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Modelling Electric Vehicle Use in Carsharing Fleet

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Modelling Electric Vehicle Use in Carsharing Fleet

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ABSTRACT

In many countries, urban transportation systems strive to serve travel demand. With increasing mobility needs and climate change concerns, carsharing, among other solutions, can be a serious alternative to private car. With current environmental concerns related to greenhouse gas emissions, carsharing operators have started to introduce electric vehicles into their fleet. The electrification of carsharing is challenging, for operators and users. In this paper, we examine the impact of weather conditions (temperature) and range anxiety on the adoption and use of electric shared cars in comparison with conventional cars.

background/ intro research Testing

The adoption of electric vehicles in the context of carsharing is simulated using the Multi-Agent Transport Simulation platform (MATSim). MATSim can simulate the rental of two types of shared vehicles (electric and conventional) under different conditions (temperature and range anxiety). Agents choose to use a vehicle type according to their trip constraints and vehicle availability. The impact of temperature and range anxiety on the use of shared vehicles can be analyzed in the distance and time of use of vehicles.

methodology

In the case of Montreal, results show that the potential negative impact of temperature and range anxiety on carsharing demand and use is limited. Findings of this research can be of interest to carsharing operators. These operators can plan the deployment of cars likely to be used on the territory concerned according to users needs and locations of charging stations to be implemented in carsharing stations.

results/ relevancy

Keywords: Carsharing, Electric vehicles, Range anxiety, Temperature, Battery, Agent-based modelling.

INTRODUCTION

With increasing urban population (*1*), urban transportation systems strive to serve travel demand. However, in various metropolitan areas around the world, transportation networks are congested (*2*) or unable to provide acceptable level of services for all users. In order to meet the growing need for mobility, new and renewed travel modes have emerged. Carsharing is one of these solutions. In 2018, the number of carsharing members in North-America was estimated to more than 2 million users served by nearly 24,000 shared vehicles (*3*).

Carsharing is a transportation system based on shared cars that can be rented, often for short periods of time, by members. By offering a cheaper alternative to the private car, carsharing meets the need for flexible and personalized possibilities for automobility, without the burden incurred by the private car (capital and operating costs, parking, maintenance, etc.). Carsharing has been reported to reduce car ownership (*4*); (*5*), by either motivating car owners to forgo their cars, postpone the purchase decision, or even cancel it. Carsharing has also been reported to reduce travel mileage and air pollution (*5*) and to foster transit and active modes use (*6*).

In view of these benefits, various cities have engaged in promoting and adopting carsharing (*4*), (*5*). First carsharing vehicles were mostly based on the internal combustion engine technology (ICEV). However, with the technological progress made in alternative-fuel engines and rising concerns about pollution and climate change, various carsharing operators opted for mixed fleets. In this context, battery-electric vehicles (BEVs or simply EVs) were gradually offered for rent in these systems.

The introduction of EVs poses unprecedented challenges to carsharing operators and their clients. In comparison with ICEVs, EVs have a limited driving range (*7*) and higher capital costs (*8*). The charging time of EV batteries often takes several hours during which the EV is out of service. The efficiency of EVs is sensitive to ambient temperature conditions. Low or high temperatures can drastically reduce the range of batteries and their life-cycle (*9*). From a client perspective, the use of EVs can, in some cases and for some users, be a source of anxiety, that is *the fear of becoming stranded* (*10*) due to battery depletion. On the other hand, EVs require less maintenance costs than ICEVs (*8*), emit less noise and pollutants in the air, and offer a new eco-friendly driving experience.

Given the opportunities and the challenges to introduce EVs in carsharing, it is critical to understand and to assess the opportunity of carsharing electrification. In this research, we evaluate the opportunity of introducing EVs in the carsharing system of Montreal, Canada. We use a transportation agent-based model (ABM) that simulates the competition of main travel modes for travel demand: private car, transit, bike, walk, and carsharing. We simulates how the modes available attract different individuals according to their needs under different scenarios regarding anxiety of clients and weather conditions. Both these parameters, i.e. range anxiety and temperature, are key in the success of the electrification of carsharing.

The next section discusses previous work on carsharing with a focus on electric carsharing. The methodology section describes the data and the methodology of this research. Simulation results are presented in the result section and these results are discussed right after. Policy implications of this research and future work are provided in the last section.

BACKGROUND

Most previous studies on the modelling of e-carsharing have addressed this question from an optimization point of view ((*11*), (*12*)) or by isolating the carsharing system from other competing travel modes, i.e. exogenous travel demand (*13*). Studies that address the question of carsharing electrification in a comprehensive manner that account for competing travel modes and adverse operating conditions, i.e. range anxiety or ambient temperature, are scarce (*14*).

Carsharing systems have come with various positive impacts. Among These impacts, one can find assuring the access to cars for households with lower income or even the decrease of pollution from private vehicles. The latest impact has been increased by the integration of EVs and hybrid cars in carsharing fleets. In fact, the first use of EVs in carsharing services goes back to 1970s (*15*). Nowadays, several carsharing operators are using EVs in their fleets ((*16*), (*17*), (*18*)). Since the use of EVs increased, modelling them in different cases is the subject of several papers ((*19*), (*20*), (*21*)). More specifically, in carsharing systems, authors have been dealing with re-positioning problem (22) and location planning depending on demand (*23*), on one hand. One the other hand, other works focuses on the free-floating carsharing system and the use of EVs and hybrid cars ((*24*), (*25*)). Paper (*25*) focuses on the probability, using a binomial logit model, to use electric vehicle or hybrid cars instead of classical cars when users have the choice. Another paper compared EVs and conventional cars in the context of carsharing systems together with the optimization of carsharing fleet size (*26*).

Past studies of EVs in carshar[ing]

From the perspective of modelling EVs in carsharing systems (*27*), an effort has been made to determine operational characteristics using a simulation tool covering EVs characteristics and those of carsharing systems. In the same vein, (*13*) presented a framework allowing the management of battery EV utilization and the operational decisions related to the use of EVs. Another framework has been presented in (*28*) aiming to highlight the impact of EVs on carsharing service. Other researchers have focused on simulating carsharing systems including EVs in their fleet using ABM. (*29*) used SimMobility, an ABM, to test different re-balancing policies for autonomous EVs offered in one-way carsharing service. (*30*) models carsharing, bike-sharing and electric bikes in the ABM mobiTopp. (*31*) works on a vehicle assignment method specifically in the case of one-way carsharing service so the ABM simulation framework allocates cars to users in order to maximize battery use. A summary of the mentioned studies is presented in table 1, where the objective and the approach are stated.

