Free-floating Carsharing and Extemporaneous Public Transit Substitution

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Abstract

The importance of substitution patterns between public transit and carsharing has been discussed in prior literature. This study provides empirical evidence of significant interaction between the two modes. On November 24, 2015 the public transit rail system in Vancouver, Canada experienced a significant service disruption due to an unforeseen mechanical failure. This study exploits this event as a natural experiment and investigates to what extent the city's largest carsharing service was utilized as a substitute. Extensive carsharing vehicle location data are used to examine how the carsharing network responded to the transit service disruption. Empirical results show a dramatic increase in the use of carsharing vehicles during the transit outage, particularly in areas close to affected transit stations. Through regression analysis, the quantity of vehicle trips accommodated by the carsharing system in response to the outage is estimated to be approximately 800. There is clear evidence of extemporaneous substitution between public transit and carsharing, suggesting the two modes act as parts of an integrated network.

Keywords: Carsharing; Transit; Mode Choice; Sharing Economy; Shared Mobility
JEL classification: R40; R41; R42

1 Introduction

The recent growth of carsharing has created an alternative mode of transportation for urban residents. How carsharing interacts with public transportation systems is an important concern for the future of public transportation, as well as the potential growth of carsharing. This paper uses data on carsharing vehicle locations, collected from Vancouver Canada's largest carsharing provider, car2go. By exploiting the impact of an unexpected outage in a public transportation service, this study provides novel estimates regarding the extemporaneous substitutability of carsharing for transit.

Prior work has argued that carsharing and public transit might operate as parts of an integrated network (Costain et al., 2012; Shaheen et al., 2004). The availability of carsharing allows those who have forgone private vehicle ownership to have an alternative mode available when public transit does not meet their needs. Empirical evidence on whether users substitute between public transit and carsharing is limited. The central contribution of the current paper is to demonstrate that commuters substitute carsharing trips for transit trips, when transit fails to meet their needs.

This study will be concerned with free-floating, one-way carsharing systems. Such systems allow users to begin and end trips anywhere within a geographic "home-zone," delineated by the system operator. Trips may end at a different location than they began. This is in contrast to round-trip carsharing services which require trips to end where they began. The world's largest free-floating carsharing provider in terms of fleet size is car2go. car2go is a subsidiary of Daimler, and as of May 2018, operated in 23 cities across eight countries.

During the afternoon and evening of November 24, 2015 in Vancouver, a large portion of the public transportation system was shuttered due to an unexpected mechanical issue. This incident provides a natural experiment to estimate whether system users substitute between public transportation and carsharing. This paper will provide strong evidence that the use of the city's car2go system increased substantially during the transit outage.

Empirical evidence is consistent with users substituting carsharing trips for public transit trips.

2 Related Literature

The way carsharing services interact with other modes of transportation has been a frequent topic of interest. This section outlines the general theory related to the relationship between carsharing and transit. The premise of the literature is that travellers will use carsharing in place of transit when transit does not meet their needs. The current paper fits into this literature by providing evidence that travellers do in fact substitute between the two modes based on relative convenience.

Early investigations into carsharing recognized a potential synergy between transit and carsharing. Shaheen et al. (2004) described carsharing as "situated between public transit and private vehicle ownership." The study pointed out the potential for carsharing programs to augment transit infrastructure by providing an option for routes that possess sparse public transit. Cervero et al. (2007) serves as a seminal foray into empirical examination of round-trip carsharing adoption. The study was cognisant of the potential interaction between public transit and carsharing. Survey data indicated that 29% of trips made with San Francisco's City carsharing system would have been instead completed by transit, had carsharing not been an available service. Costain et al. (2012) noted round-trip carsharing in Toronto is often used as a substitute for transit when service is low. A similar pattern may exist along routes that experience unexpected reductions in transit service.

Transit agencies have a strategic interest in understanding how carsharing and transit interact. Huwer (2004) analysed coordination efforts of carsharing programs and public transit agencies in Germany. Survey data were used to argue that carsharing is complementary to public transit because it allows transit users to expand their mobility while forgoing private vehicle ownership. Shaheen et al. (2015) reported survey results of carsharing operators in the Americas, finding that round-trip carsharing operators viewed their service as a complement to public transit, but were likely to view one-way carsharing to be in competition with public transit.

As noted in Kopp et al. (2015) as well as Namazu et al. (2018), the behaviours of round-trip carsharing users may differ substantially from one-way carsharing users. The ability of free-floating carsharing to accommodate diverse trip routes and one-way trips suggests it may be more easily substituted for public transportation.

