the “affordable group” than one-way members for all income brackets except $100,000 - $149,999.

Table 3. Percentage in “affordable group”, mean cars per household, and sample size by income brackets.

<table>
<thead>
<tr>
<th>Income bracket</th>
<th>Percentage in “affordable group”</th>
<th>Mean cars per household</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>one-way</td>
<td>two-way</td>
<td></td>
</tr>
<tr>
<td>&lt; $25,000</td>
<td>59%</td>
<td>69%</td>
<td>263</td>
</tr>
<tr>
<td>$25,000 – $49,999</td>
<td>72%</td>
<td>75%</td>
<td>480</td>
</tr>
<tr>
<td>$50,000 – $74,999</td>
<td>77%</td>
<td>80%</td>
<td>504</td>
</tr>
<tr>
<td>$75,000 – $99,999</td>
<td>82%</td>
<td>87%</td>
<td>401</td>
</tr>
<tr>
<td>$100,000 – $149,999</td>
<td>88%</td>
<td>84%</td>
<td>422</td>
</tr>
<tr>
<td>&gt; $150,000</td>
<td>90%</td>
<td>95%</td>
<td>283</td>
</tr>
</tbody>
</table>

To gauge the significance of these relationships, we conducted another ordinal logistic regression. The three ordered levels of the affordability index were predicted by income and type of carsharing. As before, income had a coefficient value of 0.56 with a standard error of 0.04 and a p-value of <0.001. Type of carsharing was also significant, with a coefficient value of 0.09 (by dummy variable, one-way was coded as 0 and two-way as 1) with a standard error of 0.04 and a p-value of <0.01. This suggests that wealthier participants reported higher affordability than poorer participants, and two-way carsharing members reported higher affordability than one-way members.

We also conducted a two-way ANOVA test to (income brackets: 6 levels x carsharing type: 2 levels one-way vs two-way) on the number of cars owned per household. We found that there was a main effect of income [F(5)=39.68, p<.001], a main effect of carsharing type
[F(1)=73.35, p<.001], but no interaction [F(5,1)=1.07, p=.37]. This suggests that wealthier participants owned more cars than poorer participants, one-way carsharing members owned more cars than two-way members, but the difference between one-way and two-way members remained the same across income brackets.

We note that the proportion of two-way members was higher in the $25,000–$49,999 bracket (N=56, 30%) than in the other brackets. This suggests an income threshold to join two-way carsharing memberships (i.e., paying the $500 membership fee), where below $25,000 people may find the membership fee to be a barrier.

We also examined mean income, car ownership, and membership distribution within each affordability level (Table 4).

Table 4. Mean income, mean cars per household, and sample size by affordability index.

<table>
<thead>
<tr>
<th>Affordability index</th>
<th>Mean income</th>
<th>Mean cars per household</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>one-way</td>
<td>two-way</td>
<td>one-way</td>
</tr>
<tr>
<td></td>
<td>(N=2353)</td>
<td>(N=189)</td>
<td>(N=2353)</td>
</tr>
<tr>
<td>0 = I/my household find living here unaffordable, or close to unaffordable.</td>
<td>$62,644</td>
<td>$59,722</td>
<td>1.00</td>
</tr>
<tr>
<td>1 = I/my household meet our needs but cannot save for the future.</td>
<td>$74,047</td>
<td>$63,500</td>
<td>0.95</td>
</tr>
<tr>
<td>2 = I/my household can comfortably meet our present and future needs.</td>
<td>$114,023</td>
<td>$102,857</td>
<td>1.16</td>
</tr>
</tbody>
</table>

As before, we conducted a two-way ANOVA (affordability index: 3 levels x carsharing type: 2 levels one-way vs. two-way) on income and also on cars per household. For income, we
found that there was a main effect of affordability \[F(2)=239.77, p<.001\], a main effect of carsharing type \[F(1)=8.11, p<.01\], but no interaction \[F(2,1)=0.39, p=.68\]. This suggests that participants who reported higher affordability had higher incomes, one-way carsharing members had higher incomes than two-way members, but the difference between one-way and two-way members remained the same across affordability levels. For the number of cars owned per household, we found that there was a main effect of affordability \[F(2)=7.94, p<.001\], a main effect of carsharing type \[F(1)=81.29, p<.001\], but no interaction \[F(2,1)=1.04, p=.35\]. This suggests that participants who reported higher affordability owned more cars than participants with low affordability, one-way carsharing members owned more cars than two-way members, but the difference between one-way and two-way members remained the same across affordability levels.

One possible explanation for the discrepancies in affordability and income between carshare populations is that two-way members own fewer cars than one-way members. On average, one-way members own 1 car per household, whereas two-way members own less than 0.4 cars per household. The total annual cost to own and maintain a car in British Columbia is estimated to be $9,000 (Canadian Auto Association). Such a financial obligation can be a significant strain on finances and impact reported affordability of lifestyle. Owning multiple cars can compound this. As an example, the respondents in the second highest income bracket ($100,000 - $149,999) who claimed to find their lives “unaffordable or close to unaffordable” \(n=73\) averaged 1.13 cars per household, compared to 0.84 cars per household for respondents who could “comfortably meet our present and future needs” \(n=230\) in the same income bracket.

Finally, we make one more observation on the income differences between the three affordability levels. In Table 3, the income difference between affordability level of 0 and 1 is
around $11,000, but the income difference between affordability level of 1 and 2 is around $40,000. Moreover, one-way members in the lowest affordability group (who view life as “unaffordable or close to unaffordable”) make ~$3,000 more per year than two-way members in the same affordability group. Members in the middle and upper affordability groups make ~$11,000 more per year than two-way members.

2.5 Summary and Discussion

In this chapter we aimed to understand motivations for carsharing. Our findings highlight key differences between one-way and two-way carsharing members in their motivations for carsharing, private vehicle ownerships, and modes and frequency of travel. We found that two-way carsharing members view carsharing as a way to live efficiently, save money, be environmentally friendly, and reduce their dependence on car ownership. Two-way members also make more use of walking and biking. In contrast, one-way members are more concerned with added convenience and are likely to see carsharing as a viable replacement for taxi or ride-hailing. They also take more than three times as many trips by private vehicle and twice as many trips by carshare vehicle as two-way members. These trip mode and frequency patterns are consistent across demographic variable levels.

The high membership cost of two-way carsharing has limited access to this option for the lowest income category in our respondent sample. However, where households have chosen to adopt two-way carsharing instead of car ownership, self-reported affordability of lifestyles is higher than those who have joined one-way carsharing. This group is also characterized by car ownership rates that are 2.5 times higher than two-way carsharing members, with 70% of one-way members owning at least one private vehicle compared to only 30% of two-way members.
One-way respondents who own at least one vehicle average 5.1 trips per week, while two-way members who own at least one vehicle average only 3.8 trips per week.

We initially thought there may be one of two primary motivations for carsharing: either a lifestyle choice or a financial imperative. What we found instead is that motivations varied by carsharing membership type. While promoters of one-way carsharing correctly identify it as a lifestyle choice of millennials, these younger, wealthier individuals tend to own more cars and feel greater pressure from their lifestyle on their financial wellbeing, compared to two-way carsharing members who are less wealthy but report greater ease of lifestyle affordability.

We note that the differences in carsharing motivations and travel patterns between one-way and two-way members were correlational, not causal. Although our results did not show a causal direction, there was nonetheless an association between carsharing type and motivations and travel patterns. This association has two interpretations. One is that people’s motivations and lifestyle preferences determine their carsharing choice. That is, people who are wealthier, own more private vehicles, and want convenience are more likely to choose one-way carsharing. People who care about financial savings and a more efficient sustainable lifestyle are more likely to choose two-way carsharing. The other interpretation is that the choice of carsharing reinforces motivations and lifestyle preferences. That is, one-way carsharing reinforces the idea of convenience, and two-way carsharing reinforces the idea of savings and a more efficient, sustainable lifestyle. We suspect that both causal relationships are partially responsible for the results detailed in this chapter. Further research should be done to determine the relative importance of each causal direction.
3. Spatiotemporal Patterns of Carsharing Vehicle Usage

Abstract

Previous research has shown differences in motivations for carsharing and travel patterns between one-way and two-way carshare members. Analysis of trip data in Metro Vancouver leads to further differentiations between the two modes of carsharing. One-way vehicles are used for commuting, having highest utilization during morning and afternoon commute hours and moving between residential areas and business-centric areas. A dominant spatiotemporal flow of one-way vehicle is observed, with vehicles leaving residential neighborhoods towards business-oriented neighborhoods during morning commute hours then reversing the trip during evening commute hours. Two-way vehicles are most utilized on weekends and show no geographic biases in Metro Vancouver. Municipalities may consider these differences between one-way and two-way carsharing of relevance for policy construction. This study also introduces a preliminary framework for future research distinguishing whether one-way trips are a replacement or a complement, through first mile/last mile solutions, to other travel modes, in particular public transit.

