

# Environmental Impacts of Shared Mobility Services in Metro Vancouver

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## Executive Summary

Rapid technology advancement has facilitated the adoption of shared mobility services and transformed the transportation landscape inarguably. Various shared mobility services are operating in the Metro Vancouver region such as carsharing, ridehailing, and bikesharing. Metro Vancouver residents, now more than ever, have access to a broader set of transportation options that can influence their travel behavior. The adoption of shared mobility has the potential to reduce greenhouse gas (GHG) emissions from the transportation sector. This study attempts to

1. Develop a model to quantify the environmental impact of current and emerging shared travel modes within Metro Vancouver, in terms of GHG emissions.
2. Determine the impact of shared mobility on mode choice and mode displacement through exploratory research.

The input data are acquired from local sources and in case of unavailability are synthesized from the literature. Emission factors (in terms of GHG emissions per passenger-km traveled) are developed for traditional transportation options (car and transit) along with shared mobility services considering each service's unique characteristics. The mode displacement impacts are translated into GHG emissions by calibrated emission factors. Results indicate that carsharing and bikesharing consumers can reduce GHG emissions (in the range of 11-1255 kg CO<sub>2</sub>eq per user, annually) through their mode displacement behavior. The current mode choice of carsharing users reveals that one-way and round-trip users generate 55% and 64% fewer emissions, respectively, compared to a typical Metro Vancouver resident (with mode choice behavior identical to the modal breakdown of the region). To boost the GHG emission savings, carsharing systems can benefit from cleaner fuels, a more efficient fleet, an optimal rebalancing system, and higher occupancy levels. Our findings indicate that ridehailing can further contaminate the environment by generating additional 99 kg CO<sub>2</sub>eq per user, annually (due to mode displacement impacts). Using Washington, DC (due to its similar mode shares to Metro Vancouver), the potential future state of the region under the influence of ridehailing is explored. If the ridehailing uptakes remain relatively low (about 3% of total trips), daily emissions are likely to increase by 1.4% compared to the current modal breakdown of the region. However, further assessment is necessary as no empirical data were available from ridehailing services for the Metro Vancouver context. Pooled services, zero-emission fleets, and integration into transit networks are recommended to offset the unfavorable impacts of ridehailing. The primary contributor to emissions in the ridehailing service is empty kilometers (where no passenger is on board) which should be alleviated through appropriate policies. The finding from this study can guide authorities to invest in shared mobility services proportional to

their potential of GHG emission reductions. However, the environmental impacts should not be considered as the sole factor within the decision-making framework. Future research is needed to shed light on other aspects of shared mobility with respect to travel behavior such as impacts on equity, accessibility, mobility, congestion, etc.

## Introduction

Metro Vancouver region has set ambitious goals to eliminate detrimental emissions. These goals include a 45% reduction in emission by 2030 from 2010 values as the baseline and a carbon-neutral region by 2050 (1). Passenger cars and light-duty trucks are the largest contributors to GHG emissions in the region (30.9% by on-road mobile sources in 2015) (2). The dominant mode of transportation in Metro Vancouver is private car (as driver or passenger) with 71.9% of total trips undertaken in cars, followed by active travel (15.5% via walking and cycling), and transit (11.6%) in 2017 (3). In 2019, more than 318 million boardings were recorded on the bus system followed by more than 165 million, 6.7 million, and 2.6 million boardings on Skytrain, SeaBus, and West Coast Express (4).

Shared mobility services have the potential to alleviate environmental impacts of the transportation sector (5). Shared mobility stems from the broader concept of shared economy which prioritizes access to vehicles (bicycle, car, or other modes) over ownership (6, 7). Public transit can be considered the most traditional form of shared mobility. Figure 1 displays various forms of more recent shared mobility services.

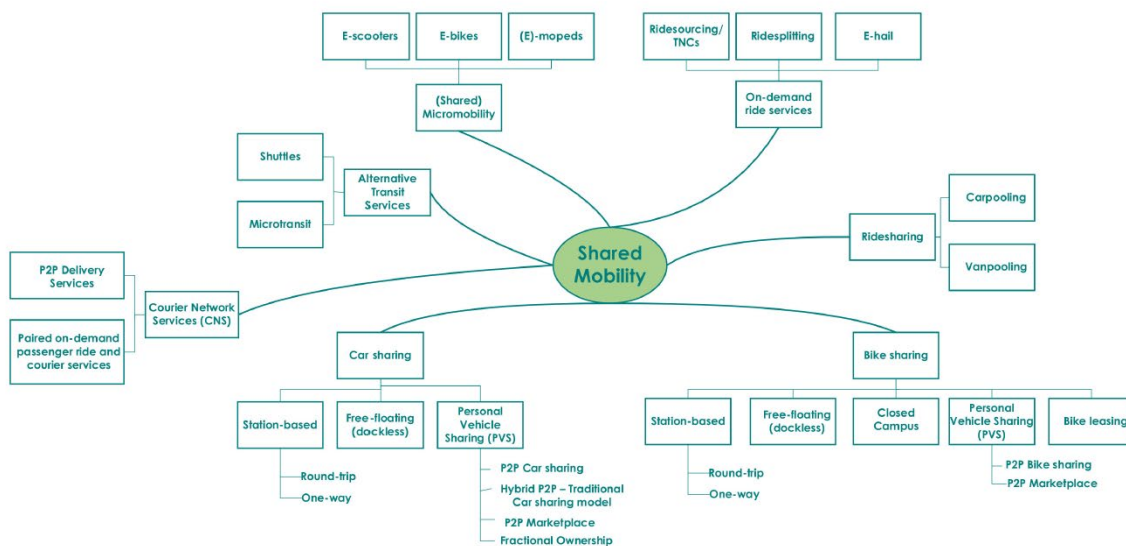


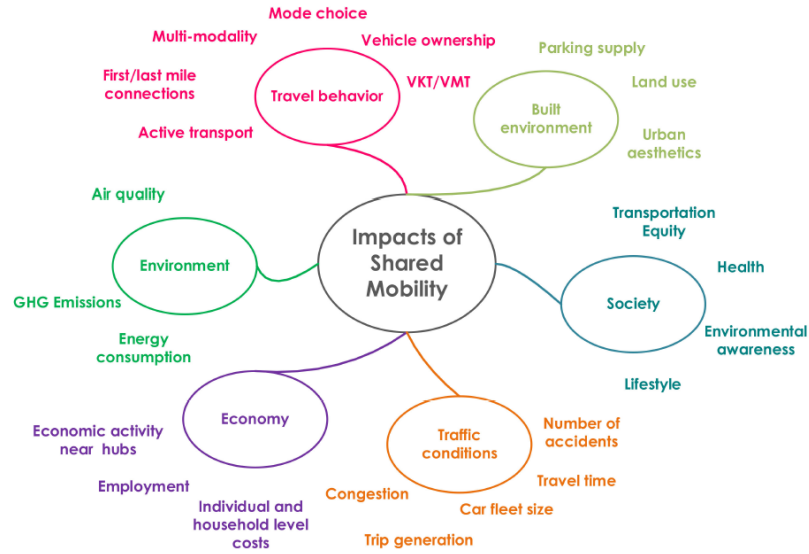
Figure 1 shared mobility services, from (8)

This report focuses on more recent shared mobility modes (including carsharing, ridehailing, and bikesharing) in addition to transit. For definitions of other forms of shared mobility, please refer to (8). Carsharing users can rent a car without concerns for typical costs of ownership through membership with an organization that provides vehicle fleet. Vehicle maintenance, fuel, and parking costs are the responsibility of the organization while members pay a fee per usage (7). Carsharing services can be free-floating or station-based. For free-floating service (one-way or point-to-point), shared cars can be returned anywhere within a designated area. Evo is an example of a free-floating carsharing service that was launched in the region in 2015 (9). Station-based services can be either one-way or round-trip (or two-way), in latter customers are obliged to return the vehicle to the origin station (7). Modo is an example of a round-trip station-based carsharing service within Metro Vancouver, founded in 1997 (10). City of Vancouver is referred to as the “carsharing capital” of North America for its 4.75 carsharing vehicles per 1000 residents (11, 12).

Ridehailing (also known as ridesourcing, transportation network companies, or on-demand ride services) offers on-demand mobility service by connecting drivers of private vehicles to passengers for a fee (13). Ridehailing came to Metro Vancouver in early 2020 with Uber, Lyft, and several smaller companies (e.g., Kater) (14). Bikesharing systems offer on-demand access to bicycles for one-way and two-way trips through dockless and station-based business models. Users of station-based bikesharing systems must return bicycles to a station (typically any station, not necessarily the one that users borrow the bikes from) while users of dockless systems have the flexibility to leave the bicycle in a predesignated area (13). Mobi by Shaw Go is a one-way station-based system that serves City of Vancouver with 2000 bicycles and over 200 stations (15).

Shared mobility services can influence travel behavior and consequently lead to various impacts (e.g, on mode displacement and vehicle ownership) (8, 13) (Figure 2). The objectives of this report are:

1. Develop a model to quantify the environmental impact of current and emerging shared travel modes within Metro Vancouver, in terms of GHG emissions.
2. Determine the impact of shared mobility on mode choice and mode displacement through exploratory research.