The relationship between carsharing and public transit has been the focus of several recent case studies. Recent evidence from California suggested carsharing users are significantly more likely to use public transportation than the general population (Clewlow, 2016). Firnkorn and Müller (2011) investigated the success of car2go in Ulm, Germany, which was the first city to receive car2go service. The ability of car2go to integrate with the public transportation system was seen as important to increased car2go uptake. Le Vine et al. (2014) constructed and parametrized a carsharing demand model where the role of access to alternative transportation modes factored prominently. Model results for London suggested the joint introduction of round-trip and one-way carsharing systems would reduce the number of individuals purchasing public transport season tickets by 1.2%. Schmöller et al. (2015) analysed free-floating carsharing trip data from Munich and Berlin and was able to explain some variation in trips by appealing to vehicle imbalances causing deficits in certain areas. Temporal patterns in the placement of available vehicles will be important to the current study.

The potential for carsharing to provide network coverage when transit service is diminished can be related to theory on transport network robustness, such as Derrible and Kennedy (2010). Kepaptsoglou and Karlaftis (2009) specifically considered "operational disruptions" to rail transit systems and the need for alternative temporary interventions to accommodate affected travellers. The study discussed the practice of "bus bridging" wherein buses are deployed to replace closed sections of a rail system. De-Los-Santos et al.

(2012) explicitly incorporated the notion of "bridges" in a model of metro system robustness. The presence of free-floating carsharing vehicles provide a form of bridging that is constantly deployed, highly flexible, though potentially quite limited in capacity.

Over the longer term, carsharing may influence transit use due to changes in perceptions of vehicle ownership and mobility (Cervero et al., 2007; Firnkorn and Müller, 2011, 2015; Kent and Dowling, 2013; Martin and Shaheen, 2011; Mishra et al., 2015). Although long term substitution effects between carsharing and alternative modes are worthy of continued study, this paper will be concerned more narrowly with extemporaneous substitution patterns. The experience of being unable to complete a trip through transit may deter an individual from future use of public transit or encourage vehicle ownership (Brown et al., 2003; Carrion and Levinson, 2012; Thøgersen, 2006). The existence of carsharing as a substitute in the event of difficulties using public transit may make transit issues less grave, making transit use more desirable. Carsharing and transit may together provide unabridged mobility without requiring the burden of private vehicle ownership. Despite prior work suggesting that transit and carsharing are employed jointly by users (Cervero et al., 2007; Costain et al., 2012; Huwer, 2004; Martin and Shaheen, 2011), to the author's knowledge there have been no studies providing empirical evidence of extemporaneous substitution patterns between transit and carsharing.

3 Carsharing and Transit in Vancouver

Vancouver is a city of 631,000 people in a metropolitan region of 2.6 million.[1] The public transit network in Vancouver is built around a light rail system referred to as the SkyTrain. The SkyTrain has 53 stations serving the Vancouver metropolitan area. According to public information from Vancouver's transit operator, the SkyTrain system accommodated 119 million passenger boardings in 2015, compared to 230 million for buses. Transportation in the city of Vancouver has a diverse modal split for a North American

[1] Statistics Canada, 2016.

city. According to 2015 statistics for residents of Vancouver, 27% of trips made by Vancouverites were on public transit, while 50% were made in a private (or carsharing) vehicle (City of Vancouver, 2016).

Vancouver is served by four major carsharing programs: Zipcar, Modo, Evo and car2go. Zipcar and Modo are round-trip, fixed location systems, while Evo and car2go are one-way, free-floating systems. Local participation in carsharing is high with 26% of Vancouver residents having a membership to a carsharing service (City of Vancouver, 2016). The empirical analysis of this paper will be limited to car2go. car2go is the largest carsharing provider in Vancouver in terms of fleet size, having a fleet of 1,250 vehicles during the period of study. The "home-zone" of car2go is roughly coterminous with the City of Vancouver. car2go is also the largest system in terms of membership, though precise membership figures are not publicly available. The scale of the car2go system in Vancouver provides an excellent case study environment. As carsharing systems in other cities grow, Vancouver can demonstrate the effects of a relatively expansive carsharing network.

car2go vehicles are almost exclusively two-seater *Smart Car* vehicles. During the period of study Vancouver hosted a pilot project for five-passenger car2go vehicles, which were *Mercedes-Benz B-Class* models. During the period of study, only 1.5% of the available vehicle fleet were five-passenger vehicles.

Users of car2go are able to reserve any vehicle that is not in use or currently reserved. Reservations are allowed up to 30 minutes in advance of use and can be made via a smartphone application. Vehicles are rented at a cost of 0.41 CAD ($0.31) per minute plus a 1 CAD ($0.75) flat fee for each trip. Users must obtain a membership before booking a car2go vehicle. Application for membership includes an audit of the applicant's driving record, entailing a brief waiting period.