3.1 Introduction

Section 2 explained differentiations in user motivations and demographic makeups between one-way and two-way carsharing members. This paper extends our understanding of differentiations between these two carsharing modes by analyzing spatiotemporal utilization patterns. One-way data was collected from the open APIs of Evo and Car2go, while two-way data was collected via correspondence with the Modo office.
This paper builds off of several recent studies that have also analyzed carsharing trip data. Rooke (2019) performed a similar analysis as found in this paper, analyzing Car2go, Evo, and Modo data from Metro Vancouver. He found that one-way usage was at its highest during weekday commuting periods, peaking at approximately 8am and 5pm, while two-way usage does not exhibit those peaks. Sprei et al. (2019) analyzed one-way travel time and usage patterns from 12 cities in the United States and Europe. They found that one-way vehicles are generally used for shorter trips with a median booking time of 27 minutes. They also found that trip numbers are at their highest on the weekdays during commuting hours (8am-9am and 4pm-6pm) and during the afternoon (1pm-6pm) on the weekends. Wang et al. (2017) compared Car2go trips to similar trips taken by public transit, finding that Car2go trips were on average $4.77 more expensive and 31.6 minutes shorter than a similar trip by transit, offering a relatively cost-effective way to reduce travel time. However, Car2go was not being used disproportionately for trips where it offers greater than average time savings, indicating that one-way carsharing is being used as a replacement, rather than a complement, for public transit. Like Rooke (2019) and Sprei et al. (2019), they also found that peaks in one-way usage follow weekly commuting patterns.

This paper hopes to expand upon these analyses by reconciling hourly and weekly trip patterns with long-term patterns, introducing different, clear data visualizations, and offering new insight into the spatiotemporal flow of vehicles. In particular, there are four goals associated with this paper:

- Reconcile different periodicities in one-way and two-way usage time series;
- Define differences in weekly aggregate utilization between one-way and two-way vehicles;
● Characterize neighborhoods in Metro Vancouver by one-way carshare utilization patterns and other neighborhood demographics and characteristics, with the aim of more deeply understanding spatiotemporal flow of one-way vehicles;

● Introduce a framework for understanding the relationship between one-way trips and public transit, in particular whether or not a one-way trip is a first mile/last mile complement to transit;

This paper is comprised of five sections. Section 3.2 describes methodologies for data collection and processing and explores periodicities within carshare usage time series. Section 3.3 analyzes patterns in weekly utilization between one-way and two-way fleets and uses clustering analysis to reconcile differences in one-way utilization patterns between Metro Vancouver neighborhoods. Section 3.4 uses logistic regression to define neighborhoods and more deeply understand the spatiotemporal flow of one-way vehicles. Section 3.4 also introduces a preliminary framework to study whether one-way trips are a replacement or a complement to public transit. Section 3.5 presents a summary and discussion of the findings.

3.2 Data

3.2.1 One-Way Data

One-way carsharing data was obtained from the publicly available Car2go and Evo application programming interfaces (APIs). Available vehicle position data was collected every 5 minutes from APIs of Car2go and Evo. Car2go data was collected from 13/2/2017 to 31/1/2018 (when they closed their API to the public). Evo data begins at the same date and ends on 3/9/2018.
The APIs provided a real-time list of available vehicles in the Metro Vancouver area. Data on vehicles during use or out of commission were not collected. The archived data included: vehicle identification, latitude, longitude, time, and date. Every five minutes, a Python script scraped the data off each API onto a server hosted by Amazon Web Services. The resulting data set is a detailed list of parked locations for every vehicle in both fleets. Figures 7 and 8 shows exploratory data validation showing the number of total data points scraped per day and the number of individual vehicles observed per day.

Figure 7. Evo data validation.
The top graph shows data points scraped per day off the Evo API. Each data point corresponds to the instantaneous location of an individual vehicle. The full API was scraped at five-minute intervals. The bottom graph shows individual Evo vehicles observed per day.
Figure 8. Car2go data validation.
The top graph shows data points scraped per day off the Car2go API. Each data point corresponds to the instantaneous location of an individual vehicle. The full API was scraped at five-minute intervals. The bottom graph shows individual Car2go vehicles observed per day. The period of no data (date > 1/31/2018) corresponds to the time period when the Car2go API was discontinued but Evo data was still being collected.

Figures 7 and 8 reveal time periods of erroneous data feeds. In particular, Evo data on January 18, 2018, January 28, 2018, and multiple dates before June 18, 2017, likely as a result of updates to the Evo API. As a result, these data were filtered out of analyses. There also were an anomalously large number of Evo vehicles observed on May 9, 2018. This was a result of the API reporting 240 unknown hashes. These data were also filtered out of analysis. Car2go data is generally cleaner, although there still were time periods of limited data collection. These days were filtered out of analysis.

After collection, the raw Car2go and Evo data were further processed into more useful forms. The processing work rendered two datasets. The first contains a list of individual trips for
each vehicle in both fleets. Associated with this dataset are vehicle latitude, longitude, time, and date are for both trip departure and trip arrival. Each trip departure and arrival were matched to one of 89 neighborhoods in Metro Vancouver. The second dataset contains hourly information for every vehicle over the entire data collection time period. This information describes exactly which hours each vehicle was in use and which hours each vehicle was parked and not in use. This reconfiguring facilitates detailed temporal analysis. Figure 9 shows time series of Evo and Car2go daily usage\(^1\), in aggregate hours booked. Figure 10 is a heatmap showing the spatial spread of one-way trips in Metro Vancouver.

![Figure 9](image.png)

Figure 9. Hours booked per day for all Evo and Car2go vehicles. Evo on top, Car2go on bottom. Periods of low data collection were unfiltered and explain periods of outlying usage.

\(^1\) Usage refers to aggregate vehicle hours booked. Utilization, which will be the primary parameter of analysis in Section 3.3.1, refers to the percentage of time a vehicle is booked.
Figure 10. Heatmap of Evo and Car2go aggregate usage
Evo and Car2go appear to share similar aggregate usage levels. They both have a periodicity with similar frequency and amplitude. While there is limited data, there does not appear to be much seasonal variability in usage. Evo usage appeared to be increasing over the time period, while Car2go usage remained fairly static. Evo and Car2go have a similar spatial spread across Metro Vancouver, with areas of highest usage roughly aligning with areas of highest population density. Section 3.2.3 contains an exploration of different periodicities within the one-way usage data.

There are several limitations with the Evo and Car2go data. Intermediary stops along each trip are unknown, as the API does not provide location information while the vehicles are in use. For the purposes of models, we assume that trips do not have intermediary stops. The API also did not distinguish between times a vehicle was booked and other instances when a vehicle is unavailable, such as when it is being moved by the operator employee or under maintenance. To partially compensate for this, vehicle booking periods longer than 16 hours, which is two standard deviations away from the mean trip, are not included in analyses (see Figure 11).

However, it is impossible to account for all the instances of a vehicle fueling, maintenance, or repositioning. This limitation inflates one-way utilization percentages (see Section 3.3.1). Utilization percentages are also inflated by the frequency of scraping. There is a five-minute margin of error for the start and end times of each trip. Since it is equally likely that a trip starts or ends anywhere within this five-minute window, both margins of error follow a uniform distribution. On average, trips have a start time 2.5 minutes earlier and an end time 2.5 minutes later than expected. To compensate, five minutes have been removed from all trip times. A final limitation is the length of data collection, approximately eleven months for the Car2go data and
nineteen months for the Evo data. This hampers a full analysis of season trends in carsharing usage.

![Density plot of all Evo and Car2go trips by duration. Trips to the right of dashed vertical line, which are greater than two standard deviations away from the mean, are not included in the analysis.](image)

3.2.2 Two-Way Data

Two-way carsharing trip was provided by Modo. We were not able to obtain trip information from Zipcar, the other major carshare operator in Metro Vancouver. Modo provided a record of all trips booked between 9/28/2001 and 1/1/2019. Parameters in the dataset include booking start time and date, booking end time and date, distance traveled, vehicle identification, and latitude and longitude of starting and ending location (referred to as the vehicle hub). This data set was reconfigured to show hourly information for every fleet vehicle over the entire data collection time period, describing exactly when each vehicle was booked and when each vehicle was not in use. To protect business intelligence, scalebars and axes describing Modo data were not included.
in some figures and analyses. Figure 12 shows a time series of Modo daily usage, in hours booked per day. Modo requested that we not include the most recent two years of information (2018 and 2019) in the visualization, due to business intelligence concerns. However, the 2018 trip data are aggregated into the analysis in Section 3.3.1.