3. Figure 2 Shared mobility impacts, from (8)

## Background

This report utilized the "Google Scholar" search engine to identify publications (2010-2021) with any of the following keywords: shared mobility, car sharing, ridehailing/ ridesourcing/ transportation network companies, bike/ bicycle sharing. Publications that used any of the listed keywords in conjunction with the following words were also identified: GHG/greenhouse gas, environment, impacts, and emissions. Furthermore, the 'snowball search' method was adopted to expand the search to non-academic resources (policy briefs, white papers, reports, etc.). The search identified over 250 resources through reading the abstracts/summaries and further categorized them based on the topic, mode, method, and geographical scope. Caution should be exercised as the search is not aimed to be exhaustive and is rather prioritized to target carsharing and ridehailing studies. From this pool of resources, 23 studies were related directly to Metro Vancouver. Figure 3 displays the distribution of mode and topic across the identified studies. This research opted to use studies in North America and Europe due to intrinsic similarities between their transportation system and Metro Vancouver's.



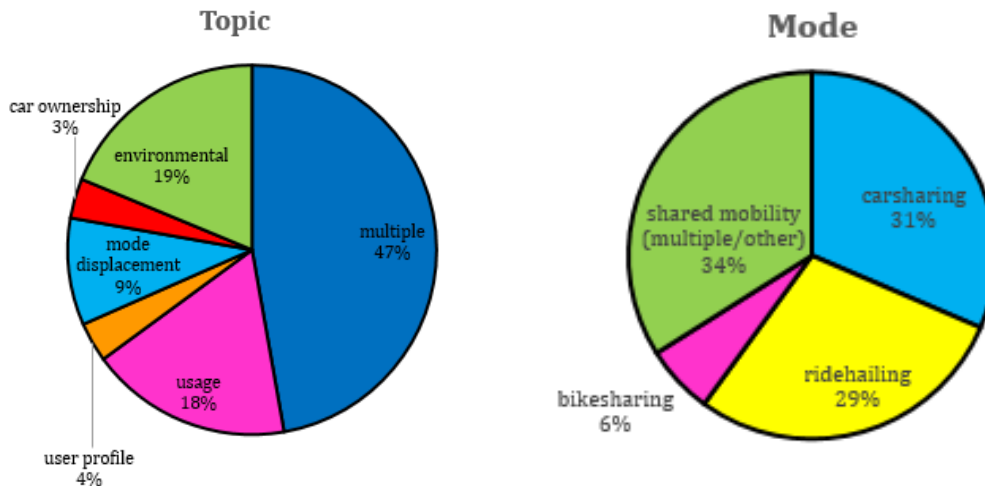


Figure 3 distribution of topic and mode across the identified studies

### *Carsharing*

Evidence suggests carsharing can result in favorable environmental impacts due to reduced VKT (vehicle kilometer traveled) and reduced vehicle ownership levels (sold vehicles or forgone/delayed purchases) (16–29). Moreover, carsharing fleets have better fuel efficiency and higher turnaround compared to private cars which can further amplify their positive impact (25, 30). On the other hand, carsharing attracts users who do not have access to a private car and the new access can shift their travel from more sustainable modes of travel (i.e., transit and active travel) to car travel. However, evidence suggests that the positive impact of people who sold their vehicles and reduced their car travel exceeds the negative impact of those who displaced sustainable modes of travel with carsharing (18, 22).

Reduced VKT by carsharing members after joining the organization is reported to be in the range of 3% to 79.8% (16–18, 22, 26, 27, 30). Some of these effects also include the impact of sold/forgone vehicles. Studies with comprehensive reviews of carsharing impacts reveal the number of removed vehicles per carsharing vehicle for round-trip carsharing is 4.6-15.3 (30, 31) and for one-way carsharing is 1-6 (31, 32). Specific to Metro Vancouver, round-trip carsharing consumers reduced their ownership levels by 50% while one-way users dropped their vehicle ownership levels by 10% (31). Another study in Metro Vancouver confirmed the trend and found that every carsharing vehicle replaces up to 3 private cars and considering avoided purchase the range extends to 5-11 (10).

Another prominent behavioral aspect is mode displacement patterns for carsharing users (i.e., what modes were/would have been used prior to/ in the absence of carsharing). There are a variety

of methods to capture such impacts. While some studies capture the subjective usage of modes before and upon joining carsharing (by asking survey respondents if they use certain modes “less often” or “more frequently”) (16, 33), other studies ask respondents to report what mode they would use in the absence of carsharing (20, 34, 35). Another informative lens is to ask about displaced distance traveled by each mode in addition to displaced modes (22). Moreover, mode displacement patterns should be distinguished for one-way and round-trip users. While one-way users displace transit trips (34, 36, 37), round-trip carsharing seems to compete with private cars (38). Travel purposes that carsharing services realize are different for each type of carsharing. Round-trip carsharing services are primarily employed for shopping trips (35, 39) while one-way services are mainly used for commuting (39). Additionally, round-trip carsharing typical travel distances tend to be longer than one-way services (40) but with a lower weekly frequency (39, 41).

### *Ridehailing*

Ridehailing is more novel than carsharing within the context of Metro Vancouver and consequently less evidence exists to be able to draw conclusions about the impact of this mode on travel behavior, locally. Evidence from ridehailing studies suggests that this service can generate new travel demand that did not exist prior to the introduction of ridehailing (5%-22% of trips would not be made in the absence of ridehailing, (42–48)). Car owners seem to displace their car travel with ridehailing while non-owners displace transit trips (47). Regardless of methodological differences in the studies that asked about mode displacement, a review study suggests around 30% of trips would be made by private car in the absence of ridehailing (30). Recent trends show that ridehailing seems to substitute trips that would have been made by car or taxi, otherwise (43). Concern about environmental impacts of ridehailing stems from “deadheading”, or empty kilometers that are traveled without a passenger. Because of deadheading, a ridehailing car can generate more emissions than a private car, given an equal travel distance. Deadheading comprises 20-81% of the total ridehailing VKT (30, 40, 47, 49–51) and accounts for 32% of lifecycle emissions from ridehailing services (40). The empty miles (Figure 4) can substantially exasperate the environment as well as congestion.

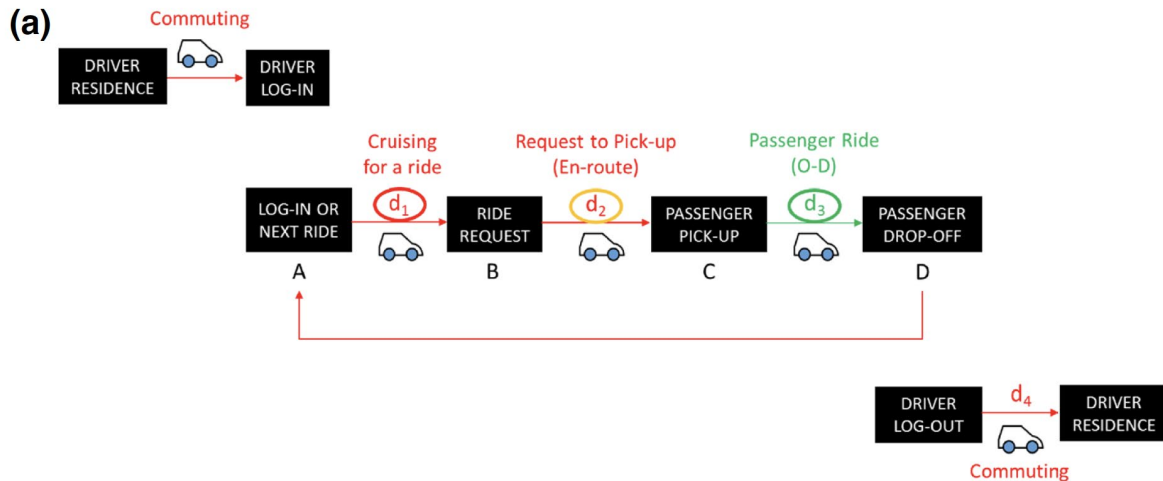


Figure 4 empty kilometers are the sum of driver commuting distances in the first and last leg of the journey plus cruising for a ride and distance traveled to pick up a customer, from (47)

Conversely, ridehailing might lead users to shed vehicles or delay the purchase of new vehicles, however, the evidence is not conclusive. In a study from Beijing, 48% of respondents reported that their decision to sell an old vehicle or purchase a new one was influenced by the permanent availability of ridehailing (52). Another study revealed that the majority of users did not change their vehicle ownership and for the 9% who did sell their vehicle, the magnitude and direction of VKT impact are unknown (48). A study conducted in Paris identified that only 4% of Uber users shed their vehicle and listed Uber as one of the main reasons. They estimated that avoided VKT due to shedding a car is 1.5-3% of daily VKT in private cars (53). In terms of the causal relationship between reduction in ownership levels and ridehailing use, an intercept survey inferred changes are irrelevant to ridehailing use (46). In line with revealed preferences, only 9% of users bought a new vehicle after the suspension of a ridehailing service in Texas (54). Henaoui et al. took all these impacts into consideration and concluded that ridehailing increases the overall VKT due to deadheading and mode displacement despite 13% of respondents owning fewer vehicles upon introduction of the service (47).

To offset detrimental environmental impacts, ridehailing can be used as a pooled service (as a result increased passenger kilometers traveled (PKT)). Electrifying the fleet can also lower the emissions while still providing a new mobility service (45). Another solution is the integration of ridehailing services into the transit network so that access/egress trips become more convenient. Currently, less than 1% of VKTs take place in electric vehicles (EVs) and only 15% of trips are pooled (45). Moreover, a mere 5.5% of ridehailing trips are made in connection with other modes (47). These solutions should be evaluated in a more comprehensive framework that accounts for other

impacts of shared mobility. For instance, addressing environmental impacts of ridehailing with EVs only resolves emissions in the usage phase while upstream emissions remain or congestion due to induced travel cannot be alleviated by using EV fleet.