4 November 24th Transit Outage

At approximately 2:30 pm on November 24, 2015 a piece of spare rail that was being stored adjacent to active SkyTrain tracks became dislodged due to vibrations, falling onto the tracks. Subsequently, a moving train struck the piece of rail, which damaged electrical infrastructure both on the train car, and on the tracks. The public transit operator began repairs in the ensuing hours, and full service was restored by 11 pm.

Figure 1 shows a map of the city of Vancouver, indicating which SkyTrain stations were subject to temporary closure. Six stations were closed for the 2:30 – 11 pm period. The shutdown was particularly affecting as it eliminated east-west SkyTrain service to and from the central business district during a weekday evening rush hour. The Millennium Line and Expo Line were both affected, while the Canada Line was not affected.

●- Operating Station ▲ - Outage Station ■ - Central Business District

Figure 1: SkyTrain Stations in Vancouver Affected by November 24 Service Outage

The unforeseen and substantial interruption of service created an interesting natural experiment to illuminate how travellers change behaviour in response to a service disruption. If there is in fact substitution between transit and carsharing, there may be anomalous carsharing usage observed during the transit disruption. This study will proceed by comparing carsharing usage during the service disruption, with carsharing usage during days of normal transit operation.

5 Data

This study uses a unique and detailed data set capturing carsharing vehicle locations. car2go provides an Application Programming Interface (API) that displays precise, real-time geographic coordinates of all available car2go vehicles. A vehicle is available if it is currently parked, and not reserved by a user. Data were obtained by recursively querying the car2go API through the months of November and December, 2015. The average interval between queries was 7 minutes, 38 seconds.

Analysis is limited to 5 am to midnight for each Tuesday in November and December, 2015. The eight days in the data set include 1,097,640 vehicle observations, derived from 1,180 API queries. Each query returns the number of available vehicles, and their respective locations. As car2go use increases there are fewer available vehicles reported, which allows for the tracking of system use through time. The mean number of available vehicles citywide was 930 and ranged from 620 to 1,142.

Vehicle observations include a unique vehicle identifier. Linking identifiers across API queries allows for the construction of trip level data. The assembly of trip data requires the assumption that the vehicle is parked long enough to be recorded by recursive API queries. Instances where a car is both dropped off and rebooked between subsequent API queries may result in two separate trips being erroneously recorded as a single trip. Such errors will be implicitly differenced out by the estimation strategy described below. In total, 32,971 unique vehicle trips can be identified in the data.

Local weather data for Vancouver are collected from the Government of Canada's

Environment and Natural Resources historical database. The database provides hourly reports of weather conditions recorded at the Vancouver International Airport, which is located at the southern border of the city of Vancouver. Some amount of rain was recorded on seven of the eight control days. There was no rain recorded on November 24. 30% of the observations occurred during hours that experienced some amount of rain.

6 Methodology

Empirical estimates will be derived by comparing car2go usage on a "typical" day to usage during the November 24 SkyTrain outage. The number of additional car2go trips during the outage that are unexplained by typical use patterns will be interpreted as the response of the car2go system to the transit outage, indicating the number of excess trips absorbed by the car2go network.

Analysis will not account for the presence of Evo, which also operates a free-floating carsharing service in Vancouver. Evo was substantially smaller than car2go during the period of study, with an active fleet size of 500 vehicles. In 2016, Evo expanded its Vancouver fleet to 1000 vehicles.

It is likely that the usage of car2go varies across the days of the week as the commuting and leisure habits of residents vary across days. This study will use data exclusively from Tuesdays. Specifically, every Tuesday from November and December, 2015 are used in analysis, with the outage period on Tuesday, November 24 acting as the treatment period. The decision to limit the data set to Tuesdays is meant to ensure a valid control group.

If the car2go network experienced increased demand for trips due to a public transit outage, there should be an observable reduction in available vehicles during the outage. Figure 2 illustrates this effect. The minimum vehicle availability during the November 24 outage occurred at 5:19 pm, at which time there were 620 available vehicles. Within the control days, the lowest vehicle availability ever observed was 717. This suggests a substantially anomalous level of vehicle availability, and inversely vehicle usage, during the transit outage. The apparent impact of the transit outage on car2go use does not persist over the entire outage period. Vehicle availability recovers to levels comparable to control days by roughly 8 pm.