Past EV models different focus scenarios

As shown in table 1, most of the studies addressed a specific issue and those who considered a larger implementation of EVs in carsharing systems including the availability of other modes are those adding autonomous vehicles to carsharing fleet (*32*) (*33*). The work in (*34*) describe the usage of non autonomous EVs in carsharing system using simulations in MATSim. However, the current literature lacks models that can explain the way EVs are included in the fleet and the impact of the usage of EVs on the performance of carsharing in competition with other modes. This paper aims to present the methodology to introduce EVs in carsharing fleet as well as the impact of temperature and range anxiety on renting electric cars. This impact of such modelling and inclusion is presented through simulations results using MATSim. The following section presents methods ans materials used to run the various simulations.

this table is helpf-l

Study	Objective	Approach
Clemente et al. (28)	Balancing vehicle supply and demand	Timed petri net and simulation case study
Bruglieri et al. (21)	Maximizing the number of served requests	Optimization
Weikl and Bogenberger (35)	Relocation of electric and conventional vehicles in Free-floating service	Mesoscopic approach
Wang et al. (36)	Relocation user-based of one-way electric carsharing system	Parameter sensitivity analysis
Li et al. (32)	Integration of Autonomous electric vehicles in carsharing system	Agent-based modelling
Zhao et al. (37)	Re-balancing stations having electric vehicles	Mixed integer linear programming
Kang et al. (33)	Integration of autonomous vehicles in carsharing services	Design framework for the optimization of fleet size and assignment schedule for stations
Bi et al. (38)	Optimization of the profitability for the operator and the usage of the system	Survival analysis
Mamalis et al. (39)	Optimization of vehicles location and the impact of a certain price on the electric grid	Queuing model
Yoon et al. (26)	Optimization of carsharing system given a demand and a fleet	Monte Carlo Simulation
Lu et al. (23)	Relocation and charging actions in a carsharing station having electric vehicles	Dynamic decision making approach
Jacquillat and Zoepf (24)	The use of electric vehicles and hybrid vehicles in carsharing system	Mixed Integer Programming optimization
Wielinski et al. (25)	The probability of choosing electric vehicle from carsharing fleet	Binomial logit model
Xu et al. (22)	Optimization of the profit of one-way carsharing operators	Mixed-integer non-linear and nonconvex programming model
Illgen and Höck (27)	The examination of the operation of electric vehicles in urban car sharing networks	Discrete event simulation tool
Hu et al. (40)	The impact of the battery level on the performance of carsharing system	Discrete event-based simulation
Zhang et al. (31)	Allocate cars to users to maximize the use of vehicles batteries	Agent-based discrete event simulation framework

TABLE 1: Summary of previous studies on the use of EVs in carsharing system

METHODS AND MATERIALS

To simulate and assess the carsharing electrification scenario, we use MATSim, a multi-agent transportation model (*41*). This framework offers the possibility to simulate and evaluate the adoption and the use of various transportation modes, including: transit, private cars, bikes, and walk, demand-responsive transportation, or carsharing. MATSim is also capable of simulating EVs and their interactions with dynamic travel demand and charging constraints.

about MATSim

In this paper, we introduce the use of shared electric cars in Montreal to assess their impacts on the adoption and use of carsharing in Montreal. Currently, the carsharing system of Montreal has nearly 70,500 members that perform 2,596,500 trips per year. Most of these trips are conducted using Hybrid and ICEV shared vehicles. The share of EVs in the Communauto fleet is less than 10% and serves less than 8%. To better understand the potential impact of the carsharing electrification scenario, we define a hypothetical scenario where carsharing members are 10% more than the actual demand. We also suppose that the share of EVs is increased to 50% of the shared fleet. In the rest of this paper, this scenario is the reference one.

scenario specifics, assumption explained

Methods

MATSim

MATSim is an open-source multi-agent transportation simulation framework (*41*). It has been under constant development by TU Berlin and ETH Zurich for more than 15 years. Currently, MATSim is used and supported by an growing transportation community and it is one of the most leading and used transportation ABM. As any ABM, MATSim models the actions and interactions of agents in response to internal and external stimuli. MATSim agents are driven by an utility maximization objective. Agents compete for mobility resources (network capacity, transportation means, etc.) to engage in their daily activities and minimize unproductive time. Given this basic behavioural rule, MATSim is capable of simulating emergent phenomena in the complex urban system. In MATSim, agents learn to make the best decisions to perform their daily activities. Like a co-evolutionary process, agents can change their travel mode, departure hours, and routes, throughout simulation iterations, to find the optimal daily plan. After a sufficient number of iterations, agents can no longer significantly increase their utility and reach an equilibrium-like state.

good explanation for this choice of tool

Electric carsharing (e-carsharing) is one of the various travel modes that can be simulated by MATSim. The simulation of e-carsharing requires the inclusion and the management, in space and time, of shared EVs and dynamic rental requests. In several respects, such a simulation is challenging as it calls for: (1) the simulation of carsharing as a travel mode that necessitates dynamic management of the interaction between travel demand (incoming requests) and supply (availability of cars in space and time); (2) the use of electric cars that require the management of their charging and discharging in relation with network conditions (congestion) and charging infrastructure (availability); (3) the competition between carsharing and conventional travel modes. In this context, the agent-based approach of MATSim is appropriate as it allows to track, in space and time, individual agents and vehicles, the availability of shared cars and the state of charge (SOC) of EVs. The possibility to simulate the competition of carsharing with other travel modes (endogenous travel demand) is also another noteworthy contribution of this framework.

complexity of EV carsharing modeling

Electric carsharing

The use of shared cars requires the possession of a carsharing membership. This membership can give access to three different carsharing services:

1. One-way shared cars
2. Two-way shared cars, i.e. round-trip cars
3. Free-floating shared cars

One-way cars can be picked up at a station and dropped-off at a different one. Two-way cars need to be returned to the same pick-up station. Free-floating cars can be picked up and dropped off anywhere inside a given service area. In this paper, only station-based electric shared cars are considered. For operational reasons, operating shared EVs is likely to be less challenging than free-floating EVs. Free-floating cars are therefore not simulated in this paper.

fair assumption?

Station-based shared vehicles can be of two types: ICEV or EV. We assume that both types have equal chances to be rented, everything else being equal. When an agent chooses to rent an EV, it requests the one with most charged battery. Moreover, prior to the reservation of an EV, agents check the available SOC of the battery and compare it with their projected travel needs. The EV is rented only if its SOC covers the a priori required energy.

We assume that carsharing operates on the basis of a membership business plan where members pay a monthly fee regardless of their use of the service to benefit from advantageous rental fees. The membership business plan is commonly adopted by the carsharing industry (*42*). For the a carsharing member, the marginal cost of a carsharing trip is often proportional to rental time or to trip distance or both.

why this assumption over other common ones?

Shared EVs are subject to discharging and recharging constraints. EVs incur discharging while driving due to: (1) energy consumption of the engine and (2) auxiliary energy consumption by on-board gadgets (air heating and cooling, lights, etc.) ((*43*), (*44*)). The driving energy depends primarily on the characteristics of the vehicle: its mass, aerodynamic shape, and engine efficiency. Auxiliary energy consumption depends mainly on temperature. With low or high temperatures, the range of the EV battery can significantly be reduced, especially due to air heating and cooling. In these situations, the driving range of shared EVs decreases while their number of charging cycles and out-of-service duration increase.