Modo installed vehicle telemetry capabilities in all of their vehicles in November 2018. These data show all locations of engine-on and engine-off events. There is less than one year of this data, so it was not appropriate for use in Section 3.3. Future work should incorporate this rich data set. Figure 13 shows the spatial spread of Modo trips based on telemetry data.
Figure 13. Heatmap of Modo aggregate usage in Metro Vancouver. Trips included cover November 2018-May 2019, period of telemetry activity.

Unlike the one-way data, Modo usage appears to follow both weekly and seasonal periods of usage, with highest carshare usage aligning with summer months. Usage has increased over time, and spatially mimics Metro Vancouver population density. These factors will all be analyzed and compared to one-way utilization in Section 3.

The Modo data, which was provided directly by Modo’s business intelligence department, was generally much cleaner than the scraped one-way data. However, there is a limitation with the Modo usage data. Other than distance traveled and time booked, the two-way booking data contain no information about potential destinations on a given trip. This limitation precludes analyses such as: mapping popular trip destinations given starting location. As mentioned previously, Modo’s recently installed telemetry capabilities can address these and other questions, and should be mined once a full, yearly period of information has been collected.
3.2.3 Long-Term Usage Patterns

Before delving into hourly and daily analysis of one-way and two-way vehicle usage and utilization, it is necessary to demonstrate the existence of consistent periodicities inherent in the data. Fast Fourier transformations were performed on both hourly and daily aggregated booking data for Modo, Evo, and Car2go. The ‘TSA’ (Time Series Analysis) R package was used to calculate the different frequencies spectral densities for different periodic components within each time series. Car2go and Evo time series consist of all trips scraped over their respective data collection time periods (see Section 3.2.1) while Modo time series consist of all trips since June 2011, when Car2go first started operating in Vancouver.

Table 5. Dominant periods associated with Evo, Car2go, and Modo utilization.
Evo and Car2go utilizations display daily and weekly patterns, while the longer Modo timeseries has also captured yearly patterns.

<table>
<thead>
<tr>
<th></th>
<th>Evo</th>
<th>Car2go</th>
<th>Modo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period (in days)</td>
<td>Spectral Density</td>
<td>Period (in days)</td>
<td>Spectral Density</td>
</tr>
<tr>
<td>0.997</td>
<td>23024363</td>
<td>1.000</td>
<td>33888632</td>
</tr>
<tr>
<td>7.111</td>
<td>521652</td>
<td>7.059</td>
<td>962919</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 5 shows the dominant periods associated with the usage time series. All three carsharing services have daily and weekly periodicities. The daily vs. weekly signals show the one-way carsharing services have relatively stronger daily patterns than weekly (weekend) signals compared to Modo. The ratio of daily to weekly signals are ~35:1 and 4:1 respectively. Furthermore, the Modo time series also demonstrates a yearly seasonality with a significant spectral density. A longer data collection period would be required to test the existence of yearly variation associated with one-way utilization.
Vehicle usage time series were then additively decomposed using the R 'forecast' package into trend, periodicities, and residual. Figure 14 shows the breakdown of one-way data. The daily and weekly periods appear to occur consistently. A few intervals of inconsistent Evo daily periodicity corresponding with intervals of erroneous data collection.

![Additive time series decomposition of Car2go and Evo vehicle usage. Data aggregated hourly.](image)

Figure 14. Additive time series decomposition of Car2go and Evo vehicle usage.

Figure 15 shows the breakdown of two-way usage data. Again, consistent daily and weekly periodicities are inherent in the data. In addition, a clear yearly seasonality is demonstrated, with usage higher during the summer months and lower during the winter months, except for a spike in hours booked during the winter holidays. Spikes in usage observed in the noise often correlate to holidays, where Modo usage peaks.
The existence of consistent daily and weekly periodicities lends credence to the analyses that aggregate vehicle usage and utilization data by time of day and day of week. No matter what time of year, these two periodicities exist and are the dominant explanation for fluctuations in vehicle use data. Even though two-way carsharing also displays a yearly seasonality, this periodicity is orders of magnitude less significant in explaining data variation than two-way daily or weekly periodicity (see Table 5).

3.3 Hourly and Daily Utilization Patterns

3.3.1 One-Way vs Two-Way: Complementary Utilization Patterns

Weekly carsharing trends over the data collection period can be observed by calculating fleet utilization for each hour of day and day of week. Utilization was calculated using a reconfigured trip usage dataset, which contains hourly information for every vehicle over the entire data collection time period. This information describes, per hour, the percentage of time each vehicle was in use and the percentage of time each vehicle sat idle. Hourly utilization is calculated by:

\[
utilization_{hd} = \frac{\sum_{v} B_{hdv}}{B_{hdv} + I_{hdv}}
\]

where \( h \) represents hour of day, \( d \) represents day of week, \( v \) represents a vehicle in the fleet, \( B \), represents time vehicle is booked, and \( I \) represents vehicle idle time. \( (B_{hdv} + I_{hdv}) \) always equals one hour.

Figure 16 shows utilization for one-way and two-way fleets over the one-way data collection period. Evo and Car2go utilization patterns were nearly identical (see Figure 24, Appendix C) so one-way data was aggregated. The findings in Section 3.2.3 of consistent,
Figure 16. Average carshare utilization by hour/day of week.

Figure shows one-way (right) and two-way (left) vehicles in Metro Vancouver over one-way data collection period (13/2/2017 to 3/9/2018). Two-Way (Modo) utilization values not included. Note that the one-way utilization values are likely inflated by periods of vehicle fueling, maintenance, or repositioning, which are not differentiated from regular booked hours in the API scraped data.
statistically rigorous daily and weekly periodicities suggest that these utilization patterns are temporally significant and will not vary much on monthly or yearly timescales. These results are also derived from a complete, or nearly complete, list of one-way and two-way trips over the data collection period. Since they account for the entire population, instead of a sample, they can be compared without the aid of statistical tools like t-tests or Monte Carlo simulations.

Note that the one-way utilization values are likely inflated by instances of vehicle fueling, maintenance, or repositioning, periods which show up as times of a booked vehicle in the API (see Section 3.2.1). These periods are likely to occur during evening and early-morning hours. Aggregate utilization is 19.5% for Evo vehicles and 22.0% for Car2go vehicles, which is higher than the expected value of approximately 15% one-way utilization (Bert et al., 2016). With the data at hand it is impossible to tell exactly how inflated utilization percentages are.

Between Monday and Friday, one-way and two-way fleets experience complementary utilization. One-way vehicles have highest utilization during the morning commute hours of 7am-9am and the afternoon commute hours of 4pm-7pm. Two-way vehicle utilization peaks in between and after commuting periods, with highest weekday utilization occurring between 10am-3pm and 7pm-9pm. During the weekend one-way and two-way vehicles follow similar relative patterns, with peaks in utilization between 12pm-6pm. However, two-way vehicles are booked a much higher percentage of time on the weekends, with an hourly high between 2pm-3pm on Saturday, compared to a lower one-way hourly high between 6pm-7pm on Saturday.

The respective peaks in one-way usage and troughs in two-way usage during commuting hours suggest that these two carshare modes are used for different purposes during the week. Namely, one-way vehicles appear to play a role in carshare members commuting habits, while two-way vehicles are not regularly used by commuters. This finding is to be expected for two-
way vehicles. The mechanics of two-way carsharing make it an unlikely choice for commuting as the vehicle would need to be booked for the entire day. It is perhaps slightly more surprising that one-way carsharing, a relatively expensive transit mode, is used for commuting with some regularity. However, the finding shown in Figure 16 is indicative but not proof that one-way trips correspond with commuting trips. Section 3.3.2 will provide more evidence of this correspondence through a geographic analysis of one-way vehicle placement.

3.3.2 Geographic Idle Time Clusters: Evidence for One-Way Commuting

While Section 3.3.1 analyzed carshare utilization, the parameter of study for the spatial testing is hours of aggregate fleet idle time. Due to the mechanics of one-way carsharing, it is difficult to assign one-way utilization, or even raw usage, to a single location. Idle time corresponds to the time in between trips when a vehicle is parked, and thus can always be attributed to a specific neighborhood. Idle time patterns convey similar, albeit inverted, information as utilization patterns. Pearson correlation between hourly idle time and utilization, aggregated across all neighborhoods in Metro Vancouver, showed strong anti-correlation, with an r-value of -0.99 and a p-value < 0.001 (see Figure 25, Appendix C).