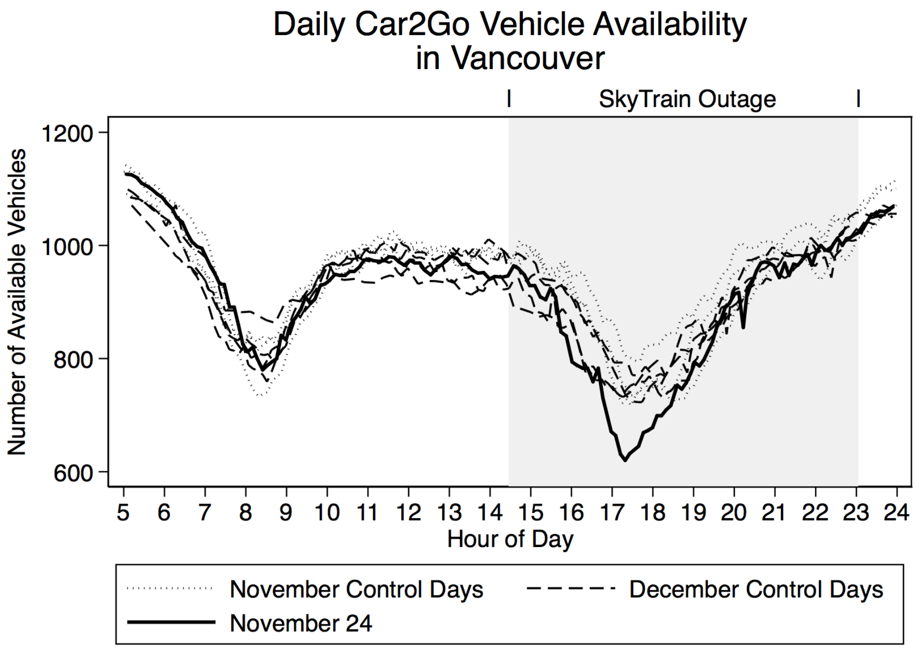

Figure 2
The figure plots vehicle availability, with a separate line for every day in the data set. There are three control days in November and four in December. November 24 was the day of the SkyTrain outage, and shows anomalous vehicle availability.

This study argues that the apparent drop in vehicle supply on November 24 is a consequence of extemporaneous mode switching during the transit outage. A testable implication of this theory is the presence of a pronounced effect in areas directly proximal to the affected SkyTrain stations, as prospective transit users in the area of the transit outage are likely to be more acutely affected.

Figure 3 shows the number of available vehicles within 250 meters of an affected station throughout the day. Although there is a strong trend towards low vehicle availability during the late afternoon and evening across all days observed, November 24 displays a particularly rapid depletion of vehicles around the evening rush hour. By 5 pm on November 24 there are zero car2go vehicles available within 250 meters of an affected station. On average, across the control days at 5 pm there are 54 available vehicles in the same geographic areas.

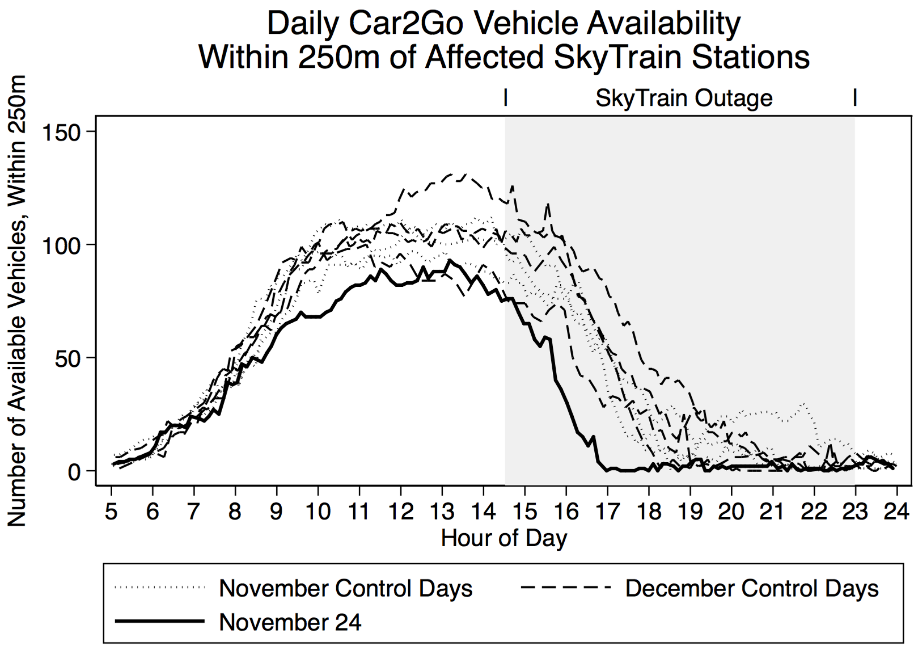

Figure 3
The figure plots vehicle availability close to affected stations, with a separate line for every day in the data set.

During the transit outage there were 859 car2go vehicles available, on average. During control days, the average availability was 932 (Table 1). The difference is consistent with higher than normal vehicle use during the outage. However, interpreting the difference as causal suffers from some barriers to causal identification. Most importantly, the outage spanned an evening rush hour. Even during control days, there is below average vehicle availability during rush hour. Therefore, controlling for time of day is important. Table 1 provides the difference in vehicles available during the outage, relative to the same hours on control days. There was an average of 38 fewer vehicles available during the outage, when compared to the same hours during control days. Table 1 also shows results when analysis is limited to the area immediately surrounding the closed stations. Vehicle availability during the outage was only 36% of what it was during the same hours of control days.