In this research, we assume that shared EVs are only allowed to be charged at carsharing stations. After each rental, clients are required to plug in the rented EV to the charging station. Each parking lot is equipped with a second generation charging station delivering a power of 7.5 kW. We also assume that shared EVs are not open for reservation when their battery state of charge (SOC) is below a minimum SOC threshold of 5%. This minimum threshold is required for routine operations, like relocation or maintenance, and to reduce the risk of empty battery.

is this common? what makes it a good assumption?

Range Anxiety

Range anxiety is defined here as the fear and the stress of being stranded due to a completely depleted EV battery ((*10*), (*45*)). From a modelling perspective, this negative affect is translated into two parameters:

- Preference for a safety or a comfort buffer when renting a car ((*45*), (*46*), (*47*))
- Experience of stress when the SOC is very low (*48*)

For a car trip that requires a minimum state of charge (SOC) of the battery SOC_{min}, research suggests that car drivers have a preference battery range SOC_{pref} that is greater than the minimum range. This is also true for ICEVs, but the safety buffer is even more significant for EVs as recharging requires time and special infrastructure. Research also suggests that preference for a safety buffer is especially dominant among inexperienced EV users ((*49*), (*45*)). The comfort or safety buffer is the relative energy surplus, i.e. $\frac{SOC_{pref}}{SOC_{min}} - 1$, needed by EV users to avoid stressful situations or adaptation strategies of their mobility or activity plans. We assume that carsharing members have a constant comfort buffer of 30% a bit more than presented by (*45*) in the more general case of EV drivers. add explanation for this assumption

The second implication of range anxiety relates to the negative affect drivers can experience when the SOC drops below a reference threshold SOC_{stress} while driving. This negative experience is translated into a penalty of the agent's utility. The duration spent driving the shared EV with a SOC less than SOC_{stress} is assumed more stressful than driving under normal conditions. Consequently, this duration has a higher opportunity cost of time than the rest of driving time.

Materials

MATSim input data

As most ABM, MATSim relies on a synthetic population of the study area. This population reproduces the main observed: (1) socio-demographic characteristics of the population, like age, gender, or household size; (2) travel habits, like the number of trips per day, or car ownership; (3) activity habits, like the location of their primary and secondary activities and their duration.

For the definition of the synthetic population, we use four data sources: household travel survey (HTS) (*50*), census data (*51*), car ownership data (*52*), and housing data (*53*). Census data are used to compute expansion factors for HTS sample records. For this, we use the Hierarchical Iterative Proportional Updating (HIPU) at the census tract and dissemination area ((*54*), (*55*)). Housing data are used to locate the daily activities of synthetic agents, like work, education, or shopping.

To engage in their daily activities, agents need to travel using a transportation mode. All conventional transportation modes are considered: private car, public transit, bike, and walk, in addition to carsharing.

Carsharing input data

The simulation of carsharing requires data on the supply and demand for carsharing. Carsharing supply includes the location, the number of carsharing stations, and their number and type of vehicles. Carsharing demand is dependent on carsharing membership.

Carsharing membership   The accessibility of carsharing stations is key to the possession of a carsharing membership (*56*). In this paper, all agents living near a carsharing station, i.e. within 500 meters, and holding a driving licence are given a carsharing membership. Members of the carsharing system are assumed to not have access to the private car. Any agent with a valid driving licence can apply for carsharing membership. The marginal cost of a carsharing trip is 0.30$/minute. As in the case of the private car or transit, the carsharing membership fee is considered as a sunk cost that is not included in the daily utility or mode choice decision of carsharing members. assumptions?

Carsharing supply   The location of carsharing stations is based on the density of car trips in the Island of Montreal (Figure 1). One-way an two-way carsharing stations are located in cells producing more than 60 daily car trips. The number of vehicles in these stations is proportional to the number of trips produced by the corresponding cell. For example, a cell producing 60 car trips per day, is assigned one carsharing station with two one-way cars and two round-trip cars. Half of these cars are EVs with battery capacity of 30 kWh and the rest ICEVs.

FIGURE 1: Carsharing stations locations in Montreal island

Study area   By its population, the Census Metropolitan Area (CMA) of Montreal, hereafter referred to as Montreal, is the second largest CMA in Canada and the first in the province of Quebec. It is home to 4 million inhabitants. Half of these live on the island of Montreal (figure 2).

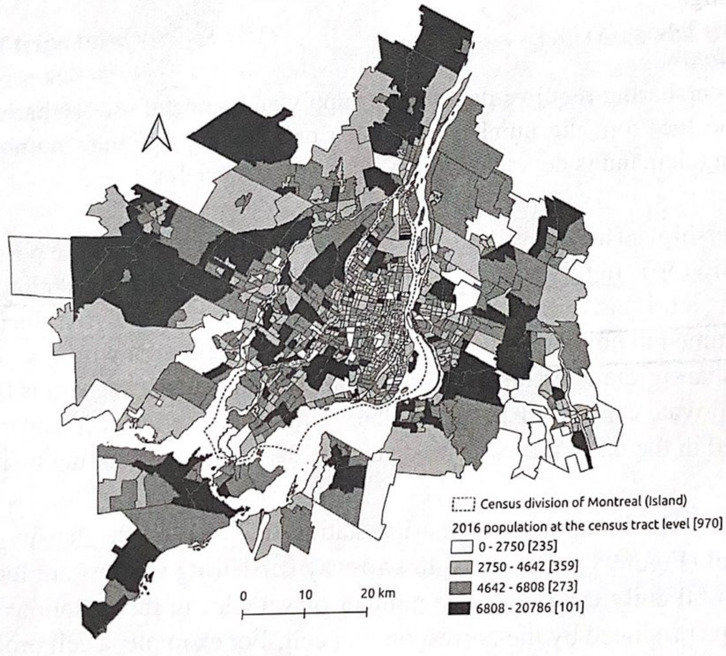


FIGURE 2: Study area of the CMA of Montreal and it population in 2016

good maps

Case study

Montreal has a continental weather with very cold winters. The minimum daily average temperature of January is $-10°C$ and the average minimum is $-14°C$, whereas the ideal temperature range of EV batteries is 15°C to 25°C (*57*). Winter weather conditions of Montreal can be challenging to the operation of EVs as there batteries are sensitive towards ambient temperatures and their driving range can drastically be reduced, especially when air heating is activated (*58*). The impact of this reduction can magnified by range anxiety. In this context, our case study evaluates the joint impact of range anxiety and ambient temperature on the adoption and use of carsharing in general and shared EVs in particular. To carry out this study, 4 scenarios are performed (table 2).

	No Range Anxiety	30% of Range Anxiety
Temperature -15 degrees	Scenario 1	Scenario 2
Temperature +15 degrees	Scenario 3	Scenario 4

TABLE 2: Electric carsharing scenarios

RESULTS

We investigate four carsharing scenarios with a mixed fleet (EV and ICEV cars) and varying conditions of temperature and range anxiety. The main contribution of this study is to highlight the impact of these conditions on the use of these two shared vehicle types in addition to distances and times of trips performed using these two types of vehicles.