In preparation for this analysis, each one-way trip departure and arrival was matched to a neighborhood in Metro Vancouver (see Figure 17 and Figure 18). Idle time was aggregated for one-way and two-way vehicles by hour and day of week, resulting in 168 (24 hours * 7 days) values for each neighborhood. Only neighborhoods that had trip and idle time information for each of these 168 periods were included in the analysis. This resulted in 42 neighborhoods being part of the analysis. For each neighborhood, hourly idle time values were converted to z-scores by subtracting the neighborhood mean and dividing by the neighborhood standard deviation.
This standardization allowed for direct comparison of trends in carshare idle time between neighborhoods with differing orders of magnitude vehicle quantity.

K-means clustering was performed on the neighborhood hourly idle time data. Two clear clusters were determined based on the values of within group sum of squares by number of clusters extracted, with the only clear inflection point in decrease sum of squares occurring between one and two clusters (Figure 26, Appendix C). Clustered neighborhoods are displayed on Figure 17. Clusters are plotted on the first two principal components, which together explain 61.5% of the variance for the 168 parameters. Neighborhoods colored by cluster are overlaid on a map of Metro Vancouver in Figure 18, while Figure 19 shows mean hourly idle time patterns for each cluster.

During the weekdays, neighborhoods in Cluster 1 display complementary idle time patterns with neighborhoods in Cluster 2. Vehicles sit parked in Cluster 1 neighborhoods during...
the workday, from 9am-4pm, and preferentially idle in Cluster 2 neighborhoods from 6pm-7am.

Vehicles transition to complementary cluster between 7am-9am (Cluster 2 → Cluster 1) and 4pm-6pm (Cluster 1 → Cluster 2). The timing of this pattern matches with hourly one-way utilization patterns (Figure 16), which reveals a spike in activity at the beginning (7am-9am)

Figure 18. Metro Vancouver neighborhoods colored by one-way idle time patterns. Only neighborhoods with complete hourly data are included.

Figure 19. Mean idle-time values for neighborhoods in Cluster 1 and Cluster 2.
and end (4pm-6pm) of each workday. The broad strokes pattern (schematized in Figure 20) for a one-way carshare vehicle consists of a trip at approximately 8am from a Cluster 2 neighborhood to a Cluster 1 neighborhood, idle time at the Cluster 1 neighborhood until approximately 5pm, when the vehicle returns to a Cluster 2 neighborhood, and then idle time until the next morning.

![Diagram of weekday movement for one-way carshare vehicles](image)

Figure 20. Schematic showing primary pattern of weekday movement for one-way carshare vehicles. Developed from results found in Figure 16 and Figure 19.

It is clear that one-way vehicle weekday utilization is linked to commuting patterns. What is less obvious is how exactly one-way vehicles are used. Are one-way vehicles primarily a replacement for public transit or private vehicle usage? Or are they a first mile/last mile complement to public transit? This distinction could be contingent on the makeup of Cluster 1 and Cluster 2 neighborhoods. A cursory inspection of Figure 18 reveals that neighborhoods in Cluster 2 are largely residential communities, while neighborhoods in Cluster 1 are more likely to be business districts. However, there are inconsistencies in this dichotomy, such as Oakridge, which has 91% of its land zoned for residential development, being a Cluster 1 neighborhood. An explanation for this could be that Oakridge contains a Skytrain station, and that its characteristic Cluster 1 idle times are a result of first mile/last mile commuting. These distinctions will be explored further in Section 3.4.
Due to the mechanics of two-way carsharing, stark geographic distinctions in utilization, or idle-times, were not anticipated. Two-way vehicles are always returned to their destination of origin, making large-scale spatiotemporal utilization patterns unlikely. Still, a parallel analysis was performed for two-way vehicles, with vehicle idle times aggregated hourly, divided by neighborhood, converted to z-scores, and clustered. The resulting analysis produced clusters with similar idle time patterns, confirming the hypothesis that two-way vehicles do not have significantly different utilization throughout Metro Vancouver.

3.4 Is One-Way Carsharing a Replacement or Complement to Transit?

The results in Section 3.3 point to a clear link between one-way carshare utilization and work commute. What is less obvious is how exactly one-way vehicles are used during commuting hours. Are one-way vehicles in Metro Vancouver used during commuting as replacements for other modes of transportation? Or are they being used as first mile and last mile complements to public transit? This is a complicated question that evades an easy answer. This subchapter will not attempt to provide a complete explanation. Instead, it will provide two preliminary analyses that will lay the groundwork for future research.

3.4.1 Neighborhood Cluster Logistic Regression

Logistic regressions were performed to better understand the composition of Cluster 1 and Cluster 2 neighborhoods and inform how one-way carsharing is used during commuting hours. Independent variables factored into the regression included neighborhood mean income, population per km², number of bus stops per km², number of metered parking spots per km², a dummy variable representing whether or not a neighborhood has a Skytrain station, and percentage of land zoned for residential development.
Table 6 shows the results of the logistic regressions. Negative estimates predict a greater likelihood of a Cluster 1 neighborhood, while positive estimates predict a greater likelihood of a Cluster 2 neighborhood. Due to inconsistencies in data acquisition, income per capita, population per area, and metered parking only use Vancouver data. Skytrain stations also only use Vancouver data, since Skytrains do not run in North Vancouver and Skytrain replacements, such as the Seabus, are not included in the analysis. Bus stops and residential zones use data from all of Metro Vancouver.

Table 6. Logistic regression of neighborhood characteristics on Cluster 1/Cluster 2 distinction.
Negative estimates predict a greater likelihood of a Cluster 1 neighborhood, while positive estimates predict a greater likelihood of a Cluster 2 neighborhood. It may be useful to refer to Figure 18 and Figure 20 when interpreting results.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Income per capita</th>
<th>Population per area</th>
<th>Bus Stops per area</th>
<th>Parking Meters per area</th>
<th>Skytrain Stations</th>
<th>Residential Zone %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate</td>
<td>9.53E-06</td>
<td>-6.98E-05</td>
<td>-0.0488</td>
<td>-0.003107</td>
<td>-0.6055</td>
<td>2.3705</td>
</tr>
<tr>
<td>Std. Error</td>
<td>2.93E-05</td>
<td>8.42E-05</td>
<td>0.03955</td>
<td>0.002324</td>
<td>0.3398</td>
<td>1.3223</td>
</tr>
<tr>
<td>P-value</td>
<td>0.745</td>
<td>0.4071</td>
<td>0.2173</td>
<td>0.18137</td>
<td>0.075</td>
<td>0.073</td>
</tr>
</tbody>
</table>

Of the parameters tested, the only two approaching significant explanatory power are the number of Skytrain Stations and the percentage of land zoned for residential development. Both parameters are significant at $\alpha = 0.1$, with p-values of 0.075 and 0.073, respectively. The number of Skytrain Stations correlates with a neighborhood having a Cluster 1 distinction, while a higher percentage of neighborhood land zoned for residences correlates with a neighborhood having a Cluster 2 distinction. This fits with the understanding developed in Section 3.3. One-way vehicles leave residential Cluster 2 neighborhoods towards less residential, more business-
oriented Cluster 1 neighborhoods during morning commute hours. This trip is reversed during evening commute hours. Cluster 1 neighborhoods having a higher likelihood of containing a Skytrain Station could be due to Skytrains being preferentially located near businesses or could suggest that a proportion of one-way commuters are using carshare vehicles as a first mile/last mile complement to public transit. These results add to the generalized understanding of the Figure 20 schematic, which is updated in Figure 21.

![Figure 21. Updated schematic showing primary pattern of weekday movement for one-way carshare vehicles. Cluster 2 neighborhoods are usually residential, while Cluster 1 neighborhoods are business-oriented and/or contain Skytrain station.](image)

All of the other variables tested exhibited relatively high p-values, suggesting limited explanatory power in regard to neighborhood cluster distinction. Neither neighborhood income per capita nor population density has any effect on relative one-way utilization patterns. However, these factors could, and likely do have an effect on raw one-way usage, in hours driven. This regression does not test for that, since the clusters were created from standardized z-scores, rather than raw hourly values.

3.4.2 Preliminary Testing for First mile/Last mile One-Way Trips

The results in the previous sections suggest a complex variety one-way trips occur during transit hours. Some trips appear to be multimodal complements to public transit, while others are
a replacement for different types of transport. Figure 22 suggests a simplified framework for differentiating one-way trips. This framework assumes that people will walk a maximum of 400-meters to get to a transit hub. With that in mind, one-way trips can be distinguished based on whether or not their origins and destinations are within 400-meters of a transit hub. This places one-way trips into one of the following four categories: (1) a first mile solution if its origin is greater than 400-meters from a Skytrain Station and its destination is less than 400-meters from a Skytrain Station, (2) a last mile solution if its origin is less than 400-meters from a Skytrain Station and its destination is greater than 400-meters from a transit station, (3) a substitute for public transit if both origin and destination are less than 400-meters from a Skytrain Station, and (4) a complement to public transit if both origin and destination are greater than 400-meters from a Skytrain Station.