### *Bikesharing*

Bikesharing bikes do not have tailpipe emissions but they need to be redistributed within the network to meet the spatial travel demand (i.e., rebalancing process). Rebalancing is implemented by light-duty trucks which engender emissions associated with bikesharing systems. Such emissions constitute 36-43% of lifecycle GHG emissions in station-based bikesharing systems in Toronto and the United States (40, 55). However, mode displacement impacts can, to some extent, offset bikesharing GHG emissions. A study revealed that 35% and 45% of bikesharing trips substituted transit trips for short-term and long-term members, respectively (30). Additionally, bikesharing affects transit mode share. According to a two-year study, bikesharing users tend to decrease their transit usage in larger cities while the reverse trend is observed in smaller cities. The results imply that substitution and complementary roles of bikesharing with respect to transit are contingent on the overall configuration of the transit network (56). Moreover, half of bikesharing users reported reduced private car usage and vehicle ownership levels (5.5% sold/delayed purchase) (56). The potential for bikesharing systems to reduce GHG emissions lies in what modes users displace, with station-based systems having a greater potential to achieve emission savings compared to dockless systems (55). The potential GHG saving per year is in the range of 38-280 metric tons CO<sub>2</sub> in the United States setting (in the review section of (57)).

Spatial context (characteristics of local transportation system), as well as temporal aspect (how long has it been since shared mobility service was introduced to the city), can drastically influence usage and mode displacement patterns for shared mobility consumers. Hence, the transferability of findings from the literature review to the context of Metro Vancouver should be exercised with caution. For instance, a recent study within Metro Vancouver revealed that more than 90% of shared mobility users do not change their vehicle ownership and the majority of the sample (87%-93%) is not likely to alter their mode choice due to the availability of ridehailing and carsharing services (14).

## **Methodology & Data**

This report draws its method from a recent study (40) and focuses on obtaining GHG emissions (global warming potential) in the usage phase (i.e., tank-to-wheel emissions caused by fuel consumption in motorized modes, excluding emissions from maintenance). Furthermore, to

capture mode displacement and mode choice impacts in terms of GHG emissions, we extend our study to include private cars and transit, as well. Figure 4 illustrates the share of GHG emissions from the usage phase compared to lifecycle emissions. These shares constitute the majority of lifecycle emissions for internal combustion engine vehicles (ICEV). EVs are excluded from this study because they do not produce tailpipe emissions. However, the upstream emissions from EVs constitute a larger portion of lifecycle emissions. The EVs' upstream emissions are contingent on the power grid system that generates electricity. The functional unit for this study is set to PKT. PKT is considered a more appropriate functional unit compared to VKT as it can determine more efficient modes of transportation in regard to occupancy (58, 59).

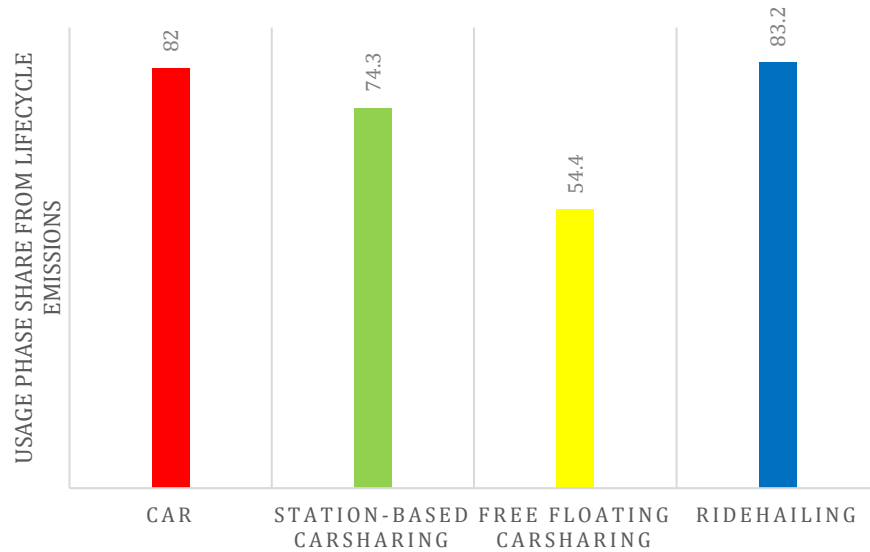


Figure 5 usage phase share of emissions from lifecycle emissions for ICEVs, from (40) based on the results for Toronto

Emission factors for each mode  $j$  ( $e_j$ ) are obtained by Equation 1:

$$e_j = \frac{GHG_{j\text{-usage phase}}}{PKT_j} \quad \text{Equation 1}$$

Where  $GHG_{j\text{-usage phase}}$  is the amount of GHG emissions generated by mode  $j$  and  $PKT_j$  is passenger kilometers traveled by mode  $j$ . PKT for each mode is the product of  $VKT \times Occupancy$ . Occupancy for private car and carsharing systems includes driver while for ridehailing (similar to taxi), it excludes the driver (40).

### Private car

GHG of usage phase for private cars is from fuel consumption which can be derived from Equation 2:

$$GHG_{fuel\ consumption} = TTW\ fuel\ emission\ factor \times fuel\ consumption\ rate \times VKT$$

Equation 2

Replacing Equation 2 in Equation 1 results in:

$$e_{car} = \frac{TTW\ fuel\ emission\ factor \times fuel\ consumption\ rate}{average\ vehicle\ occupancy\ per\ trip}$$

Equation 3

Fuel emission factors and consumption rates are obtained from (60) and are listed in Table 1. It is worth noting that however the values in Table 1 are specific to British Columbia, they are average values and not indicative of variation in passenger cars within Metro Vancouver with respect to fuel efficiency.

**Table 1 TTW emission factors and fuel consumption rates from (60)**

VEHICLE TYPE (FUEL)	TTW EMISSION FACTOR (KG CO <sub>2</sub> EQ/L)	FUEL CONSUMPTION RATE (L/100 KM)
Passenger car (gasoline)	2.346	9.2
Passenger car (hybrid)	2.346	7
Light truck (gasoline)	2.379	12.3

Occupancy is set to 1.24 according to (61). Furthermore, to reflect the fleet breakdown in Metro Vancouver a weighted average of private car emission factors based on car distribution in Metro Vancouver is yielded. Private car distribution is inferred from ICBC vehicle registration data for the lower mainland, 2020<sup>1</sup>. The data are filtered to only reflect personal use. Furthermore, passenger cars, as well as light-duty trucks (SUVs and minivans), are distinguished based on the “Body Style” filter. The inferred shares are compared to Metro Vancouver’s projections for 2020 based on 2017 ICBC data and 2015 MOVES data to ensure accuracy.

**Table 2 private car distribution in Metro Vancouver**

DATA SOURCE	PASSENGER CAR (GASOLINE)	PASSENGER CAR (HYBRID)	LIGHT-DUTY TRUCK (GASOLINE)
ICBC-2020	593,383 (48%)	21,674 (2%)	621,073 (50%)
Metro Vancouver-2020	530,229 (38%)	2,155 (0%)	863,282 (62%)

### *Transit*

The emission factors for various transit modes are elicited from (60) and listed in Table 3. Similarly, to have a representative emission factor for transit, in general, we used the weighted average of emission factors for each transit mode. Weights are assumed to be the number of annual boarding

<sup>1</sup> <https://public.tableau.com/app/profile/icbc/viz/VehiclePopulationIntroPage/VehiclePopulationData>

times route length (extracted from (4)). The better approach is averaging by PKTs which are not available to this study. To ensure representativeness of weights we compared our estimated weights to 2009 PKTs (62).

**Table 3 characteristics of the transit system**

VEHICLE TYPE	CITY BUS	SKYTRAIN	SEABUS	RAIL
Emission factor (kg CO <sub>2</sub> eq/PKT)	0.1014	0.002334	0.1547	0.1215
# boarding *				
Route length <sup>a</sup> (km), annual 2019	4,143,520,989 (34.08%)	7,816,880,000 (62.29%)	21,286,400 (0.18%)	176,800,000 (1.45%)
2009 PKT <sup>b</sup> , daily	4,728,000 (39.21%)	7,330,000 (60.79%)	-	-

a. for bus system (216 routes), source (4) does not have route length and instead has average one-way trip distance. To obtain route length, GFTS data are used (available from <https://developer.translink.ca/ServicesGtfs/GtfsData>). Data should be filtered to exclude road\_type: rail, Ferry, Subway. Metro and further cleaned to only include average length for different directions (so only 216 rows of data). For routes 32, 43, 44, 95, 96, 125, 143, 239, 242, 258, 480, GFTS files of August 06 and July 23, 2021 do not have any entry, so we used the average trip distance for these routes, instead ( from <https://translink.maps.arcgis.com/apps/MapSeries/index.html?appid=482ed47ba3bd47c3a24262c7c5810275>).