Carsharing in terms of trips time and distance

Depending on temperature and range anxiety levels, the use in terms of distance and travel time of electric and conventional shared vehicles in the four scenarios by hours of day can change. In each simulation scenario, we highlight the departure time and the arrival time of various trips. The following figures show the distribution of combustion vehicles (ICEV in blue bubbles) and electric vehicles (EV in orange bubbles) according to the duration of trips during the day. Trips distance is represented by the size of the bubbles.

In figure 3, we note that longer trips are more likely to be performed by ICEV shared vehicles (Blue points) than EVs (Orange points). Short trips are made equally with both vehicle types. Results also show that ICEVs are more likely to be used at the end of the day (16h - 19h) than EVs. This can mean that the decrease in the level of the batteries, intensified with the low temperature during the day, without EVs being recharged during the day, pushes users to choose an ICEV to make their trips. The size of points representing the distance travelled by rented vehicles, one can notice through the bullet size that the greatest distances are travelled with ICEV cars in comparison to smaller distances travelled with EVs.

Range anxiety is found to limit travel times and distances of trips made with shared EVs (figure 4). The distances travelled with EVs are less important than those travelled with EVs when anxiety is not modelled together with a low temperature. In this case, trips made with ICEVs have longer travel times and distances regarding those performed by EVs.

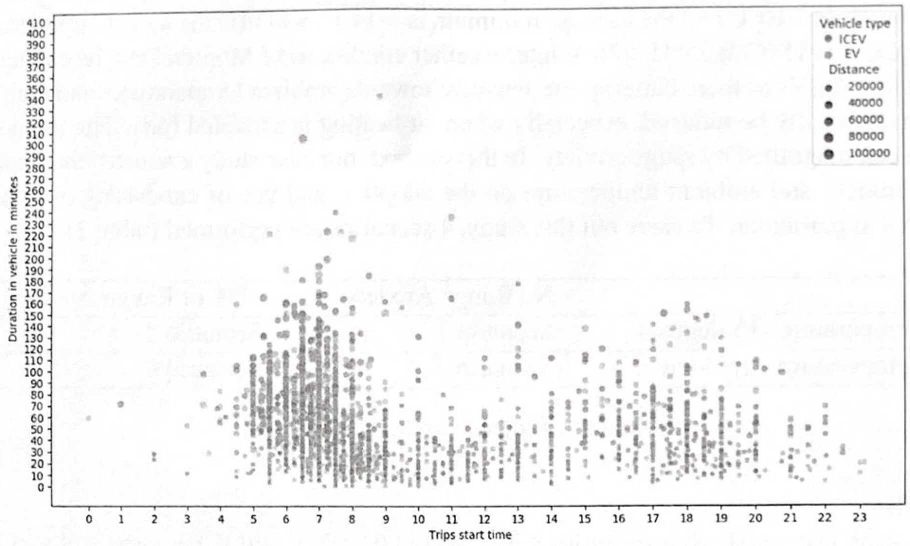


FIGURE 3: Distribution of travel time and travel distance by rental start time for scenario 1

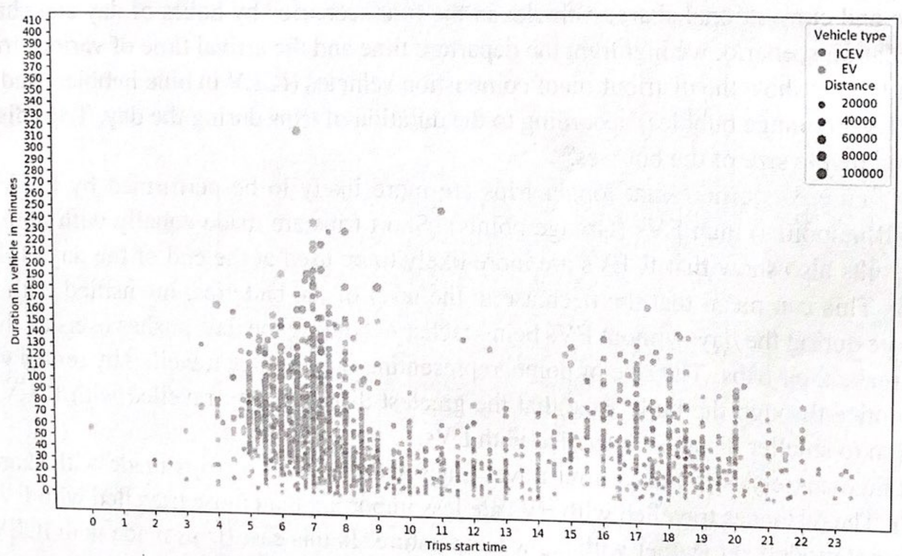


FIGURE 4: Distribution of travel time and travel distance by rental start time for scenario 2