Table 1: Average Number of car2go Vehicles Available

	City of Vancouver		Within 250m of a Closed Station	
	All Day	2:30pm to 11 pm	All Day	2:30pm to 11 pm
November 24	916	859	33	12
Control Day Average	932	897	51	33
Vehicle Deficit	-16	-38	-18	-21

Beyond time of day, additional confounding effects may be present. For example, if there was unusually high or low demand on a particular day, for reasons unrelated to the transit outage, the effect could bias results. Additionally, as suggested in Schmöller et al. (2015), the presence of rainfall may affect the popularity of carsharing. Therefore, controlling for the presence of rainfall may also be important to results. In order to control for all of these factors simultaneously, I estimate the effect of the transit outage on car2go usage through a regression model.

Regression analysis will use fixed effects for the particular day and hour of day, and a dummy variable to control for the presence of rainfall, enabling the isolation of the partial effect of the transit outage on car2go vehicle usage. Equation 1 displays the basic regression model to be estimated. V denotes the number of available vehicles, Ω is an indicator variable for whether the observation was made during the transit service outage, and ψ and ϕ are fixed effects for day and hour of day respectively. R is a dummy variable capturing the presence of rainfall. The parameter of interest is β_1, which captures the partial effect of the outage on vehicle availability.

$$V_{dh} = \beta_0 + \beta_1 \Omega_{dh} + \psi_d + \phi_h + R_{dh} + \varepsilon_{dh} \tag{1}$$

The impact of the transit outage is potentially heterogeneous through the duration of the service disruption. To check the robustness of this study's main finding to model specification, an alternative model will also be estimated that allows the partial effect of the outage to vary through time. Equation 2 expands on the previous regression strategy by replacing the indicator variable for transit outage with a set of interaction terms that capture the effect of the transit outage on vehicle availability, hour by hour. While equation 1 is a more standard econometric approach, equation 2 has the advantage of providing information on how the intensity of the partial effect changed through the outage period. The inclusion of day and hour fixed effects absorb the partial effects of time of day and the particular day. Subsequently, the day-hour interaction terms capture any variation in vehicle availability that can be specifically attributed to the effect of a particular hour on November 24. If the vehicle availability during transit outage hours on November 24 was typical for that day-hour, the partial effects of the interaction terms should all be indistinguishable from zero.

$$V_{dh} = \beta_0 + \sum_{h=14}^{22} \beta_h(\psi_{d=\text{Nov.24}} \times \phi_h) + \psi_d + \phi_h + R_{dh} + \varepsilon_{dh} \tag{2}$$

I report Newey-West standard errors for all OLS results (Newey and West, 1987). Given that the observations are collected through time, it is possible that the error structure is not iid (independent and identically distributed), but may exhibit serial correlation. While hourly fixed effects will reduce this issue, they may not fully eliminate it. Newey-West standard errors correct for the possibility of serial correlation between subsequent observations. Newey-West standard errors are of a similar magnitude to regular robust standard errors, suggesting autocorrelation is not a large concern.

Analysis will also test for the presence of "bridging" trips along affected SkyTrain routes. An increase in trips that trace the outage in the transit system would provide clear evidence of direct substitution. Trip level regressions will use an approach analogous to equation 1, but with the dependent variable set to an indicator for particular trip characteristics. The trip level estimation equation is shown in equation 3, where B is a dummy variable that takes a value of one if the trip was a bridging trip and is zero otherwise. Other equation 3 variables share definitions with equation 1, but are indexed at the trip level, where t refers to a unique trip. Trip level regressions implement a probit model rather than an OLS design to heed the presence of a discrete dependent variable.

$$B_t = \beta_0 + \beta_1 \Omega_t + \psi_t + \phi_t + R_t + \varepsilon_t \tag{3}$$

The use of trip data rather than vehicle stock data subjects estimate to a possible source of bias, due to the imperfect identification of trips. In particular, the lag between observations means it is possible that a vehicle is both dropped off and rebooked between observations, causing two trips to be mistakenly identified as a single, longer trip. The presence of these errors will not necessarily bias results. Estimation of β_1 in equation 3 relies on the *difference* in the likelihood of a bridging trip occurring between outage and non outage observations. If the measurement error occurs equally in treated and control periods, the effect will be differenced out in estimation. However, this measurement error makes it difficult to identify the absolute number of trips that are occurring, which is why the stock of available vehicles can provide a more reliable measure of overall system usage.

car2go as a firm manages its fleet of vehicles in order to satisfy demand. During the study period, employees of car2go potentially intervened in the system, redirecting vehicles to where they were needed. Rebalancing is heavily constrained given that after an employee drives a single car to a high demand area, the employee would need to be shuttled back to the low demand area to transport an additional vehicle. The effect of rebalancing is likely small in comparison to the large change in market demand. To the extent that rebalancing does occur, it can be considered as a feature of the carsharing service that contributes to the levels of vehicle availability and use.