### *Carsharing*

VKT of carsharing should also reflect the rebalancing that is implemented by the operator to optimize the system. VKT for carsharing is denoted by Equation 4 (40):

$$VKT_{carsharing} = \frac{\text{number of trips provided by vehicle per day} \times \text{average trip length} \times \text{lifespan of vehicle}}{1 - \frac{\text{percent mileage used for rebalancing}}{\text{total lifetime mileage of vehicle}}}$$

Equation 4

Thus, the emission factor of carsharing based on Equation 1 is yielded by Equation 5:

$$e_{carsharing} = \frac{TTW\ GHG\ emission\ factor\ of\ fuel \times fuel\ consumption\ rate}{\text{average vehicle occupancy per trip} \times \left(1 - \frac{\text{percent mileage used for rebalancing}}{\text{total lifetime mileage of vehicle}}\right)}$$

Equation 5

Evo and Modo provided their fleet characteristics data (as of June 2021) which are used in the above equations to obtain emission factors for one-way and round-trip carsharing in Metro Vancouver. While Evo’s fleet features only one type of vehicle (Toyota Prius Hybrid), Modo has more diversity. Hence, emission factors corresponding to each vehicle type are calculated for Modo fleet and averaged by fleet size to represent a typical round-trip carsharing trip (in the weighted average, EVs and hydrogen fuel cell vehicles with zero tailpipe emissions (ZEVs) are taken into

account). Neither operator has data on occupancy levels<sup>2</sup> so the occupancy levels are set equal to private cars. Moreover, Evo reported the share of rebalancing to total lifetime mileage of carsharing vehicles as 1.6%. Modo has a negligible rebalancing due to the round-trip design of the system and thus rebalancing percentage is considered zero. Table 4 summarizes the necessary input to calibrate emission factors for one-way and round-trip carsharing systems.

**Table 4 characteristics of one-way (Evo) and round-trip (Modo) carsharing (as of June 2021)**

OPERATOR	VEHICLE TYPE (FUEL)	TTW EMISSION FACTOR (KG CO <sub>2</sub> EQ/L) <sup>A</sup>	FUEL CONSUMPTION RATE (L/100 KM) <sup>B</sup>	FLEET SHARE	REBALANCING %
Evo	Passenger car (hybrid)	2.346	5.91	100%	1.6%
Modo	Passenger car (gasoline)	2.346	7.66	59.42%	0%
	Passenger car (hybrid)	2.346	5.16	26.73%	
	Light truck (gasoline)	2.379	11.63	10.47%	
	All above	2.350 <sup>d</sup>	7.40 <sup>d</sup>	96.62%	
	Passenger car (ZEV) <sup>c</sup>	-	-	3.38%	

a. from (60)

b. weighted average based on operator data

c. ZEVs consisted of battery electric vehicles and hydrogen fuel cells

d. weighted average

### Ridehailing

Empty kilometers are considered in ridehailing emission factors through increased VKT (Equation 6) (40).

$$VKT_{ridehailing} = \frac{\text{number of trips provided by vehicle per day} \times \text{average passenger trip length} \times \text{lifespan of vehicle}}{1 - \frac{\text{deadheading length}}{\text{deadheading length} + \text{passenger trip length}}} \quad \text{Equation 6}$$

Replacing Equation 6 into Equation 1 yields emission factor for ridehailing (Equation 7)

$$e_{ridehailing} = \frac{\text{TTW GHG emission factor of fuel} \times \text{fuel consumption rate}}{\text{average vehicle occupancy for the passenger trip length} \times \left(1 - \frac{\text{deadheading length}}{\text{deadheading length} + \text{passenger trip length}}\right)} \quad \text{Equation 7}$$

<sup>2</sup> Evo's market search indicated that 10-15% of trips have more than one person in the car



As local data are not available at the time of this study, the necessary input is synthesized from literature (Table 5) and the average emission factor for ridehailing is estimated.

**Table 5 characteristics of ridehailing**

VEHICLE TYPE (FUEL)	TTW EMISSION FACTOR (KG CO <sub>2</sub> EQ/L) <sup>A</sup>	FUEL CONSUMPTION RATE (L/100 KM) <sup>A</sup>	OCCUPANCY <sup>B</sup>	DEADHEADING <sup>C</sup> %
Passenger car (gasoline)	2.346	9.2	1.24	42%

a. from (60)

b. equal to private car from (61)

c. from (47)

### *Bikesharing*

Occupancy of a bicycle is usually fixed and equal to one (the rider), so PKT and VKT are equal. Although bicycles do not generate emissions, rebalancing in the usage phase leads to emissions. Thus, the emission factor for bikesharing system is obtained by Equation 8 (40):

$$e_{bikesharing} = TTW \text{ GHG emission factor of fuel} \times \text{fuel consumption rate}_{rebalancing \text{ truck}} \times VKT_{rebalancing \text{ for every 1PKT bike}} \quad \text{Equation 8}$$

To account for seasonal patterns of bicycling, we opted to use a monthly average of rebalancing for the year 2020 (consistent with other modes temporal scope) from data provided by Mobi. Rebalancing VKT for every 1 PKT bike trip is calculated by Equation 9:

$$VKT_{rebalancing-bikesharing} = \frac{1}{12} \sum_{j=1}^{12} \frac{\text{Total km driven by vans for month } i}{\text{Total km ridden on bikes for month } i} \quad \text{Equation 9}$$

Necessary input to obtain the emission factor for bikesharing system (Mobi) is listed in Table 6.

**Table 6 characteristics of bikesharing (Mobi)**

OPERATOR	VEHICLE TYPE (FUEL)	TTW EMISSION FACTOR (KG CO <sub>2</sub> EQ/L) <sup>A</sup>	FUEL CONSUMPTION RATE (L/100 KM) <sup>B,C</sup>	REBALANCING FOR EVERY 1 KM BIKE TRIP <sup>D</sup>
Mobi	Light truck (gasoline)	2.379	12.1	0.0362 km

a. from (60)

b. weighted average by km driven by each light-duty truck based on operator data, year-around (Metris cargo van and Sprinter cargo van), this number for 2017 is 12.0

- c. fuel efficiency for Metris cargo van is derived from <https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/fuel-consumption-guide/21002>, as EPA<sup>3</sup> does not provide the same information for Sprinter, the fuel efficiency is obtained from [https://www.fuelly.com/car/mercedes-benz/sprinter\\_2500](https://www.fuelly.com/car/mercedes-benz/sprinter_2500)
- d. for comparison, rebalancing km per each 1 km bike trip for 2017 is 0.0722

### Monte Carlo Simulation

To assess uncertainty, Monte Carlo simulation is employed. Distributions rather than a central value are more insightful as a range addresses the uncertainty within the input data and captures how varying input variables and their interaction can affect emission factors. To draw the range of input data, local data and studies from the literature review are used. Table 7 lists the assumed distribution for each variable and the sources used for informing the distribution across shared mobility modes.

## Results

This section explicates the results of the method described above and applied on a set of transportation modes (including private car, transit, carsharing, ridehailing, and bikesharing). Calibrated emission factors are reported and the environmental impacts of users’ mode choice along with mode displacement behavior are discussed. Caution should be exercised with regards to assumptions and studies used to capture travel behavior impacts of shared mobility services. While some assumptions and inputs reflect the local context, others are elicited from the literature. Limitations of the method and assumptions are explained for each shared mobility service. An exhaustive survey is recommended to validate the magnitude and direction of the environmental impacts obtained in this report. Table 7 lists emission factors associated with various types of passenger cars.

**Table 7 estimated emission factors for private car**

VEHICLE	ESTIMATED EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )
passenger car (gasoline)	174.06
passenger car (hybrid)	132.44
light-duty truck (gasoline)	235.98

<sup>3</sup> EPA (US Environmental Protection Agency) does not determine fuel efficiency for commercial vehicles with a gross-vehicle-weight rating of more than 8500 pounds (<https://www.caranddriver.com/features/g20111998/worst-mpg-highway-tested/>)

Following the discussed methodology, weighted emission factors for private car and transit are 204.44 and  $38.09 \frac{\text{gCO}_2\text{eq}}{\text{PKT}}$ , these numbers are used to capture the mode displacement impacts of shared mobility modes.

Carsharing fuel emission factors are reported in Table 8 along with distributions yielded by Monte Carlo simulation. Increasing occupancy levels from 1.24 to 4 (which results in increased PKT) can decrease emissions by 69% for both one-way and round-trip carsharing systems (Figure 5). Thus, in addition to encouraging the acquisition of a more efficient fleet by carsharing operators, one of the solutions to enhance the environmental impacts of carsharing is devising incentives for pooled rides. Furthermore, it is suggested that carsharing organizations collect and provide occupancy data so that the estimates become more robust.