Figure 22. Simplified framework for categorizing one-way carshare trips.
This framework is by no means ironclad. A person taking a category (1) trip, for example, might end her trip at the carshare destination without proceeding to take public transit. A category (3) trip is not necessarily a substitute for transit if the journey by transit necessitates multiple line changes. This framework also treats all transit hubs as the same, which is an incorrect assumption. A Skytrain station in a dense urban center is different in use and purpose than a station in a more residential community. Further subtlety of analysis, that includes these and other factors, is needed to categorize trips with certainty. However, this framework is valuable in that it provides a preliminary necessary condition for categorization.

Figure 23 is a recreation of the Figure 22 data using one-way carsharing data. During the weekdays, trip times were separated into morning trips (7am-10am), midday trips (10am-4pm), and evening trips (4pm-7pm). Weekday trips between 7pm and 7am were excluded from the analysis. Weekend trips were included separately. Bold lines at 400-meter marks indicate the four quadrants described in Figure 22.

Morning trips are more likely to be categorized first mile solutions, while evening trips are more likely to be categorized as last mile solutions. Based on the Figure 22 framework, more than a third of all weekday morning trips can be categorized as first mile solutions, with 15.5% of morning trips categorized as last mile solutions. Evening categorizations are inverted, with 28.7% of weekday evening trips fit into the last mile solution category, with only 12.2% of trips being first mile solutions. It is important to note that all of these figures are steep upper bounds, since Skytrain Stations are preferentially located in business-oriented neighborhoods. Many of the trips that are categorized as first mile/last mile are likely trips to businesses located around the station.
The inherent upper bound nature of these results is further evidence that this analysis is not sufficient to draw meaningful conclusions about first mile/last mile commuting patterns. As mentioned previously, this analysis is based off a simplified framework, which is useful for understanding high-level patterns but insufficient for rigorously determining percentage of first mile/last mile trips. In addition to this, only Skytrain Stations are incorporated when determining distances from trip origins and destinations. Terminals for other modes of public transit, such as buses and ferries, were not included. Still, the results in this section can be used as a jumping off point for more thorough, subtle examinations of first mile/last mile carshare usage in Metro Vancouver.
Figure 23. Distribution trips by distance of origin and destination from nearest Skytrain Station.
400x400 meter grid with percentage of trips overlaid on density plot. Bold lines at 400-meters marks break chart into the four quadrants described in Figure 22.
3.5 Summary and Discussion

In this chapter we aimed to differentiate one-way and two-way carsharing trip patterns. Figure 16 highlights that these two carsharing modes are utilized in different ways. One-way vehicles appear to play a role in carshare members commuting habits, while two-way vehicles are not regularly used by commuters. This veracity of this result is strengthened by fast Fourier transform analysis (Table 5), which confirms that the dominant periodicities inherent in carshare utilization are on an hourly and daily scale. These findings confirm the results of Rooke (2019), Wang et al. (2017) and Sprei et al. (2019) who found similar distinctions in weekly utilization patterns.

Results of geospatial clustering analysis and logistic regression provides further evidence that one-way vehicles are used for commuting. Neighborhoods exhibit one of two types of complementary idle time patterns (Figure 19) and are also characterized by number of Skytrain Stations and percentage of land zoned for residential development (Table 6). The dominant spatiotemporal flow of one-way vehicles shows vehicles leaving residential neighborhoods towards business-oriented neighborhoods during morning commute hours then reversing the trip during evening commute hours (Figure 21).

The analyses in Section 3.3.2 and Section 3.4.1 show that a link between one-way carsharing and commuting exists. What is unclear is the effect this link has on the holistic transportation ecosystem. The preliminary analysis of Section 3.4.2 introduces a framework (Figure 22) to help distinguish whether one-way trips are first mile/last mile complements to public transit or replacements for transit. This framework posits that trips that start within a 400-meter radius and end outside of a 400-meter radius of a transit hub are last mile solutions, and trips that start outside of a 400-meter radius and end inside a 400-meter radius of a transit hub are
first mile solutions. One-way trips were categorized according to the framework. Adhering to the Figure 22 framework, morning one-way trips are more likely to be first mile solutions, while evening one-way trips are more likely to be last mile solutions.

Unfortunately, the results of Section 3.4.2 (Figure 23) are insufficient to draw meaningful conclusions regarding the percentage of one-way first mile trips, last mile trips, and trips that are a substitute for public transport. Future research should work to distinguish between transit hubs, perhaps performing a clustering analysis similar to Section 3.3.2 to categorize hubs based on neighborhood demographics. This could partially distinguish whether people who originate or end trips close to a hub are linking their carsharing with public transit or if the transit station is incidentally close to their final destination. This second possibility is likely in business-centric neighborhoods, such as Downtown Vancouver. Since Section 3.4.2 focused on Skytrain stations, future research also should account for carsharing trips that are close to other types of transit hubs, such as major bus stops and sea bus terminals.

However, even making this distinction between transit hubs will not lead to a fully sufficient answer. Using the data gathered for this study, there is no way to assess with certainty the percentage of trips that are linked to public transit. While there are strategies to minimize the margin of error, the best solution would be to conduct a survey aimed at one-way users. Questions would be geared at how often they use carsharing for commuting and how often they use carsharing trips in conjunction with other modes of transportation.
4. Conclusion and Policy Recommendations

Our two studies aimed to differentiate one-way and two-way carsharing based on user motivations for carsharing, user transportation modes, and differences in one-way and two-way vehicle utilization patterns. The first study, in Section 2, found differences in membership motivations for carsharing and trip patterns. One-way members, primarily millennials, self-report that they carshare for convenience, using shared vehicles twice as frequently and private vehicles three times as frequently as two-way members. Two-way members choose carsharing for financial savings and a more efficient lifestyle. They tend to walk and bike more often than one-way members and the overall Vancouver population. The second study, in Section 3, found that one-way and two-way vehicles are utilized differently during the week. One-way vehicles have a peak of utilization during commuting times, while two-way vehicles have a daily trough of utilization during those times.

Section 2 showed strongly differentiated motivations by type of carsharing membership. Neglecting such differences can lead to perceptions of contradictory results such as those found in analysis of the impact of ridehailing on other modes of transit (Hall et al, 2018, Sadowsky and Helson, 2017, Clewlow and Mishra, 2017). We believe what appear to be contradictions is likely to be heterogeneity of motivations and preferences within the pool of ridehailing users – as found here among carsharing users. Future studies on the effects of shared transportation may want to examine discongruities within the user base, taking differing motivations and lifestyles into account. By better understanding these underlying populations, the findings can be better contextualized.

Our analysis identified at least two distinct populations of carshare users. Within these distinct populations, we suspect that the choice of carsharing reinforces lifestyle preferences.
However, we acknowledge that this study cannot sufficiently address this question. We believe long-term studies or randomized control trials are needed to assess whether a lifestyle built around the flexibility of one-way carsharing is harbinger of a greater tendency to rely on private car ownership in the future. The corollary would suggest two-way members grow accustomed to using public transit, active modes of travel and become more efficient at trip planning when needing a private vehicle. These traits help reduce future car ownership.

One-way and two-way carsharing are also utilized differently on a geospatial scale. One-way vehicles follow a spatiotemporal flow, with vehicles leaving residential neighborhoods towards business-oriented neighborhoods during morning commute hours then reversing the trip during evening commute hours. Municipalities should consider this when creating carshare policy. One-way vehicles can be expected to preferentially idle and cluster at different times in different neighborhoods, depending on whether or not a neighborhood is primarily residential or business-oriented. Two-way vehicles do not follow such a spatiotemporal flow and are utilized similarly regardless of these neighborhood characteristics.

It is likely that some percentage of carshare trips are first mile/last mile complements to public transit. Figure 5 shows that one-way members use public for a higher percentage of their trips than the overall Vancouver population, potentially a result of compatibility between carsharing and public transit. However, the results in Section 3.4.2 are inconclusive and cannot determine what proportion of one-way trips are complements for transit, and what proportion are substitutes for transit. It is hard to know if the differences in distances from Skytrain stations between morning commute and evening times, as shown in Figure 23, are indications of great degree of first mile/last mile trips or simply a corollary of Skytrain hubs being preferentially located in business-oriented neighborhoods. We recommend that future analysis differentiate
between types of transit hubs, those in residential areas and those in business-oriented neighborhoods. A future study could also benefit from a survey with questions geared at how often carsharing is used in conjunction with other modes of transportation.