7 Results

Table 2 displays regression results from the estimation of equation 1. Column 1 shows a bivariate regression which omits fixed effects; this naive estimate suggests that throughout the period of transit outage there were on average 75 fewer vehicles available across the city than is typical of the sample. Of course, because the outage occurred during the evening rush hour, the bivariate estimation may be biased as there would have been low vehicle availability during rush hour regardless of the transit outage. Column 2 includes fixed effects for hour of day, to remove the potentially biasing effects of when the outage occurred. Column 2 also includes fixed effects for day of observation, to remove any idiosyncratic effects of the particular day. A dummy variable for the presence of rainfall during the hour of observation is included. The direction of the partial effect on rainfall is consistent with Schmöller et al. (2015), suggesting carsharing becomes more popular during rainfall events. Given the relatively small sample period, rainfall results are only tentative. After the introduction of controls, the estimate indicates that during the transit outage there were on average 44 fewer vehicles available than would be expected. The result is highly statistically significant.

Table 2: Partial Effect of Transit Outage on car2go Vehicle Availability

	Citywide	Citywide	Within 250m	Within 250m
	(1)	(2)	(3)	(4)
Transit Outage	-75.431**	-43.722**	-39.064**	-9.174**
	(20.005)	(7.901)	(3.925)	(2.851)
Precipitation (dummy)		-17.078**		-3.712**
		(2.983)		(1.043)
Const.	934.806**	1008.115**	50.897**	14.458**
	(3.956)	(5.923)	(1.724)	(1.761)
Hour Fixed Effects?	N	Y	N	Y
Day Fixed Effects?	N	Y	N	Y
Obs.	1180	1180	1180	1180
R^2	.035	.898	.053	.947

Significance levels: $*$: 5% $**$: 1%. Newey-West standard errors in parenthesis.

On average across non-outage observations between 2:30 and 11 pm, 3.7% of available vehicles were within 250 meters of one of the stations that would be closed due to the transit outage. If the reduction in availability estimated in Table 2, column 2 affected all areas of Vancouver equally, the 44 vehicle reduction implies there should be only two fewer vehicles available within 250 meters of affected stations. However, Table 2, column 4 repeats the methods of column 2, while limiting the analysis to areas within 250 meters of an affected station. The regression estimates there were in fact nine fewer vehicles in these areas on average. This suggests the drop in available vehicles was driven by increased demand close to affected stations, supporting the hypothesis that the drop in vehicle availability was driven by prospective transit users substituting transit trips with car2go trips.

There is clear evidence that vehicle demand was higher during the transit service outage, particularly near the affected stations. The ability of the carsharing system to provide trips to affected transit users can be approximated by first calculating the number of vehicle-hours the car2go system accommodated in response to the transit outage, and subsequently estimating the number of trips that this response represents.

Table 2, column 2 indicates that the transit outage resulted in 43.7 fewer vehicles available, on average during the outage. The outage lasted 8.5 hours, suggesting car2go provided 372 vehicle-hours of additional service during the outage. Trip duration can be estimated from the data. Once a vehicle is booked by a user, it disappears from the API. Therefore, trip durations are interpreted as the length of the vehicle trip plus any delay between booking the vehicle and arriving at the vehicle. During the outage the average trip duration was 27.3 minutes. While average trip duration is subject to some measurement error, the result is consistent with a recent analysis of car2go data that found average trips to be roughly 30 minutes (Habibi et al., 2017). I estimate the number of trips provided by the car2go system by dividing the additional vehicle hours by the average trip length. There were 817 (roughly 800) vehicle trips provided by the carsharing system during the outage, beyond what the system typically provides. If some of these 800 trips included passengers in addition to the driver then the number of transit riders that substituted towards car2go would be higher, proportional to average vehicle occupancy. As a point of reference, the number of carsharing trips completed across the entire Vancouver car2go system during outage hours on a typical day was roughly 4,600. car2go trips therefore rose by approximately 18% during the transit outage, suggesting significant ties between the two modes.

As described in the methodology section, an alternative estimation approach can allow the partial effect of the outage on vehicle availability to vary through time. The estimation of equation 2 is displayed in Table 3. Column 1 shows that across the city, vehicle availability is below expectations for every hour of the transit outage. The largest deficit occurred between 5 pm and 6 pm when there were 115 fewer vehicles available than would be predicted, representing 9% of the fleet. Subsequently, column 2 shows a negative effect when analysis is restricted to within 250 meters of an affected transit station, particularly towards the beginning of the transit outage. In response to the transit disruption the alternative specification estimates there were 394 additional vehicle-hours of car2go service provided, translating to 865 additional vehicle trips. The vehicle trip estimate generated by equation 2 differs from equation 1 by only 5.9%.