**Table 8 estimated emission factors for carsharing system (one-way: Evo and round-trip:Modo)**

OPERATOR-ATTRIBUTES	ESTIMATED EMISSION FACTOR ( $\frac{\text{gCO}_2\text{eq}}{\text{PKT}}$ )	SIMULATION RESULTS				
		Average	Standard deviation (SD)	Coefficient of variation % (	25 <sup>th</sup> percentile	75 <sup>th</sup> percentile
Evo-passenger car (hybrid)	113.63	80.53	10.92	13.56	72.85	86.73
Modo-passenger car (gasoline)	144.92	92.98	13.52	14.55	83.49	100.73
Modo-passenger car (hybrid)	97.62	68.02	10.40	15.28	60.73	74.00
Modo- light-duty truck (gasoline)	223.13	134.31	18.41	13.71	121.37	144.61
Modo-all above	140.24	99.74	20.60	20.66	85.45	112.21

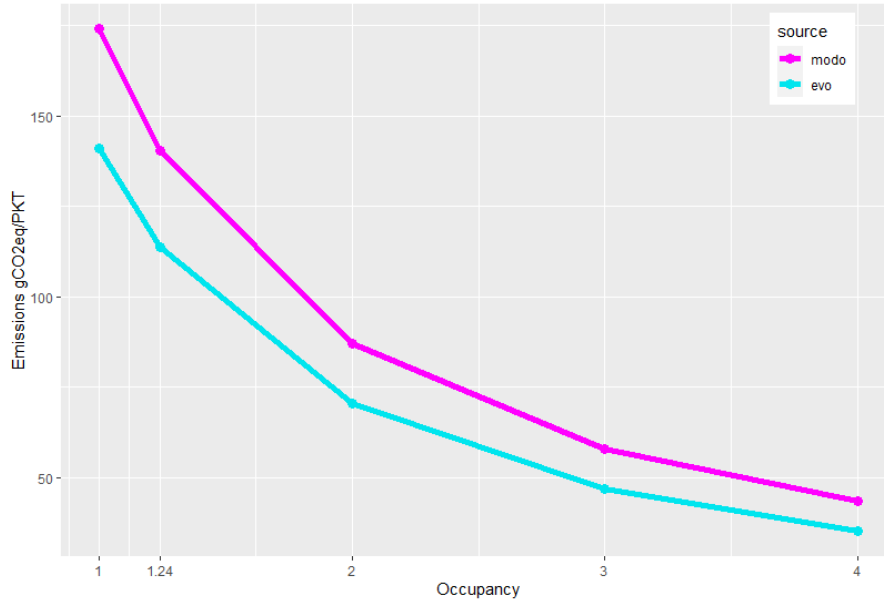


Figure 6 impact of occupancy on emission factors for carsharing system

To reflect ZEVs within the Modo fleet, the weighted average emission factors based on the number of cars are estimated for Modo (Table 9).

Table 9 Modo overall emission factor

OPERATOR-ATTRIBUTES	FLEET SIZE	ESTIMATED EMISSION FACTOR ( $\frac{GCO2EQ}{PKT}$ )	ESTIMATED EMISSION FACTOR (OVERAL)
Modo fleet (without ZEVs)	600	140.24	135.50
Modo fleet-ZEVs	21	0	

To capture the environmental impacts of carsharing travel behavior, usage data are necessary. Such data are not available to this study and therefore, usage (in terms of weekly frequency) and average trip distance (km) are inferred from carsharing studies. It is important to distinguish between one-way and round-trip carsharing travel behavior as they are utilized for different purposes and with different frequency levels. Average weekly frequency for one-way system is 2.75 (from (37, 40) and approximate numbers from (41)) with average trip distance of 5.67<sup>4</sup> km (from (16, 20, 22, 36, 38, 40, 63, 64)). For a round-trip system, the frequency is 1.33 (from (39) and approximate numbers

<sup>4</sup> For study (63) travel times are reported, speed of 50 km/hr is assumed to convert the numbers to km, (22) and (16) (in addition to average trip length) reported the annual VKT which is converted by weekly trip frequency (i.e., 2.75) and number of weeks within a year (i.e., 52) to travel distance

from (41)) and the average travel distance is 19.42<sup>5</sup> km (from (18, 22, 40)). Although these numbers are drawn from North American and European contexts, they should be applied with caution to Metro Vancouver as the specificity of the carsharing system and urban structure (for example, population density) impacts travel distances and frequencies (see for instance, (16) for a range of travel distances for cities with different population densities). Operator data can reduce uncertainty immensely, however such data are not available to this study. Using annual VKT in carsharing vehicles and emission factors, annual emissions generated by a carsharing user are estimated (Table 10).

**Table 10 annual GHG emissions generated by a user from carsharing**

CARSHARING	ESTIMATED EMISSION FACTOR ( $\frac{\text{GCO}_2\text{EQ}}{\text{PKT}}$ )	ANNUAL VKT <sup>A</sup>	ESTIMATED EMISSION (KG CO <sub>2</sub> EQ)
One way	113.63	811	92.15
Two way	135.50	1343	181.98

a. weekly frequency \* average trip distance\* 52

A local study provides insight into mode choices of one-way and round-trip carsharing users (41). We used Figure 6 from their study to approximately derive the shares for modes used by carsharing users (Table 10) and compare their mode choice behavior to the generic modal breakdown of the region from 2017 travel diary (3) (we assume the modal breakdown is representative of typical travel behavior of a Metro Vancouver resident). Hence, a daily emission profile is developed for each group (one-way user, round-trip user, and typical resident). With regards to “other” modes (carpool and taxi), as the travel diary does not report such figures we redistributed the shares equally across other modes. For travel distances, the estimates above are used for carsharing systems while for other modes we used average trip distance in the 2017 travel diary (3). We should acknowledge that the assumption of the identical travel distances by transportation modes across three groups might not be realistic. Another assumption is setting the number of trips equal across three groups to 3.2 (based on the total number of trips 7,906,302 from (3) divided by Metro Vancouver population of 2,463,000, i.e, the daily number of trips per capita). We assume the mode shares listed in Table 11 reflect the distribution of daily trips made by each group. Moreover, users that participated in the 2017 travel diary possibly included their carsharing trips into car travel. Within the city of Vancouver for the year 2017, 31% of residents aged +18 with a driving license

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<sup>5</sup> Similarly, for (18, 22) the annual VKT is reported which is converted to average trip distance by weekly trip frequency (i.e., 1.33) and number of weeks within a year (i.e., 52).

subscribed to a carsharing system (65), so the assumption that trip diary mode shares reflect non-user group is limiting in itself.

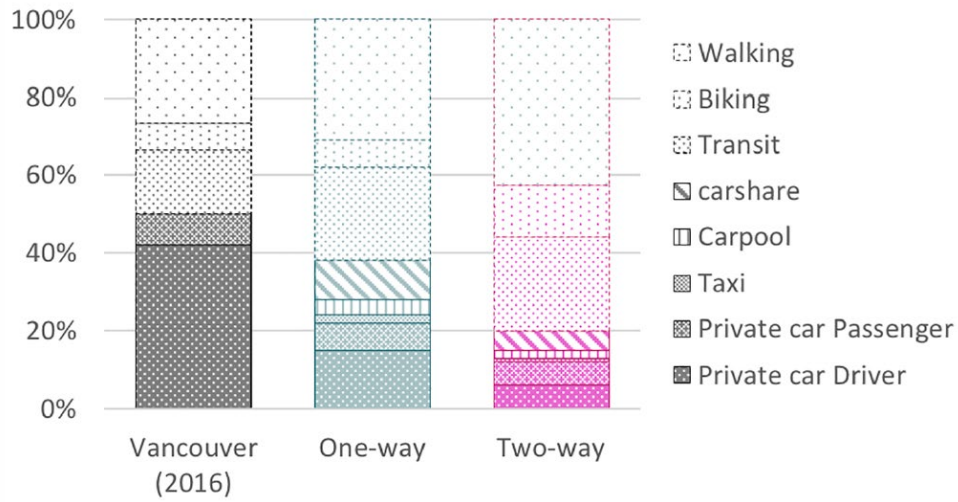


Figure 7 mode split for residents of Vancouver compared to one-way and round-trip users, from (41)

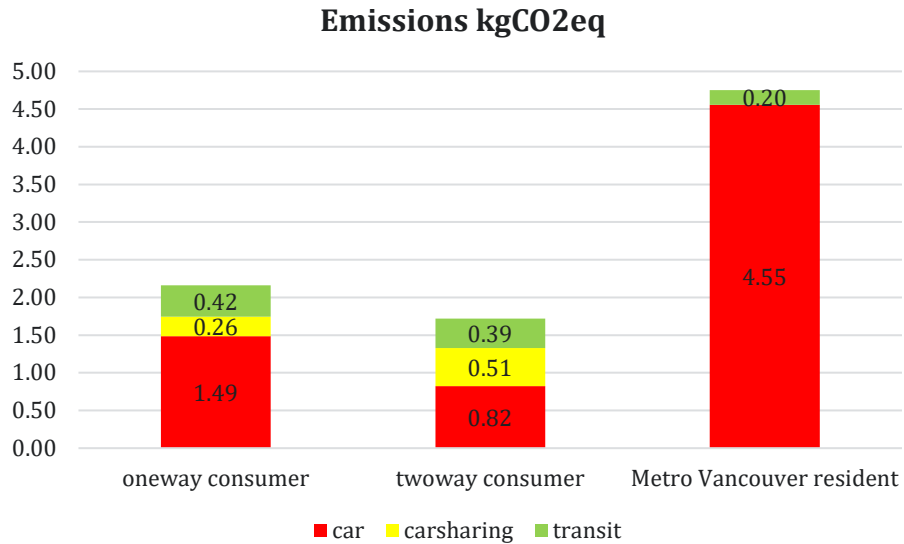
Table 11 displays that a one-way and round-trip user approximately generate 55% and 64% less emissions due to their mode choice behavior compared to a typical resident (with mode choice identical to the modal breakdown of the region). Figure 7 displays each mode's share of emissions across three groups. Carsharing users use transit more often which results in more transit emissions while their use of private cars is significantly lower. Carsharing users have lower PKTs in cars compared to a typical resident. Lower PKTs coupled with more efficient vehicles (compare  $113.63 \frac{\text{gCO}_2\text{eq}}{\text{PKT}}$  (emission factor of one-way) and  $135.50 \frac{\text{gCO}_2\text{eq}}{\text{PKT}}$  (emission factor of round-trip) to  $204.44 \frac{\text{gCO}_2\text{eq}}{\text{PKT}}$  (emission factor of a private car)) leads to overall lower emissions generated by carsharing users compared to residents. Within carsharing users, round-trip members make fewer carsharing trips however with longer distances compared to one-way members. This coupled with greater emission factors for round-trip systems leads to higher emissions due to carsharing for round-trip users. However, the overall private car and carsharing emissions for both user groups are comparable since round-trip users tend to use a private car less often than one-way users.