A policy recommendation to continue to provide subsidies for one-way vehicles, largely through parking permits, are partially contingent on such an analysis. However, the results of both studies suggest that two-way carsharing is used as a sustainable travel mode by a sustainability-inclined subsegment of the population. While it is unclear if two-way carsharing is used as a first mile/last mile complement to public transit, relatively low utilization during morning and evening commute hours (Figure 16) indicate that two-way carsharing is not a substitute for transit during transit’s most effective periods.

Municipal governments’ ultimate goal is sustainable urban transportation. This requires far more than reducing congestion and GHG emissions. The advent of each new mode of transport, from ride-hailing to shared scooters, adds to the portfolio of travel modes and their impact on society and the environment. Many of these new mobility options are forms of one-way transportation that can be expected to compete with one-way carsharing. It is imperative for municipal governments to understand how the proliferation of one-way services will impact the transportation ecosystem. The results of this thesis paint a complicated, incomplete picture of this impact. It is unclear whether one-way services are leading to a more efficient, sustainable system or if their inherent convenience is leading to an increase in VKT (aka Jevons paradox). More research needs to be done to better understand the effects of one-way transportation. Until then, municipalities should be cautious in creating policies that support and encourage the proliferation of one-way modes of transportation. The impacts of two-way services are more clear and likely to contribute positively to sustainable transportation goals.
References


New York City Department of Transportation (2017), Carshare Permit Application.


Appendices

Appendix A: Reproduction of Questions Probing Motivations for Carshare Use

Q7: Please indicate your level of agreement (Agree, Mildly Agree, Neutral, Mildly Disagree, or Disagree) with the following reasons you might use carsharing.

- Q7_1: To reduce your carbon footprint and help the environment.
- Q7_2: To save money.
- Q7_3: For convenience.
- Q7_4: Your membership is ‘just in case’ you need it.
- Q7_5: Because we have no Uber/Lyft in town.
- Q7_6: Personal safety - safer than using public transit.

Q10: The statements below are all reasons you might use carsharing. Please rate your agreement or disagreement (Agree, Mildly Agree, Neutral, Mildly Disagree, or Disagree) for each.

- Q10_1: Carsharing saves me money because I don’t have to own a vehicle (or another vehicle).
- Q10_2: Carsharing saves me money because it’s cheaper than using a taxi.
- Q10_3: I look at the cost of carsharing versus the cost of walking or biking.
- Q10_4: I look at the cost of carsharing versus the cost of public transit.
- Q10_5: I rarely evaluate the cost of using carsharing versus the alternatives.

Q13: Please tell us whether or not carsharing benefits you in the following ways (1-5 scale, where 1 = no benefit to 5 = major benefit).

- Q13_1: Easier to meet up with friends and family.
- Q13_2: I go to more places in the city.
- Q13_3: I go to more places outside the city.
- Q13_4: I get ‘stuff’ done more efficiently; errands, meetings, shopping, etc.

Q14: Now for some ways carsharing might benefit your state of mind (1-5 scale, where 1 = no benefit to 5 = major benefit).
- Q14_1: I enjoy the freedom.
- Q14_2: I like not having to rely on others for a ride.
- Q14_3: Peace of mind knowing I have personal mobility when needed.
- Q14_4: I like not owning a vehicle (or another vehicle).
- Q14_5: I like having different options for getting around.

Appendix B: Additional Tables for Section 2

Table 7. Difference in transportation mode use by demographic.

<table>
<thead>
<tr>
<th></th>
<th>N (One-Way)</th>
<th>N (Two-Way)</th>
<th>Walking</th>
<th>Biking</th>
<th>Transit</th>
<th>Carpool</th>
<th>Taxi</th>
<th>Carshare (Passenger)</th>
<th>Carshare (Driver)</th>
<th>Total Trips</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Population</strong></td>
<td>2996</td>
<td>248</td>
<td>-1.76**</td>
<td>-1.19**</td>
<td>0.49</td>
<td>0.18**</td>
<td>0.14</td>
<td>1.13**</td>
<td>0.8**</td>
<td>2.47**</td>
</tr>
<tr>
<td>19-30</td>
<td>1394</td>
<td>50</td>
<td>-3.33**</td>
<td>-0.81</td>
<td>-0.71</td>
<td>0.14</td>
<td>0.17</td>
<td>1.71**</td>
<td>0.54*</td>
<td>1.68**</td>
</tr>
<tr>
<td>31-40</td>
<td>852</td>
<td>59</td>
<td>-1.31</td>
<td>-1.14</td>
<td>-0.20</td>
<td>-0.11</td>
<td>0.12</td>
<td>0.99**</td>
<td>0.69**</td>
<td>3.05**</td>
</tr>
<tr>
<td>41-50</td>
<td>360</td>
<td>48</td>
<td>-1.42</td>
<td>-1.26</td>
<td>-0.45</td>
<td>0.12</td>
<td>0.11</td>
<td>0.45</td>
<td>0.97*</td>
<td>3.06**</td>
</tr>
<tr>
<td>51-60</td>
<td>210</td>
<td>38</td>
<td>-1.59†</td>
<td>-1.55</td>
<td>-1.05†</td>
<td>-0.17</td>
<td>-0.02</td>
<td>0.02</td>
<td>1.09*</td>
<td>3.65**</td>
</tr>
<tr>
<td>61-70</td>
<td>86</td>
<td>32</td>
<td>-3.43*</td>
<td>-0.17</td>
<td>-0.88</td>
<td>0.17</td>
<td>0.09</td>
<td>0.18</td>
<td>1.61*</td>
<td>4.23**</td>
</tr>
<tr>
<td>70+</td>
<td>20</td>
<td>13</td>
<td>-1.10</td>
<td>-0.60</td>
<td>-1.08</td>
<td>0.13</td>
<td>0.35†</td>
<td>0.68</td>
<td>1.92**</td>
<td>4.33**</td>
</tr>
<tr>
<td><strong>Female</strong></td>
<td>1589</td>
<td>132</td>
<td>-2.55**</td>
<td>-0.90</td>
<td>0.57</td>
<td>0.23*</td>
<td>0.13†</td>
<td>1.40**</td>
<td>1.05**</td>
<td>2.49**</td>
</tr>
<tr>
<td><strong>Male</strong></td>
<td>1289</td>
<td>97</td>
<td>-0.94</td>
<td>-1.48</td>
<td>-0.04</td>
<td>0.22†</td>
<td>0.15</td>
<td>0.75**</td>
<td>0.85*</td>
<td>2.56**</td>
</tr>
<tr>
<td><strong>Unaffordable</strong></td>
<td>562</td>
<td>42</td>
<td>-1.47</td>
<td>-0.45</td>
<td>-1.39</td>
<td>0.15</td>
<td>0.17</td>
<td>1.11**</td>
<td>1.22**</td>
<td>2.46**</td>
</tr>
<tr>
<td><strong>Meet present needs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>cannot save</td>
<td>1437</td>
<td>103</td>
<td>-1.26*</td>
<td>-0.59</td>
<td>0.64</td>
<td>0.04†</td>
<td>0.15</td>
<td>1.44**</td>
<td>0.72**</td>
<td>2.14**</td>
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<tr>
<td>Affordable</td>
<td>727</td>
<td>80</td>
<td>-2.81**</td>
<td>-2.17**</td>
<td>1.06</td>
<td>0.28*</td>
<td>0.12</td>
<td>0.92*</td>
<td>0.69†</td>
<td>2.94**</td>
</tr>
<tr>
<td>Under $25,000</td>
<td>279</td>
<td>19</td>
<td>1.77</td>
<td>-0.47</td>
<td>0.88</td>
<td>0.43</td>
<td>0.10</td>
<td>1.63**</td>
<td>0.43</td>
<td>1.54**</td>
</tr>
<tr>
<td>$25,000 - $49,999</td>
<td>498</td>
<td>58</td>
<td>-1.44†</td>
<td>-1.18</td>
<td>1.38†</td>
<td>0.21</td>
<td>0.15</td>
<td>1.89**</td>
<td>0.13</td>
<td>0.99*</td>
</tr>
<tr>
<td>$50,000 - $74,999</td>
<td>518</td>
<td>41</td>
<td>-2.11*</td>
<td>-0.61</td>
<td>0.61</td>
<td>-0.10</td>
<td>0.20</td>
<td>1.03*</td>
<td>0.98*</td>
<td>2.02**</td>
</tr>
<tr>
<td>$75,000 - $99,999</td>
<td>411</td>
<td>32</td>
<td>-2.66†</td>
<td>-1.03</td>
<td>1.10</td>
<td>-0.12†</td>
<td>0.08</td>
<td>1.27*</td>
<td>1.21*</td>
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<td>$100,000 - $149,999</td>
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<td>25</td>
<td>-0.48</td>
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<td>0.16</td>
<td>0.41</td>
<td>0.15</td>
<td>1.18**</td>
<td>0.53</td>
<td>3.20**</td>
</tr>
<tr>
<td>Over $150,000</td>
<td>297</td>
<td>21</td>
<td>-2.48†</td>
<td>-2.65**</td>
<td>-0.75</td>
<td>-0.25</td>
<td>0.01</td>
<td>0.19</td>
<td>1.46**</td>
<td>2.78**</td>
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</table>
Table 8. Victoria vs. Vancouver trips and difference of means.