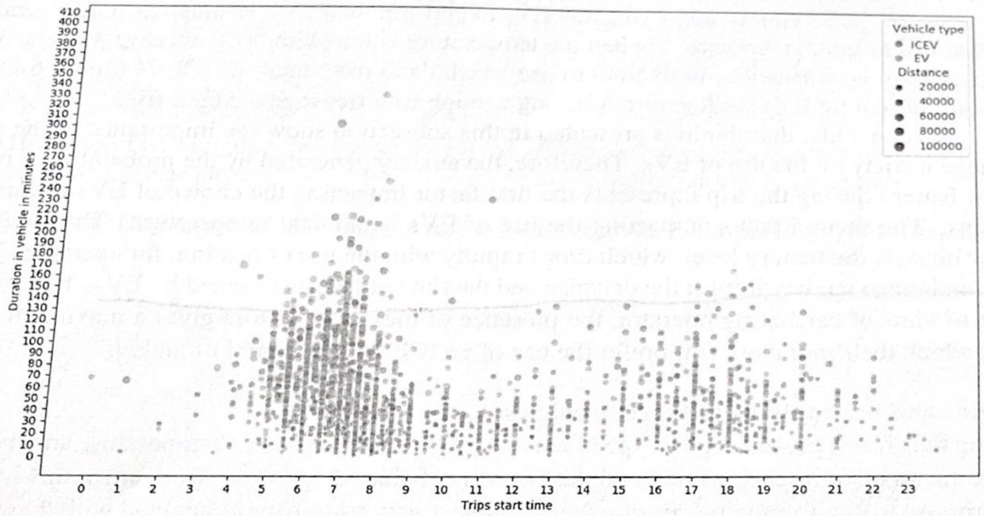
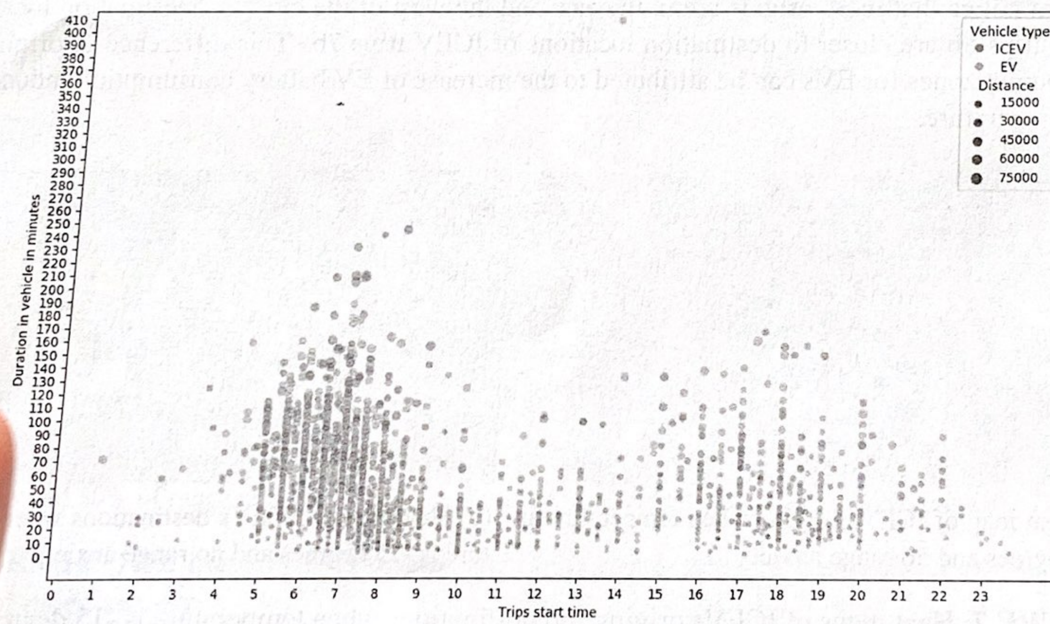
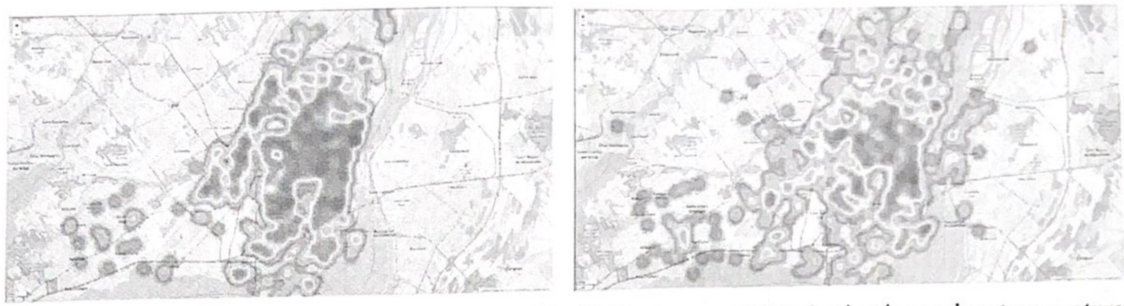


FIGURE 5: Distribution of travel time and travel distance by rental start time for scenario 3



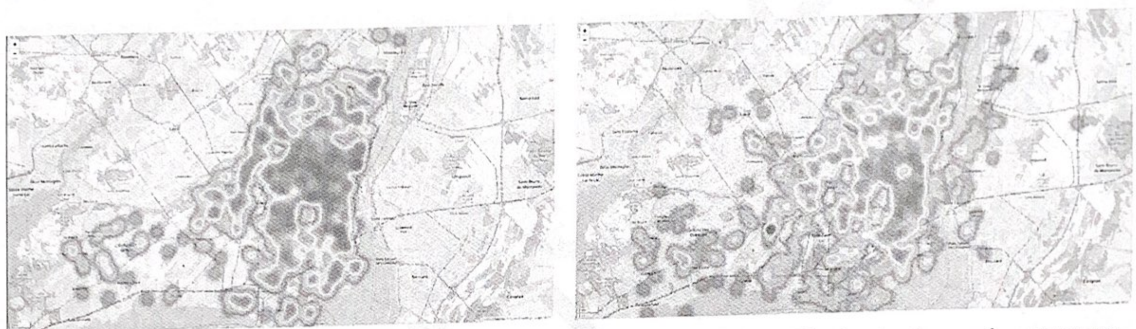
GURE 6: Distribution of travel time and travel distance by rental start time for scenario 4



(a) Heat map of EVs origins when temperature is -15 degrees and no range anxiety

(b) Heat map of EVs destinations when temperature is -15 degrees and no range anxiety

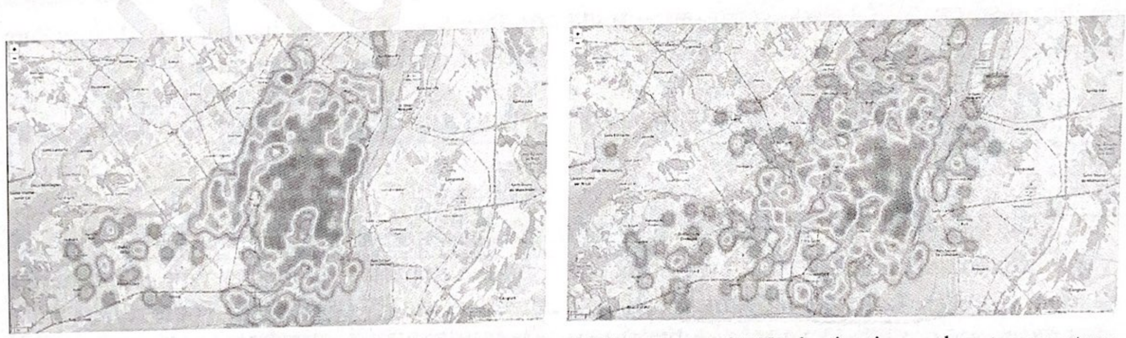
FIGURE 8: Heat maps of EVs origins and destinations when temperature is -15 degrees and no range anxiety



(a) Heat map of ICEVs origins when temperature is -15 degrees and 30% of range anxiety

(b) Heat map of ICEVs destinations when temperature is -15 degrees and 30% of range anxiety

FIGURE 9: Heat maps of ICEVs origins and destinations when temperature is -15 degrees and 30% of range anxiety

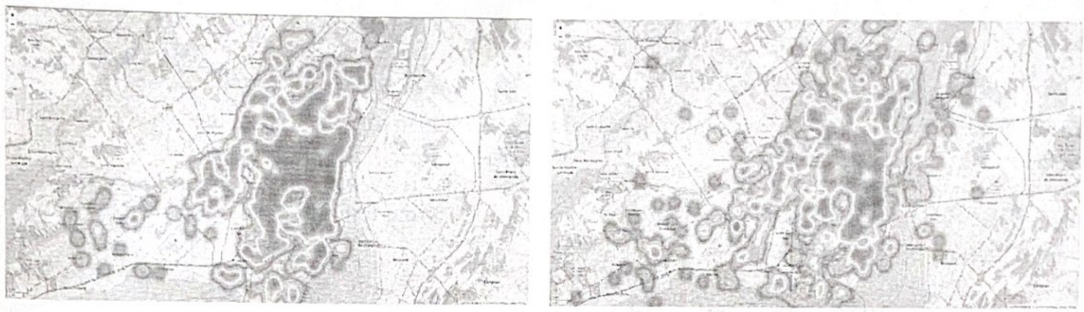


(a) Heat map of EVs origins when temperature is -15 degrees and 30% of range anxiety