**Table 11 mode choice and daily emissions by one-way and round-trip carsharing members along with Metro Vancouver resident**

MODE	ONE-WAY USER MODE SHARE <sup>A</sup>	ROUND-TRIP USER MODE SHARE <sup>A</sup>	METRO VANCOUVER RESIDENT MODE SHARE <sup>B</sup>	AVERAGE TRIP LENGTH (KM)	EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )
Car	22%+1.5%(from other)=23.5%	12%+1% (from other)=13%	72%	9.67	204.44
carsharing	11%+1.5%=12.5%	5%+1%=6%	-	One-way=5.67 and round-trip=19.42	One-way=113.63, round-trip=135.50
Transit	24%+1.5%=25.5%	23%+1%=24%	12%	13.40	38.09
Walking and bicycling	37%+1.5%=38.5%	56%+1%=57%	16%	1.17	0
Other	6%	4%	-	-	-
Daily emissions (kg CO <sub>2</sub> eq)	2.16	1.72	4.75		

a. approximately from Figure 6

b. car travel is sum of passenger and driver, walking and bicycling are also aggregated, trip length is based on weighted average for these modes



**Figure 8 daily emission profile from transportation for carsharing consumers and Metro Vancouver resident**

**Table 12 distribution for input variables informed by operator data and literature review**

MODE	OPERATOR-ATTRIBUTES	INPUT VARIABLE	DISTRIBUTION	NOTE
One-way carsharing	Evo-hybrid passenger car	Fuel consumption rate	Normal distribution (average=6.45 SD=0.18 range=[5.91-7])	Is considered equal to private car in (22, 23, 26, 29, 40, 59) and more efficient (on average 25%) in (16, 25, 27, 66) as well as operator data, private car from (60), operator data=5.91
		occupancy	Normal distribution (average=2 SD=0.25 range=[1.24-2.75])	Is considered equal to private car in (25, 26, 28) and more in (19, 29, 40, 59, 67) (on average 1.98 times more)
		rebalancing	Normal distribution (average=4.55% SD=0.98% range=[1.6%-7.5%])	3.4%, 7.5%, 2.5-12.5% in (16, 40), operator data=1.6%
Round-trip carsharing	Modo- gasoline passenger car	Fuel consumption rate	Normal distribution (average=7.8 SD=0.47range=[6.4-9.2])	Is considered equal to private car in (22, 23, 26, 29, 40, 59) and more efficient in (16, 25, 27, 66) as well as operator data, private car from (60) for gasoline 9.2, for hybrid 7, and for light duty truck=12.3, operator data most efficient car=6.4 for gasoline, 4.4 for hybrid, and 9.9 for mini van/cargo
	Modo- hybrid passenger car	Fuel consumption rate	Normal distribution (average=5.7 SD=0.43range=[4.4-7])	
	Modo- cargo/minivan	Fuel consumption rate	Normal distribution (average=11.1 SD=0.4range=[9.9-12.3])	
	Modo-all fleet (except ZEV)	Fuel consumption rate	Normal distribution (average=8.35 SD=1.32range=[4.4-12.3])	
	Modo-all fleet	occupancy	Normal distribution (average=2 SD=0.25 range=[1.24-2.75])	
Ridehailing		Fuel consumption rate	Normal distribution (average=8.6 SD=0.23 range=[7.9-9.2])	Compared to private car, 3.2 miles per gallon more efficient from (50),17% better efficiency in (45), equal in (40, 64)
		occupancy	Normal distribution (average=1.37 SD=0.04 range=[1.24-1.5])	1.31 and 1.4 from (47), 30% of rides are shared between two people (50), 1.8 in (46), pooled service 1.5 and non-pooled equal to car and 1 (45), 1.66 in (30),1.56 in (44), 1.41 in (40)
		Deadheading %	Triangular distribution (average=45%, minimum=25%, maximum 65%)	42% in (47) and literature review within (47): 56-81%,61%,46-67%, 45% in (50), 33-45% with average of 41% in (40), 33-47% and assumed 41.8% in (45), 42.5% in (49) and 20% in literature review of (30)
Bikesharing	Mobi	Fuel consumption rate	Normal distribution (average=11.25 SD=0.35 range=[10.2-12.3])	Lower bound from most efficient car in operator data and upper bound for light-duty truck in (60)
		Rebalancing km per 1 PKT bike trip	Normal distribution (average=0.0766 SD=0.0203 range=[0.0158-0.1374])	For Toronto, 0.0275-0.0525 in (40), monthly range of operator data in 2017 and 2020:0.0158-0.1374



To capture the impacts of mode displacement for one-way carsharing user, the method from (26) is replicated. The study uses results from another one-way carsharing study (16) to derive impacts of mode displacement (also known as “rebound effects”) for Calgary in conjunction with three other cities. Similarly, we used results from (16) for Vancouver to infer the current VKT and VKT before the introduction of one-way carsharing. The advantage of this method is that it accounts for reduced VKT (as well as reduced vehicle ownership levels) for carsharing members. Furthermore, the method assumes a constant travel demand for both periods of “before” and “after” carsharing (thus, it ignores the possible induced travel impact) and uses the modal breakdown of Calgary to estimate the annual traveled distance in other modes. Due to lack of data, we used modal breakdown of Metro Vancouver assuming a 1:1 mode -distance relationship (i.e., if 72% of trips are made by car so 72% of total travel distances are made in car). Replication of the method for Metro Vancouver along with emission factors from above, the impact of mode displacement in terms of emissions is captured (Table 13). Unfortunately, same information (VKT for car travel before and after joining carsharing) is not available for round-trip system, locally. However, we consider annual VKT of private car in Canada (equal to 14,520 km from (40)) to represent the “before” period for round-trip users and use the observed average reduced VKT of 43% from a round-trip study (18) that included Vancouver as a case study along with other North American cities. Other key data are annual VKTs in round-trip carsharing vehicles. The weekly frequency of 1.33 and the average trip distance of 19.42 km are used to arrive at the annual estimated VKT (estimated from literature and discussed above). For the rest of the modes, we followed the same method from (26) as the one-way carsharing.

**Table 13 impact of mode displacement for carsharing system accounting for reduced VKT**

MODE	ONE-WAY CARSHARING		ROUND-TRIP CARSHARING		EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )
	before	after	before	after	
Car	10638	9648	14,520	6993	204.44
Carsharing	-	229	-	1343	One-way=113.63, round-trip=135.50
Transit	1773	2099	2420	5096	38.09
Walking and Bicycling	2364	2799	3227	6794	0
Total	14775 km		20167 km		-
Annual emissions (kg CO <sub>2</sub> eq)	2242.37	2078.41	3060.65	1805.73	

According to Table 13, a one-way carsharing user can achieve 163.96 kg CO<sub>2</sub>eq saving in emissions while the number for round-trip users is 1254.92 kgCO<sub>2</sub>eq. Although assumptions underlying the

above estimates warn us to interpret these numbers with caution, the same story is confirmed in Figure 7. Round-trip users can achieve higher savings in emissions due to their travel behavior (i.e., the trips that they displace by carsharing and their current mode choice).

The disadvantage of the above method is not accounting for specific displacement impacts across non-car modes (i.e., transit and active travel). The above method assumes the demand stays constant in both periods and therefore ignores the impact of induced travel. After estimating VKT in carsharing and private vehicles, the rest of the demand is redistributed between transit, walking, and cycling proportional to the region mode split. However, it should be noted that the mode choice for carsharing users (in terms of transit and walking/cycling shares of their travel demand) is different from the generic modal split of the region (Figure 6). The shortcoming of the mode displacement method can be resolved by measuring all aspects of changes in travel behavior upon joining carsharing (i.e., reduced vehicle ownership levels, induced travel, reduced VKT in private cars, as well as km-displaced (as opposed to trip displaced) across non-car modes of transportation). Moreover, the dynamic nature of such studies should not be neglected. The evolution of service can impact the magnitude and direction of changes in travel behavior (17).

Table 14 details the estimated emission factor for ridehailing along with simulation results to give the range of possible emission factors based on variation in input variables. Annual emissions by a ridehailing user can be estimated by inferring key values for ridehailing travel behavior (trip frequency and travel distance) from the literature. The average ridehailing trip distance (the segment with a passenger onboard) is 6.85 km (average from (30, 40, 44–47, 50, 56, 64)) and users tend to use the service up to 7.22 times a month (approximate average from (43, 44, 68, 69)). Therefore, the estimated annual emissions for a ridehailing user is 178.26 kg CO<sub>2</sub>eq.