Note that the only significant differences in members transportation are biking (higher for Victoria residents) and transit (higher for Vancouver residents) perhaps due to a more robust public transit system in Vancouver.

<table>
<thead>
<tr>
<th>Mode of Transit</th>
<th>Trips per Week for Vancouver Residents</th>
<th>Trips per Week for Victoria Residents</th>
<th>P-Value of difference of means</th>
<th>Significant at alpha 0.05/8 = 0.00625?</th>
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<tbody>
<tr>
<td>Walking</td>
<td>9.7</td>
<td>10.7</td>
<td>0.25</td>
<td>No</td>
</tr>
<tr>
<td>Biking</td>
<td>2.3</td>
<td>4.1</td>
<td>0.006</td>
<td>Yes</td>
</tr>
<tr>
<td>Transit</td>
<td>5.9</td>
<td>4.0</td>
<td>0.0008</td>
<td>Yes</td>
</tr>
<tr>
<td>Carpool</td>
<td>0.5</td>
<td>.2</td>
<td>0.74</td>
<td>No</td>
</tr>
<tr>
<td>Taxi</td>
<td>0.2</td>
<td>.2</td>
<td>0.88</td>
<td>No</td>
</tr>
<tr>
<td>Carshare</td>
<td>1.1</td>
<td>0.9</td>
<td>0.26</td>
<td>No</td>
</tr>
<tr>
<td>Private Vehicle (Passenger)</td>
<td>0.9</td>
<td>0.6</td>
<td>0.46</td>
<td>No</td>
</tr>
<tr>
<td>Private Vehicle (Driver)</td>
<td>1.4</td>
<td>0.8</td>
<td>0.03</td>
<td>No</td>
</tr>
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</table>
Table 9. Motivational usage for CS by demographic for questions Q7 and Q10.

See Reproduction of questions probing motivations for CS use (SI) for information on column headers.

Difference is (one-way minus two-way). p-value ≤ .05: **  p-value ≤ .1: *

<table>
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<tr>
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<th>N (One-Way)</th>
<th>N (Two-Way)</th>
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<th>Q7_2</th>
<th>Q7_3</th>
<th>Q7_4</th>
<th>Q7_5</th>
<th>Q7_6</th>
<th>Q10_1</th>
<th>Q10_2</th>
<th>Q10_3</th>
<th>Q10_4</th>
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</thead>
<tbody>
<tr>
<td>Total Population</td>
<td>2996</td>
<td>248</td>
<td>-0.55**</td>
<td>-0.78**</td>
<td>0.31**</td>
<td>0.55**</td>
<td>1.20**</td>
<td>0.51**</td>
<td>-0.93**</td>
<td>0.49**</td>
<td>0.25**</td>
<td>0.60**</td>
</tr>
<tr>
<td>19-30</td>
<td>1394</td>
<td>50</td>
<td>-0.14</td>
<td>-0.96**</td>
<td>0.16</td>
<td>0.12</td>
<td>0.73**</td>
<td>0.56**</td>
<td>-0.65**</td>
<td>0.62**</td>
<td>0.05</td>
<td>0.51**</td>
</tr>
<tr>
<td>31-40</td>
<td>852</td>
<td>59</td>
<td>-0.66**</td>
<td>-0.64**</td>
<td>0.29**</td>
<td>0.36**</td>
<td>0.92**</td>
<td>0.73**</td>
<td>-0.97**</td>
<td>0.56**</td>
<td>0.25</td>
<td>0.61**</td>
</tr>
<tr>
<td>41-50</td>
<td>360</td>
<td>48</td>
<td>-0.43**</td>
<td>-0.54**</td>
<td>0.33**</td>
<td>0.48**</td>
<td>0.94**</td>
<td>0.19</td>
<td>-1.01**</td>
<td>0.65**</td>
<td>0.18</td>
<td>0.38</td>
</tr>
<tr>
<td>51-60</td>
<td>210</td>
<td>38</td>
<td>-0.25</td>
<td>-0.61**</td>
<td>0.42**</td>
<td>0.86**</td>
<td>0.97**</td>
<td>0.65**</td>
<td>-1.11**</td>
<td>0.57**</td>
<td>-0.08</td>
<td>0.16</td>
</tr>
<tr>
<td>61-70</td>
<td>86</td>
<td>32</td>
<td>-0.53*</td>
<td>-0.83**</td>
<td>-0.02</td>
<td>1.61**</td>
<td>1.08**</td>
<td>0.14</td>
<td>-1.01**</td>
<td>0.02</td>
<td>-0.09</td>
<td>0.25</td>
</tr>
<tr>
<td>70+</td>
<td>20</td>
<td>13</td>
<td>-0.49*</td>
<td>-0.59**</td>
<td>0.77**</td>
<td>1.83**</td>
<td>0.98*</td>
<td>-0.26</td>
<td>-1.50**</td>
<td>-0.05</td>
<td>0.75</td>
<td>0.87</td>
</tr>
<tr>
<td>Female</td>
<td>1589</td>
<td>132</td>
<td>-0.51**</td>
<td>-0.71**</td>
<td>0.2**</td>
<td>0.54**</td>
<td>1.29**</td>
<td>0.46**</td>
<td>-0.9**</td>
<td>0.47**</td>
<td>0.28</td>
<td>0.71**</td>
</tr>
<tr>
<td>Male</td>
<td>1289</td>
<td>97</td>
<td>-0.54**</td>
<td>-0.86**</td>
<td>0.34**</td>
<td>0.54**</td>
<td>1.06**</td>
<td>0.57**</td>
<td>-0.98**</td>
<td>0.52</td>
<td>0.29</td>
<td>0.42**</td>
</tr>
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<td>Unaffordable</td>
<td>562</td>
<td>42</td>
<td>-0.34*</td>
<td>-0.82**</td>
<td>0.16</td>
<td>0.55**</td>
<td>1.26**</td>
<td>0.45**</td>
<td>-0.65**</td>
<td>0.74</td>
<td>0.25</td>
<td>1.07**</td>
</tr>
<tr>
<td>Meet present needs cannot save</td>
<td>1437</td>
<td>103</td>
<td>-0.47**</td>
<td>-0.65**</td>
<td>0.42**</td>
<td>0.48**</td>
<td>0.93**</td>
<td>0.47**</td>
<td>-0.76**</td>
<td>0.71**</td>
<td>0.35**</td>
<td>0.58**</td>
</tr>
<tr>
<td>Affordable</td>
<td>727</td>
<td>80</td>
<td>-0.78**</td>
<td>-0.87**</td>
<td>0.26**</td>
<td>0.59**</td>
<td>1.54**</td>
<td>0.5**</td>
<td>-1.27**</td>
<td>0.27**</td>
<td>0.18</td>
<td>0.42**</td>
</tr>
<tr>
<td>Under $25,000</td>
<td>279</td>
<td>19</td>
<td>-0.59**</td>
<td>-1.01**</td>
<td>0.54**</td>
<td>0.36**</td>
<td>1.59**</td>
<td>1.03**</td>
<td>-0.59*</td>
<td>0.00</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>$25,000 - $49,999</td>
<td>498</td>
<td>58</td>
<td>-0.55**</td>
<td>-0.75**</td>
<td>0.21**</td>
<td>0.34**</td>
<td>0.90**</td>
<td>0.48**</td>
<td>-0.7**</td>
<td>0.78**</td>
<td>0.32</td>
<td>0.81**</td>
</tr>
<tr>
<td>$50,000 - $74,999</td>
<td>518</td>
<td>41</td>
<td>-0.61**</td>
<td>-0.78**</td>
<td>0.28**</td>
<td>0.74**</td>
<td>1.36**</td>
<td>0.53**</td>
<td>-0.74**</td>
<td>0.52**</td>
<td>0.28</td>
<td>0.76**</td>
</tr>
<tr>
<td>$75,000 - $99,999</td>
<td>411</td>
<td>32</td>
<td>-0.64**</td>
<td>-1.05**</td>
<td>0.47**</td>
<td>0.71**</td>
<td>0.83**</td>
<td>0.77**</td>
<td>-1.2**</td>
<td>0.34**</td>
<td>0.30</td>
<td>0.43</td>
</tr>
<tr>
<td>$100,000 - $149,999</td>
<td>433</td>
<td>25</td>
<td>-0.30</td>
<td>-0.47*</td>
<td>0.13</td>
<td>0.44**</td>
<td>1.61**</td>
<td>0.48**</td>
<td>-0.88**</td>
<td>0.83**</td>
<td>0.47</td>
<td>0.98**</td>
</tr>
<tr>
<td>Over $150,000</td>
<td>297</td>
<td>21</td>
<td>-0.75**</td>
<td>-0.44</td>
<td>0.63**</td>
<td>-0.06</td>
<td>1.68**</td>
<td>0.51</td>
<td>-1.17**</td>
<td>0.75**</td>
<td>0.31</td>
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</table>
Table 10. Motivational usage for CS by demographic for questions Q13 and Q14.