(b) Heat map of EVs destinations when temperature is -15 degrees and 30% of range anxiety

FIGURE 10: Heat maps of EVs origins and destinations when temperature is -15 degrees and 30% of range anxiety

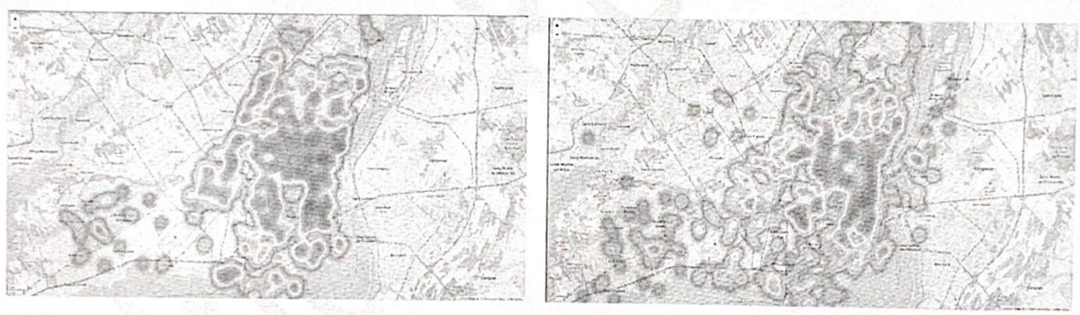
In figures 9 and 10, one can notice that EVs are less used than ICEVs in carsharing (figures 9a, 10a). Regarding destinations of shared vehicles (figure 9b), destination zone for trips using ICEVs is wider than that of trips using EVs 10b. Destinations of trips using EVs are more centred near carsharing stations equipped with charging stations due to the low temperature (-15 degrees) and the range anxiety of 30%.



(a) Heat map of ICEVs origins when temperature is +15 degrees and no range anxiety

(b) Heat map of ICEVs destinations when temperature is +15 degrees and no range anxiety

FIGURE 11: Heat maps of ICEVs origins and destinations when temperature is +15 degrees and no range anxiety

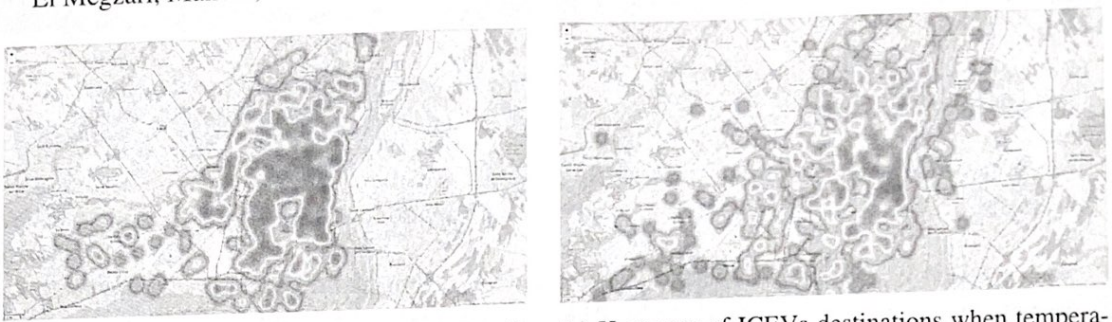


(a) Heat map of EVs origins when temperature is +15 degrees and no range anxiety

(b) Heat map of EVs destinations when temperature is +15 degrees and no range anxiety

FIGURE 12: Heat maps of EVs origins and destinations when temperature is +15 degrees and no range anxiety

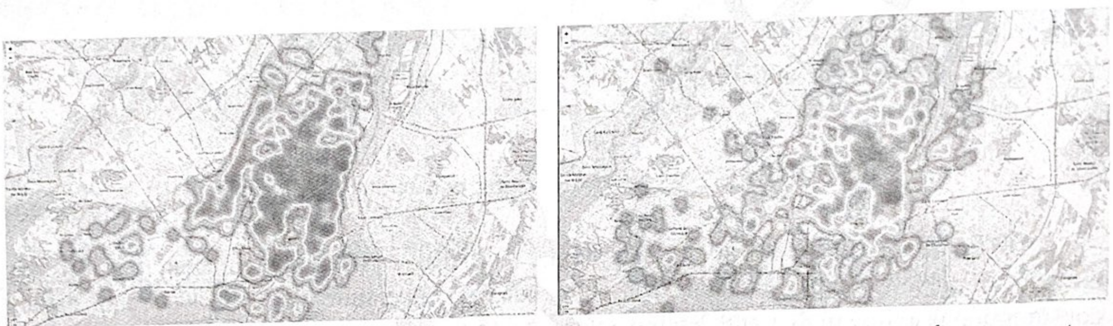
In figures 11 and 12, origin and destination zones of trips using EVs and ICEVs are not very different. This means that carsharing users are not impacted by the car type in carsharing station. Users are targeting the same location whether they use EVs or ICEVs. These results mean that a temperature of +15 degrees and the nonexistence of anxiety help carsharing users to choose equally between both car types : EV and ICEV.



(a) Heat map of ICEVs origins when temperature is +15 degrees and 30% of range anxiety

(b) Heat map of ICEVs destinations when temperature is +15 degrees and 30% of range anxiety

FIGURE 13: Heat maps of ICEVs origins and destinations when temperature is +15 degrees and 30% of range anxiety



(a) Heat map of EVS origins when temperature is +15 degrees and 30% of range anxiety

(b) Heat map of EVs destinations when temperature is +15 degrees and 30% of range anxiety

FIGURE 14: Heat maps of EVs origins and destinations when temperature is +15 degrees and 30% of range anxiety

In figures 13 and 14, origin zone and destination zones in trips using EVs are more concentrated near carsharing stations. Origin and destination zones for ICEVs are more expanded than zones of origins and destinations of trips using EVs. This means that carsharing users are impacted by range anxiety. Their choice of car type in carsharing station is closely related to the ability of the battery state of charge to achieve the trip. These results mean that even if the temperature (+15 degrees) don't impact the battery consumption, 30% of range anxiety pushes carsharing users to choose ICEVs instead of EVs to achieve trips with longer distances.

EV battery use in carsharing

During their trips, carsharing EVs consume different levels of electricity depending on the scenario: 1374 Kwh when the temperature is -15 with 30% of anxiety, 1421 Kwh when the temperature is -15 without anxiety, 1430 Kwh when the temperature is +15 without anxiety and 1348 Kwh when the temperature is +15 with 30% anxiety. The objective of the figure 15 is to show the consumption of EVs in the four scenarios by time of day in order to point the differences in consumption depending on the temperature and range anxiety.