**Table 14 ridehailing emission factors**

ESTIMATED EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )	SIMULATION RESULTS				
	Average	SD	CV %	25 <sup>th</sup> percentile	75 <sup>th</sup> percentile
300.10	274.15	44.22	16.13	241.15	300.83

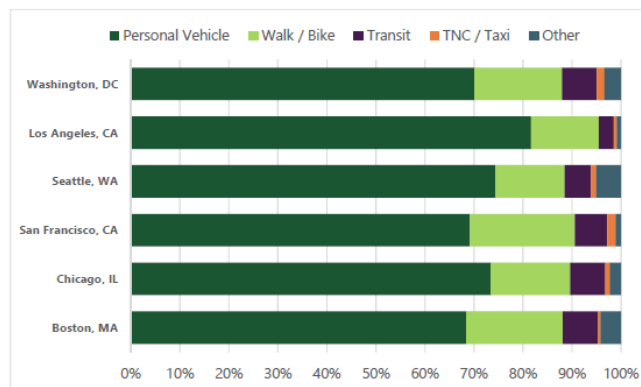
As ridehailing is still new to the region, the impacts are less known. However, using the National Household Travel Survey of the United States, Fehr & Peers elicited mode splits for six American regions (Figure 9) (49). Using Figure 9, we can have an estimate of how the future of Metro Vancouver would be shaped by ridehailing. Washington, DC mode split profile is used as a comparison basis as it has a similar mode split to Metro Vancouver (see commute mode split comparison in Figure 10). Similar to carsharing, same assumptions are used in Table 15 for the daily

number of trips as well as travel distances. Thus, if the ridehailing uptake follows the mode split of Washington (i.e., low adoption rate), daily emissions will increase by 1.4%.

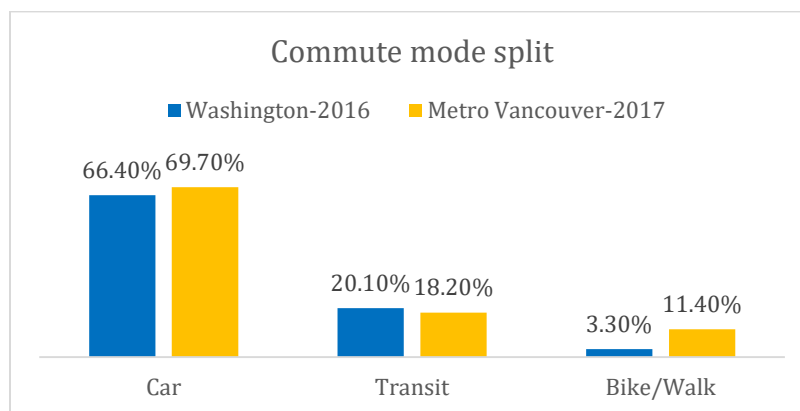
**Table 15 mode choice and daily emissions for future and current states within Metro Vancouver**

MODE	CURRENT (2017-METRO VANCOUVER)	FUTURE (WASHINGTON-FIGURE 9)	AVERAGE TRIP LENGTH (KM)	EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )
Car	72%	70%+1% (from other)=71%	9.67	204.44
Transit	12%	7%+1%=8%	13.40	38.09
Walking and Bicycling	16%	18%+1%=19%	1.17	0
ridehailing		2%+1%=3%	6.85	300.10
Other <sup>a</sup>	-	4%	-	-
Daily emissions (kg CO <sub>2</sub> eq)	4.75	4.82		

a. other share is redistributed evenly across other modes



**Figure 9 person-trip mode split from (49)**



**Figure 10 commute mode split for Washington (70) and Metro Vancouver (3), car includes car driver and passenger for Metro Vancouver and drive alone, carpool, and vanpool for Washington. 10.2% of work trips in Washington are “compressed work schedule day off and telework”**

Table 16 summarizes the emission impacts of mode displacement for ridehailing users. To infer mode displacement impacts of ridehailing, we assume a 1:1 relationship between mode and km traveled. For instance, 26% of trips would be made by car in the absence of ridehailing service, this assumption implies that 26% of annual VKT ridden in ridehailing service would be driven in a private vehicle. However, such an assumption is limiting, for instance, people in private cars might travel longer as out-of-pocket costs can be perceived lower than ridehailing services. Furthermore, this assumption does not capture the holistic picture of travel behavior. For example, although a ridehailing user tends to displace more transit and active travel they might reduce their annual VKT due to shedding their personal vehicles. Thus, the estimates should be interpreted with caution.

**Table 16 mode displacement impacts of ridehailing**

MODE	DISPLACEMENT IMPACT			EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )
	Displaced %	Reference study	Displaced km	
Car	26	(42–48, 54)	158 <sup>b</sup>	204.44
Carsharing <sup>a</sup>	11	(42, 47, 54)	69	127.27
Transit	19	(42–48, 54)	117	38.09
Walking and bicycling	12	(42–44, 46–48, 54)	75	0
Induced	10	(42–48)	63	-
Taxi <sup>c</sup>	18	(43–48, 54)	111	300.10
Other <sup>d</sup>	4		-	-
Total	100		594	
Annual emissions from ridehailing			178.26	
Annual emissions due to mode displacement			78.86	
Net emissions (kg CO <sub>2</sub> eq)			+99.40	

- a. For carsharing as the type is not specified. Weighted average of emission factors based on annual VKT is used.  
b. displaced distance is calculated based on %displaced (here 26%) times annual VKT of ridehailing user (here 594 km)+ 1/6 of other displaced distance (here 23.7 km)  
c. As ridehailing competes with taxi services, we opt to report taxi, separately. The same emission factor with ridehailing services is assumed for taxi services. Taxi services can have more deadheading (30) but as they are regulated by cities, they are probably more fuel efficient than ridehailing services. These two factors justify the assumed emission factor. Moreover, (40) estimated taxi emissions are very similar to ridehailing services in Toronto.  
d. "Other" is 100%- remaining mode shares, the km displaced for "other" is distributed equally across other modes

Displaced and induced travel leads to 99.40 kg more CO<sub>2</sub>eq annually per ridehailing user (excluding other impacts such as reduced vehicle ownership level). The results are aligned with Table 15 with respect to increased emissions expected from ridehailing services.

Figure 11 displays the average trip distance in bikesharing system in 2017 and 2020 as well as corresponding rebalancing distances (Equation 9). Overall, in 2020 the average trip distance increased marginally (by 0.23 km) while the efficiency of the system improved significantly (50%

decrease in the average rebalancing km per 1 PKT bike trip). Furthermore, according to Mobi 2017 survey, the usage frequency for the year 2016 is approximated as 4.86 and for the year 2017 as 7.02 times a month (the monthly frequency of 7.02 is used in the rest of the analysis).

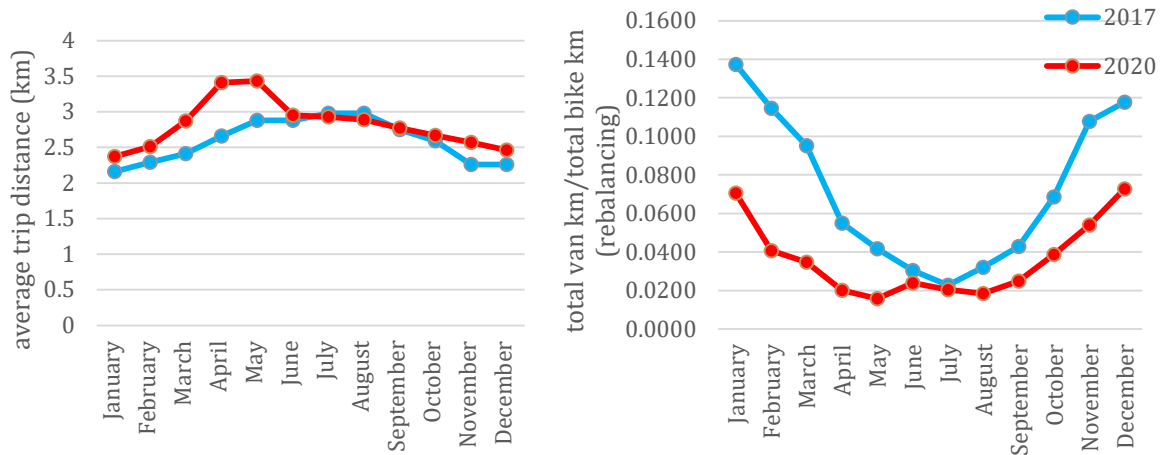


Figure 11 Mobi system characteristics

The bikesharing system emission factors, as well as simulation results, are reported in Table 17.

Table 17 bikesharing emission factors

ESTIMATED EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )	SIMULATION RESULTS				
	Average	SD	CV %	25 <sup>th</sup> percentile	75 <sup>th</sup> percentile
10.42	20.49	5.47	26.72	16.79	24.16

Based on usage characteristics and the emission factor, bikesharing trips give rise to 2.48 kg CO<sub>2</sub>eq per user per year. We further assessed mode displacement impacts in two years, 2017 and 2021. Table 18 summarizes the estimates of mode displacement impact. In 2017, every user saved 8.41 kg CO<sub>2</sub>eq by undertaking their trips by bikesharing, while every user saved 11.24 kg CO<sub>2</sub>eq in 2021. The comparison highlights the impact of the detailed mode displaced reported in the 2017 survey (transit modes are individually reported and induced travel is considered in the 2017 survey). Future surveys are recommended to similarly inquire about specific transit mode displaced and take into account the trips that would not have been made in the absence of bikesharing (induced trips).