See Reproduction of questions probing motivations for CS use (SI) for information on column headers.

Difference is one-way minus two-way. p-value ≤ .05: ** p-value ≤ .1: *

<table>
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<tr>
<th></th>
<th>N (One-Way)</th>
<th>N (Two-Way)</th>
<th>Q13_1</th>
<th>Q13_2</th>
<th>Q13_3</th>
<th>Q13_4</th>
<th>Q14_1</th>
<th>Q14_2</th>
<th>Q14_3</th>
<th>Q14_4</th>
<th>Q14_5</th>
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<td>0.52**</td>
<td>0.08</td>
<td>-1.24**</td>
<td>-0.39</td>
<td>0.06</td>
<td>-0.03</td>
<td>-0.14</td>
<td>-0.97**</td>
<td>0.11</td>
</tr>
<tr>
<td>19-30</td>
<td>1394</td>
<td>50</td>
<td>0.72**</td>
<td>0.22</td>
<td>-1.57**</td>
<td>-0.16</td>
<td>-0.07</td>
<td>-0.01</td>
<td>0.07</td>
<td>-0.53**</td>
<td>0.19</td>
</tr>
<tr>
<td>31-40</td>
<td>852</td>
<td>59</td>
<td>0.45**</td>
<td>0.08</td>
<td>-1.60**</td>
<td>-0.36*</td>
<td>0.09</td>
<td>-0.02</td>
<td>-0.14</td>
<td>-1.08**</td>
<td>0.12</td>
</tr>
<tr>
<td>41-50</td>
<td>360</td>
<td>48</td>
<td>0.25</td>
<td>-0.27</td>
<td>-1.22**</td>
<td>-0.72**</td>
<td>0.08</td>
<td>0.00</td>
<td>-0.14</td>
<td>-1.11**</td>
<td>-0.02</td>
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<tr>
<td>51-60</td>
<td>210</td>
<td>38</td>
<td>0.02</td>
<td>-0.19</td>
<td>-1.30**</td>
<td>-0.62**</td>
<td>-0.01</td>
<td>-0.29</td>
<td>-0.39**</td>
<td>-0.98**</td>
<td>0.29</td>
</tr>
<tr>
<td>61-70</td>
<td>86</td>
<td>32</td>
<td>-0.36</td>
<td>-0.69**</td>
<td>-1.48**</td>
<td>-1.10**</td>
<td>-0.36</td>
<td>-0.34</td>
<td>-0.74**</td>
<td>-0.73**</td>
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<td>70+</td>
<td>20</td>
<td>13</td>
<td>-0.51</td>
<td>-0.54</td>
<td>-1.14**</td>
<td>-0.92*</td>
<td>0.00</td>
<td>-0.41</td>
<td>-0.28**</td>
<td>-1.53**</td>
<td>0.12</td>
</tr>
<tr>
<td>Female</td>
<td>1589</td>
<td>132</td>
<td>0.57**</td>
<td>0.09</td>
<td>-1.29**</td>
<td>-0.43**</td>
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<td>-0.18</td>
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<tr>
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<td>1289</td>
<td>97</td>
<td>0.44**</td>
<td>0.04</td>
<td>-1.28**</td>
<td>-0.42**</td>
<td>0.13</td>
<td>0.08</td>
<td>-0.17</td>
<td>-1.04**</td>
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<tr>
<td>Unaffordable</td>
<td>562</td>
<td>42</td>
<td>0.64*</td>
<td>-0.30</td>
<td>-1.5**</td>
<td>-0.12</td>
<td>0.02</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.7**</td>
<td>0.16</td>
</tr>
<tr>
<td>Meet present needs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cannot save</td>
<td>1437</td>
<td>103</td>
<td>0.64**</td>
<td>0.25*</td>
<td>-1.18**</td>
<td>-0.17</td>
<td>0.09</td>
<td>0.15</td>
<td>0.01</td>
<td>-0.7**</td>
<td>0.17*</td>
</tr>
<tr>
<td>Affordable</td>
<td>727</td>
<td>80</td>
<td>0.31*</td>
<td>-0.12</td>
<td>-1.27**</td>
<td>-0.87**</td>
<td>0.00</td>
<td>-0.27</td>
<td>-0.42**</td>
<td>-1.36**</td>
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<td>0.17</td>
<td>-0.14</td>
<td>-0.29</td>
<td>-0.36</td>
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</tr>
<tr>
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<td>498</td>
<td>58</td>
<td>0.60**</td>
<td>0.01</td>
<td>-1.32**</td>
<td>-0.14</td>
<td>0.10</td>
<td>0.12</td>
<td>0.07</td>
<td>-0.99**</td>
<td>0.17*</td>
</tr>
<tr>
<td>$50,000 - $74,999</td>
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<td>41</td>
<td>0.76**</td>
<td>0.19</td>
<td>-1.1**</td>
<td>-0.17</td>
<td>0.08</td>
<td>0.09</td>
<td>-0.11</td>
<td>-0.5*</td>
<td>0.11</td>
</tr>
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<td>$75,000 - $99,999</td>
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<td>32</td>
<td>0.47</td>
<td>0.13</td>
<td>-1.63**</td>
<td>-0.19</td>
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<td>0.17</td>
<td>-0.16</td>
<td>-1.16**</td>
<td>0.19</td>
</tr>
<tr>
<td>$100,000 - $149,999</td>
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<td>25</td>
<td>0.10</td>
<td>-0.17</td>
<td>-0.96**</td>
<td>-0.67**</td>
<td>0.04</td>
<td>0.08</td>
<td>-0.25</td>
<td>-0.79**</td>
<td>0.13</td>
</tr>
<tr>
<td>Over $150,000</td>
<td>297</td>
<td>21</td>
<td>0.45</td>
<td>0.21</td>
<td>-1.17**</td>
<td>-0.97**</td>
<td>-0.17</td>
<td>-0.57</td>
<td>-0.48</td>
<td>-1.95**</td>
<td>0.04</td>
</tr>
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</table>
Table 11. Difference in income and affordability index.
Difference is one-way minus two-way. p-value ≤ .05: **  p-value ≤ .1: *

<table>
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<th>Income Difference</th>
<th>Affordability Difference</th>
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<tr>
<td>19-30</td>
<td>$8,660.91</td>
</tr>
<tr>
<td>31-40</td>
<td>$12,282.60**</td>
</tr>
<tr>
<td>41-50</td>
<td>$11,706.43</td>
</tr>
<tr>
<td>51-60</td>
<td>$28,731.90**</td>
</tr>
<tr>
<td>61-70</td>
<td>$12,251.34</td>
</tr>
<tr>
<td>70+</td>
<td>$32,401.96**</td>
</tr>
<tr>
<td>Female</td>
<td>$12,001.27**</td>
</tr>
<tr>
<td>Male</td>
<td>-$2,926.27</td>
</tr>
</tbody>
</table>

Appendix C: Additional Figures for Section 3

Figure 24. Average carshare utilization by hour/day of week for Car2go and Evo vehicles

Note that utilization values are likely inflated by vehicle fueling, maintenance, or repositioning, periods that are not differentiated from regular booked hours by the API scraped data.
Figure 25. Scatterplot of hourly utilization vs idle time for aggregate one-way carsharing.

R-value = -0.99 and p-value < 0.001. Each point represents aggregate data for one hour of week (168 total hours).

Figure 26. Within group sum of squares by number of clusters extracted.