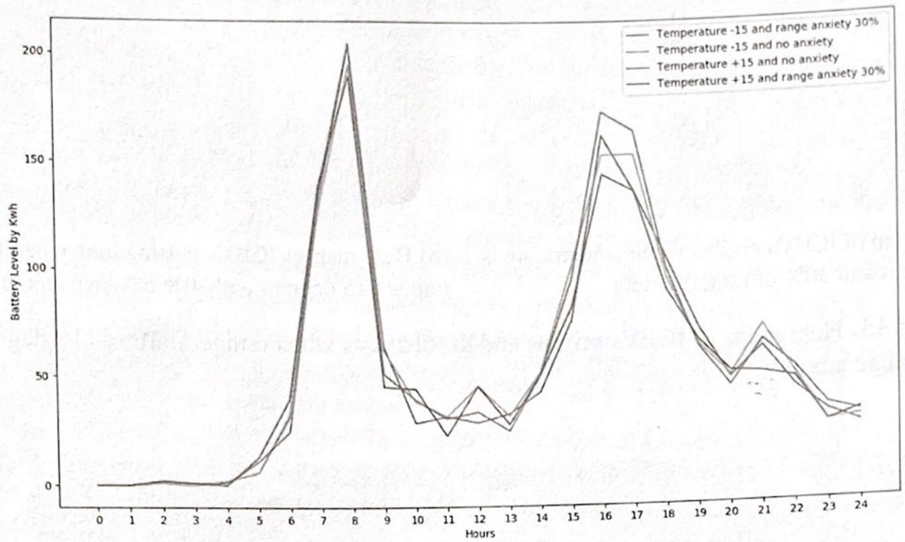


FIGURE 15: EVs energy consumption in the 4 scenarios

In figure 15, energy consumption is similar in both cases when the temperature is low. It is the same thing between the two other scenarios when the temperature is +15. However, the battery consumption is a little higher with a temperature of +15 than in scenarios simulating a temperature of -15. This result is due to the increase in the use of EVs with the increase in temperature contrary to what one might think, i.e., a higher consumption of energy when it is colder than when it is hotter.

DISCUSSION

Impact on carsharing user's decisions

In line with our working hypotheses, the results presented in the previous section confirm the significant impact of temperature and anxiety on the use of EVs in a carsharing system. Thus, according to these results, we can say that the temperature impacting the energy consumption of the batteries pushes users to consider the battery level when choosing the vehicle type to rent in carsharing stations. The second factor having an important impact on the choice of vehicle type is the range anxiety. This factor allows users to consider the ability of the battery level to complete the desired trip. Thus, ambient temperature has an impact on carsharing use. In low temperatures, shared EVs are less chosen than ICEVs. In moderate temperatures, both vehicles are used interchangeably, everything else being equal.

The choice of EVs is also motivated by the impact of temperature on the level of batteries. Lower temperatures cause cars to consume more energy than at higher temperatures.

So in addition to the user-based relocation effect on the adoption of EVs in carsharing system discussed in (*36*), carsharing operator can consider weather conditions (temperature), the apprehension that users have of renting EVs and the possibility of these types of vehicles to make trips without interruption.

The results show that distances and times of trips performed in carsharing with EVs are strongly impacted by the temperature and the apprehension of users regarding the state of charge to perform the desired trips. Thanks to maps of origins and destinations using carsharing cars, we were able to show that distances travelled with EVs in carsharing are less important than those travelled by ICEVs in the same condition of low temperature (-15 degrees) and 30% of range anxiety.

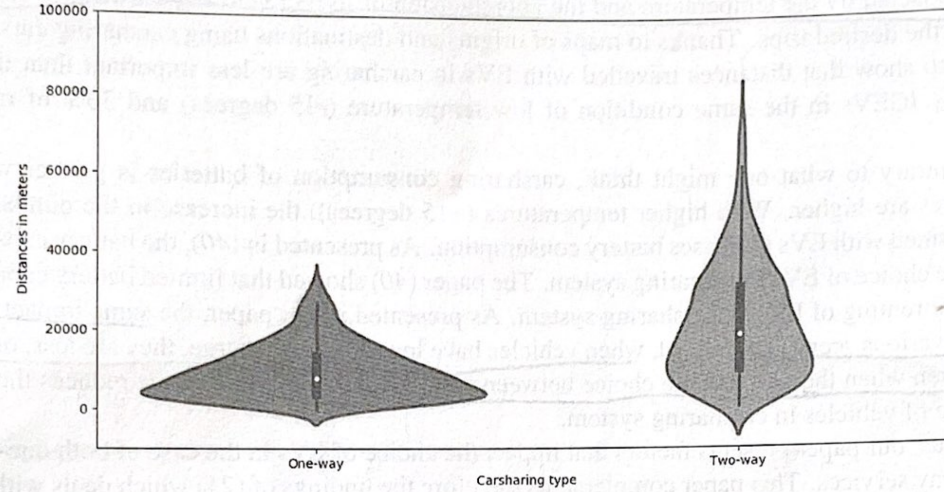
Contrary to what one might think, carsharing consumption of batteries is greater when temperatures are higher. With higher temperatures (+15 degrees), the increase in the number of trips performed with EVs increases battery consumption. As presented in (*40*), the battery capacity impacts the choice of EV in carsharing system. The paper (*40*) showed that limited battery capacity lowered the renting of EVs in carsharing system. As presented in our paper, the same impact was noticed in various scenarios. Indeed, when vehicles have lower state of charge, they are less, or not at all, chosen when the user has the choice between an EV and ICEV. This choice reduces the use of this type of vehicles in carsharing system.

Thus, our paper presents factors that impact the choice of EVs in the case of both one-way and two-way services. This paper complements therefore the findings of (*25*) which deals with the choice of electric and hybrid vehicles in the case of free-floating service in carsharing service in Montreal.

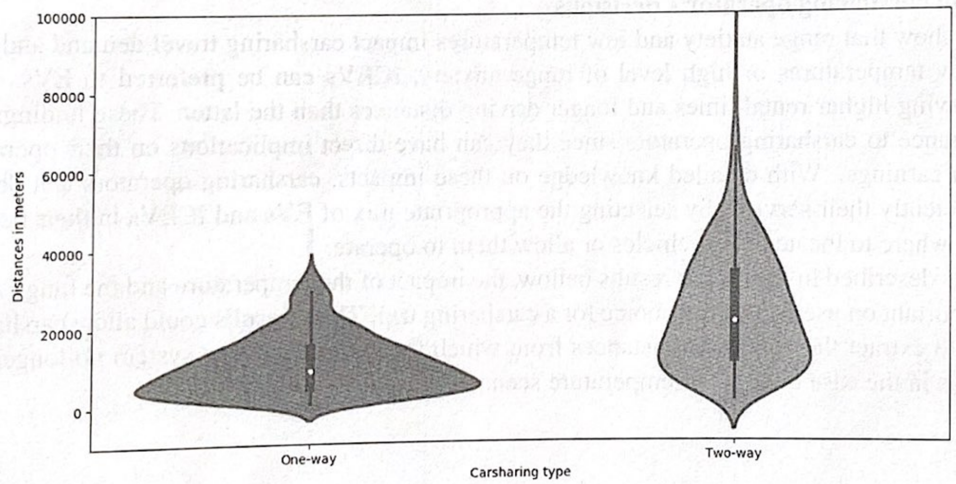
Impact on carsharing operator's decisions

Findings show that range anxiety and low temperatures impact carsharing travel demand and use. Under low temperatures or high level of range anxiety, ICEVs can be preferred to EVs. The former having higher rental times and longer driving distances than the latter. These findings are of importance to carsharing operators since they can have direct implications on their operating costs and earnings. With detailed knowledge on these impacts, carsharing operators can design more efficiently their services by selecting the appropriate mix of EVs and ICEVs in their fleet or choosing where to locate these vehicles or allow them to operate.