**Table 18 mode displacement impacts of bikesharing**

MODE	DISPLACEMENT IMPACT FROM 2021 MOBI SURVEY		DISPLACEMENT IMPACT FROM 2017 MOBI SURVEY		EMISSION FACTOR ( $\frac{GCO_2EQ}{PKT}$ )
	Displaced %	Displaced km	Displaced %	Displaced km	
Car	16	39 <sup>b</sup>	8	17	204.44
Carsharing <sup>a</sup>	5	12	5	11	127.27
Transit <sup>c</sup>	23	55	Bus/seabus=20, skytrain=6	Bus/seabus=44, skytrain=13	For 2021: 38.09 For 2017 bus/seabus <sup>d</sup> = 101.67 and skytrain=2.334
Walking and bicycling	53	126	45	98	0
Induced <sup>c</sup>	-	-	14	31	-
Taxi/ridehailing <sup>e</sup>	3	7	2	4	300.10
Motorcycle <sup>c</sup>	-	-	0.3	1	131.69 <sup>f</sup>
Rental bike <sup>c</sup>	-	-	0.2	0	0
Total	100	238	100	218	
Annual emissions from bikesharing	2.48		2.27		
Annual emissions due to mode displacement	13.61		10.68		
Net emissions (kg CO <sub>2</sub> eq)	-11.13		-8.41		

a. For carsharing as the type is not specified. The weighted average of emission factors based on annual VKT is used.  
b. Displaced distance is calculated based on %displaced (here, 16.25%) times annual VKT of bikesharing user (here, 238 km)

c. In 2021 survey, the transit modality, motorcycle, or rental bike were not given as options. Neither was an option for not making the trip

d. Weighted average based on information in Table 3 is used.

e. As ridehailing competes with taxi services, we opt to report taxis, separately. The same emission factor with ridehailing services is assumed for taxi services. Taxi services can have more deadheading (30) but as they are regulated by cities, they are probably more fuel-efficient than ridehailing services. These two factors justify the assumed emission factor. Moreover, (40) estimated taxi emissions are very similar to ridehailing services in Toronto.

f. from (60) and assumed fuel consumption rate of 5.9 L/100 km from <https://afdc.energy.gov/data/>

g. average trip distance in 2017 Mobi data is 2.59 km, same monthly frequency of 7.02 is used for both years.

To put these results into perspective, the annual GHG impacts from mode displacement are converted to tangible equivalents<sup>6</sup>. GHG savings from carsharing and bikesharing and added emissions in case of ridehailing are converted to miles driven in a passenger car that produce the same emissions. Additionally, we reported the number of smartphones that their charging

<sup>6</sup> By EPA Greenhouse Gas Equivalencies Calculator available at <https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator>

generates equal emissions to mode displacement emissions from shared mobility services (Figure 12).



Figure 12 equivalents for emissions from mode displacement across shared mobility modes

## Findings & Recommendations

This study obtains emission factors for shared mobility services (one-way and round-trip carsharing, ridehailing, and bikesharing) within Metro Vancouver. Further, the impacts of mode displacement are captured in terms of GHG emissions for each shared mobility mode. Except for ridehailing, all other shared mobility modes can achieve emission reductions. Although the round-trip carsharing system on average has less efficient vehicles and more kilometers are traveled within round-trip carsharing vehicles compared to the one-way system, the general travel behavior of round-trip carsharing users is more environment friendly. However, this finding needs to be validated with further research that captures mode choice and mode displacement behavior of carsharing users within the context of Metro Vancouver. To achieve higher emission savings by one-way and round-trip carsharing systems, they can benefit from cleaner fuels (such as ZEVs), more

efficient cars, an optimal rebalancing process, and higher occupancy levels. Per user, emission savings by bikesharing system is limited, however, 5% of Vancouver residents are Mobi members (71). Thus, on the system level (based on Table 18), users can save 351 metric tons CO<sub>2</sub> eq. Ridehailing can cause unfavorable environmental impacts due to empty kilometers and mode displacement impacts. Pooled rides and more efficient vehicles (as well as ZEVs) can offset such impacts to a degree. Integration of ridehailing services into the transit network can be also deemed as a solution to reduce their emissions by increasing transit usage in areas with lower transit ridership (72). It is worth noting that these solutions should be assessed in a more exhaustive framework that accounts for other impacts of shared mobility services such as congestion, accessibility, equity, etc.

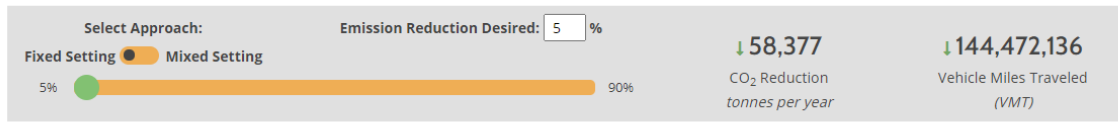
One of the applications of this study is to devise a tool that guides authorities with decision-making regarding the expansion of shared mobility services. Shared Mobility Benefits Calculator<sup>7</sup> is an example of such a tool, developed for the American context. Using Washington as the selected city (due to similar modal breakdown to Metro Vancouver, see Figure 10) to reduce emissions by 5%, the tool delivers a set of shared mobility options that can inform investment plans (Figure 13). The findings of this study are specific to Metro Vancouver and can be extended to potential emission reductions on the system level and similarly guide authorities to invest in shared mobility services. Another application of this research is to inform travelers to make environmentally aware decisions with respect to their mode choice. Using the emissions factors calibrated in this study, we can estimate emissions from each mode and include that in trip planning applications. For instance, a trip from UBC campus to Canada Place by different modes of transportation can be translated into emissions generated (Table 19). This application can be enhanced by providing specific vehicle/trip characteristics (such as fuel emission rates of the private car or occupancy levels of the ridehailing vehicle) and real-time travel time information (for example, added distance in congestion) to obtain more realistic results. Tailoring the application to account for user preferences can furthermore increase users' adoption (for example, travel times can be penalized on routes with heavy traffic for cyclists or be reduced on routes with less exposure to pollution for people with such preferences). Table 19 indicates that the least polluting trip is the one undertaken via bus and bikesharing bike with a comparable travel time to car travel, while ridehailing trip generates the highest emissions if it is made only by one passenger in the car.

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<sup>7</sup> available at <https://learn.sharedusemobilitycenter.org/benefitcalculator/>



### Set Overall Emissions Reduction by Mode



### Reductions by Transit and Shared Mobility

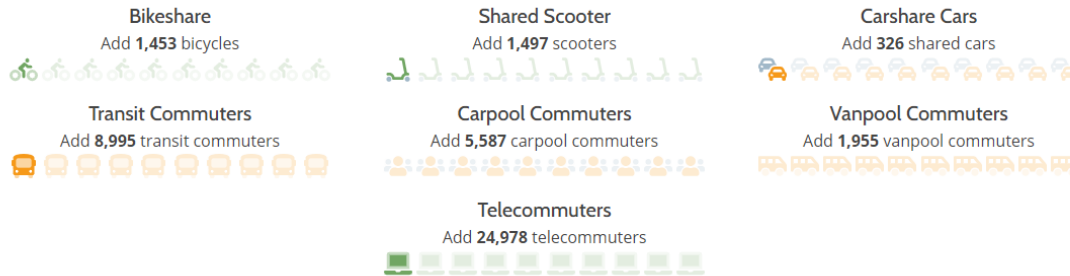


Figure 13 set of shared mobility options to target a 5% reduction in GHG emissions

Table 19 Accounting for emissions in trip planning (example trip with origin: UBC campus and destination: Canada Place)

DISTANCE TRAVELLED BY MODE	EMISSIONS (KG CO <sub>2</sub> EQ)	TRAVEL TIMES (NON-PEAK HOUR) <sup>A</sup>
12.9 km by passenger car via W16 <sup>th</sup> Ave	2.63	24 minutes
12.9 km by Evo via W16 <sup>th</sup> Ave	1.47	24 minutes
12.9 km by Ridehailing	3.87	24 minutes
1.3 km walking and 12.7 km by bus 004	1.29	55 minutes
1 km walking and 10.2 km by bus 025 and 4 km by Canada Line	1.04	1 hour and 2 minutes
1km walking, 7.3 km by bus 033 and 4.8 km by Mobi	0.76	48 minutes

a. distances and travel times are estimated by Google Maps

The weighted transit emission factor used in the mode displacement and mode choice impacts can be further improved by accounting for PKTs within various transit modes. Furthermore, in terms of mode displacement impact, an exhaustive survey is suggested to be conducted to capture all aspects of change in travel behavior (mode-displaced, trip-induced, km-displaced, km-induced, reduced VKT, and sold/avoided vehicles). With regards to mode-displaced, the survey is recommended to inquire about specific transit modes to account for the different emission factors by each mode (for example, bus vs rail). Using such a survey, the assumption of 1:1 mode-distance relationship can be improved by considering km displaced rather than mode displaced. Moreover, the survey would enable us to test the potential causal relationship between reduced VKT (as well as vehicle ownership levels) and the adoption of shared mobility services, so inference about environmental impacts due to mode displacement becomes more robust. On a broader scale, travel diary can be enhanced by including shared mobility modes within the set of transportation

options and ask respondents to report their usage behavior. All the shared mobility services are recommended to be requested to provide data to the public sector (e.g., aggregate data (system-level) about fleet fuel efficiency and disaggregate data (trip/ride-level) on deadheading, rebalancing, trip distance, frequency of usage, characteristics of specific vehicle used, and occupancy levels). The integration of such data within travel diary empowers analysts to draw more realistic conclusions.

Findings of this research, particularly with respect to mode choice and mode displacement can be validated by future research that collects context-specific information on adoption and usage rates of various types of shared mobility services along with mode choice and mode displacement behavior of users. Particularly for more recent shared mobility services (such as e-scooters and ridehailing) whose impacts are less known and documented, a future study can identify potential population segments that are more likely to adopt such services. Furthermore, scenarios can be designed and evaluated with respect to varying spatio-temporal usage of such services by potential adopters and eventually their environmental impacts can be gauged on the system level.

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