Figure 4 depicts Table 3 in graphical form, showing the progression of the vehicle deficit throughout the day of November 24, after controlling for hour and day fixed effects as well as precipitation. Figure 4 highlights the stark drop in vehicle availability, relative to expectations, beginning contemporaneously with the transit outage. Figure 4 also reveals that much of the early drop in citywide vehicle availability is explainable by changes proximal to affected SkyTrain stations. Once the stock of available vehicles was depleted from areas adjacent to affected stations, the drop in vehicles continues in areas farther from affected stations.

Finally, this section will test whether carsharing users executed "bridging" trips across closed stations. Appealing to Figure 1, the stations that would most plausibly act as destinations for displaced travellers are VCC-Clark Station, Renfrew Station, and Nanaimo Station. These are the closest stations able to accommodate trips to the extensive eastern portions of the Millennium and Expo lines that remained in operation.

Table 4 implements the probit regression shown in equation 3. The dependent variable takes a value of one if the observed route possessed the origin-destination characteristics indicated, and zero otherwise.

Table 3: Estimate of Hourly Vehicle Deficit Attributable to Transit Outage

	Citywide	Within 250m
	(1)	(2)
Nov 24 x 2 pm	-14.579*	-12.811**
	(6.925)	(3.157)
Nov 24 x 3 pm	-38.628*	-25.471**
	(16.815)	(4.972)
Nov 24 x 4 pm	-90.347**	-43.143**
	(18.573)	(4.940)
Nov 24 x 5 pm	-115.105**	-25.726**
	(11.079)	(2.855)
Nov 24 x 6 pm	-53.003**	-3.598
	(14.727)	(2.339)
Nov 24 x 7 pm	-38.111	.098
	(19.480)	(1.775)
Nov 24 x 8 pm	-19.699	3.340
	(15.376)	(1.786)
Nov 24 x 9 pm	-22.346**	4.344*
	(7.295)	(2.107)
Nov 24 x 10 pm	-9.618	7.133**
	(7.187)	(1.721)
Precipitation (dummy)	-17.221**	-3.662**
	(2.994)	(1.024)
Const.	1121.426**	4.873**
	(7.036)	(1.543)
Hour Fixed Effects?	Y	Y
Day Fixed Effects?	Y	Y
Obs.	1180	1180
R^2	.905	.956

Significance levels: $*$: 5% $**$: 1%. Newey-West standard errors in parenthesis.

Trips beginning adjacent to closed stations, and ending adjacent to nearby stations that were still operating represent a "bridging" scenario. Table 4, column 1 tests the likelihood of a randomly selected carsharing trip beginning within 500 meters of a closed station and ending within 250 meters of VCC-Clark Station, Renfrew Station or Nanaimo Station. The interpretation of probit results rely on holding covariates constant. In the absence of the outage at 5 pm on November 24, the likelihood a particular trip followed the bridging route was only 0.02%. During the outage the route was eight times as likely to be completed, occurring with a probability of 0.16%. Column 2 repeats the estimation

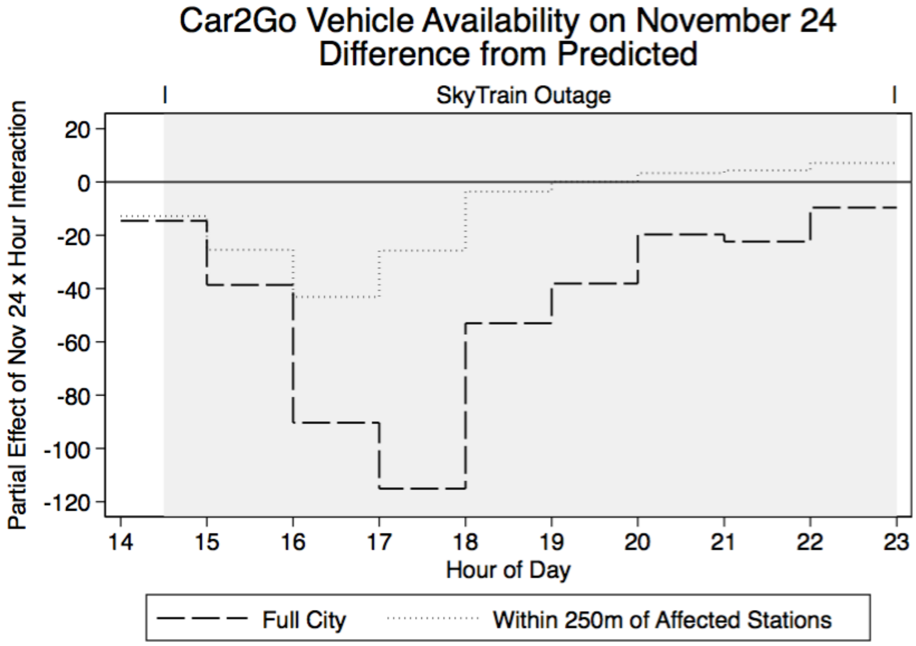

Figure 4

strategy while expanding the origin bandwidth to one km, capturing travellers who needed to travel farther to obtain an available carsharing vehicle. Column 2 results indicate trips of this type increased in likelihood during the outage by a factor of seven.

Column 3 uses the one km origin bandwidth but breaks the treatment dummy variable in half, allowing the partial effect of the outage to vary temporally. During the first half of the outage the likelihood of a bridging trip taking place was significantly heightened. At 5 pm on November 24 the likelihood was increased by a factor of 13. However, during the second half of the outage there was no significant change in the probability of a trip being a bridging trip. This temporal finding is consistent with observed vehicle location patterns and the presence of carsharing capacity constraints. The significant evidence of bridging trips suggest that some transit trips were directly substituted with carsharing trips.

Table 4: Route Likelihood Along SkyTrain Corridors, Probit Regressions

	Dependant Variable: Trip was from a closed station to an open station		
	(1)	(2)	(3)
Transit Outage	.579*	.610**	
	(.246)	(.191)	
Outage (1st Half)			.820**
			(.225)
Outage (2nd Half)			-.028
			(.349)
Precipitation (dummy)	.120	.086	.069
	(.140)	(.113)	(.116)
Const.	-3.177**	-3.056**	-2.952**
	(.361)	(.428)	(.417)
Hour Fixed Effects?	Y	Y	Y
Day Fixed Effects?	Y	Y	Y
Origin Bandwidth	500m	1000m	1000m
Destination Bandwidth	250m	250m	250m
Obs.	32971	32971	32971
Pseudo R^2	0.057	0.052	0.058

Significance levels: $*$: 5% $**$: 1%. Robust standard errors in parenthesis. The dependent variable in columns 1-3 are binary variables indicating whether the trip began within the indicated distance from an outage station and ended within 250m of VCC-Clark Station, Renfrew Station or Nanaimo Station. Outage (1st Half) is an indicator variable for whether the observation was made on Nov. 24 between 2:30 pm and 6:45 pm. Outage (2nd Half) is an indicator variable for whether the observation was made on Nov. 24 between 6:45 pm and 11:00 pm.

8 Conclusion

Free-floating carsharing provides a flexible mode of transportation that previous research has indicated may be synergistic to public transit. There is little previous evidence that these two modes are used in concert. Using a natural experiment, this study has shown that commuters substitute carsharing trips for public transit trips when they are subjected to delays in public transit. This finding supports prior work attempting to understand how carsharing fits into a broader transportation network. The presence of a clear response among carsharing users suggests that gaps in the transit network may be overcome through access to free-floating carsharing. A transit disruption may cause a traveller to experience significant delay if not for the presence of an alternative mode.

Carsharing may therefore provide a useful stop-gap mode, compatible with public transit.

During the transit outage, available carsharing vehicles were depleted rapidly in areas where they were most needed. Counteracting this market response may be in the interest of carsharing providers and transportation planners. Temporarily increasing rental prices in areas of heightened demand may be a rational demand management strategy. Alternatively, monetary incentives could be offered to carsharing users to end their trip in areas of high demand. Either strategy would improve vehicle availability for high demand locations. The continued growth of free-floating carsharing suggests its capacity to supply trips will increase over time. However, the physical constraints of parking and the unknown demand of marginal consumers to opt into carsharing suggest the scalability of carsharing is finite.

It has become a common practice among transportation agencies to locate dedicated carsharing parking adjacent to transit stations in order to increase vehicle supply and to take advantage of some supposed synergy between the two modes. The substitution patterns observed in this study provides some justification for such policies.

As explored in Cervero et al. (2007), Costain et al. (2012), Sioui et al. (2013) and Tyndall (2017), notwithstanding the relative affordability of carsharing, the urban poor participate in carsharing programs at low rates. As a result, the benefits of carsharing may only accrue to particular groups. The equity implications of carsharing are deserving of additional exploration.

Bieszczat and Schwieterman (2012) described the current state of government incentives for carsharing services, arguing that the *de facto* rate of taxation on carsharing is higher than for other services. The ability of carsharing to integrate with, and support public transit should be considered by policy makers in the context of previously discussed advantages and drawbacks to carsharing. The creation of optimal carsharing policy must consider the myriad impacts of carsharing on citizen welfare.

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