As described in scenario's results bellow, the impact of the temperature and the range anxiety is important on user's car type choice for a carsharing trip. These results could allow carsharing operator to extract the maximum distances from which the members of the system no longer use the EVs as in the case of the low temperature scenario with 30% anxiety.



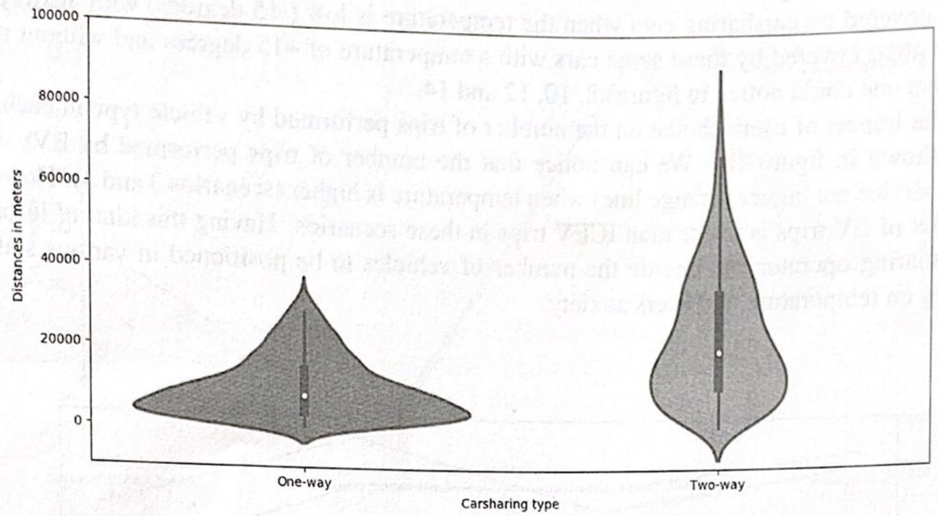
(a) Carsharing EVs trip distances in temperature of -15 degrees and no range anxiety



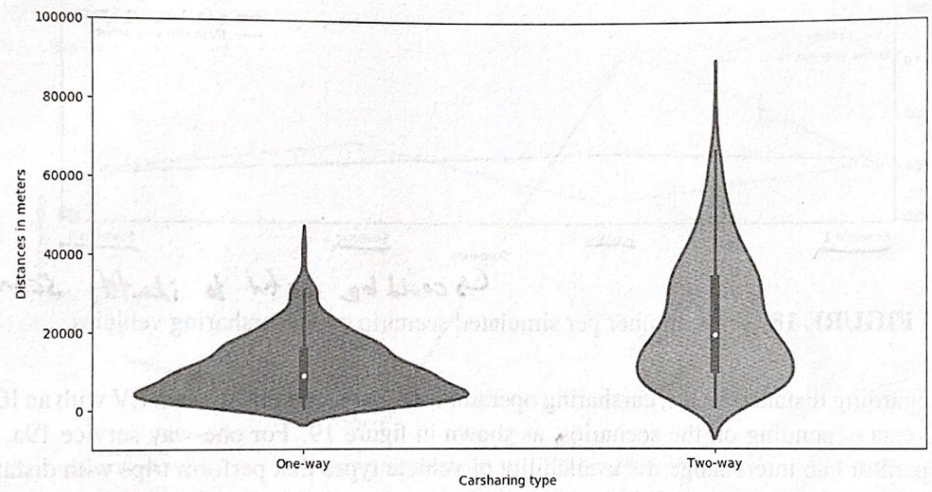
(b) Carsharing EVs trip in temperature of -15 degrees and 30% range anxiety

FIGURE 16: Carsharing EVs trip distances in temperature of -15 degrees

In figure 16, distances of trips made in carsharing with the one-way service is higher in the case where anxiety is not taken into account (an average of 17 km) than in the scenario with low temperature and a range anxiety of 30% (an average of 15 km).



(a) Carsharing EVs trip distances in temperature of +15 degrees and no range anxiety



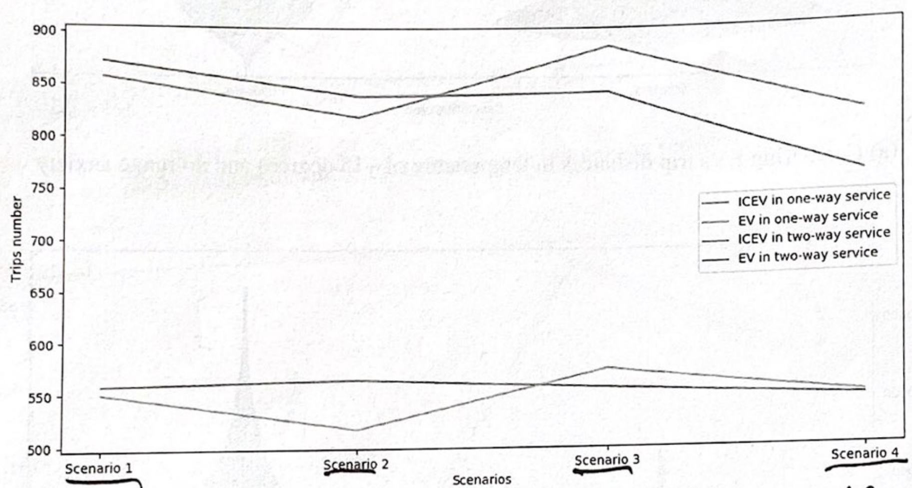
(b) Carsharing EVs trip distances in temperature of +15 degrees and 30% range anxiety

FIGURE 17: Carsharing EVs trip distances in temperature of +15 degrees good figures

As the case where the temperature is lower, in the figure 19, the distance of trips made in carsharing with the one-way service is higher in the case where anxiety is not taken into account (an average of 17.5 km) than in the scenario with an average temperature in one-way service (an average of 15.5 km).

However for the two-way service, the distances travelled are 30 km when the temperature is low (-15 degrees) and 35 km when the temperature is high (+15 degrees). Thus, carsharing users use EVs for distances of 500 m more and 5 km more for one-way service and two-way service respectively when temperature is high. In conclusion, these results confirm the difference between the areas covered by carsharing cars when the temperature is low (-15 degrees) with anxiety and the larger areas covered by these same cars with a temperature of +15 degrees and without range anxiety that one could notice in figures 8, 10, 12 and 14.

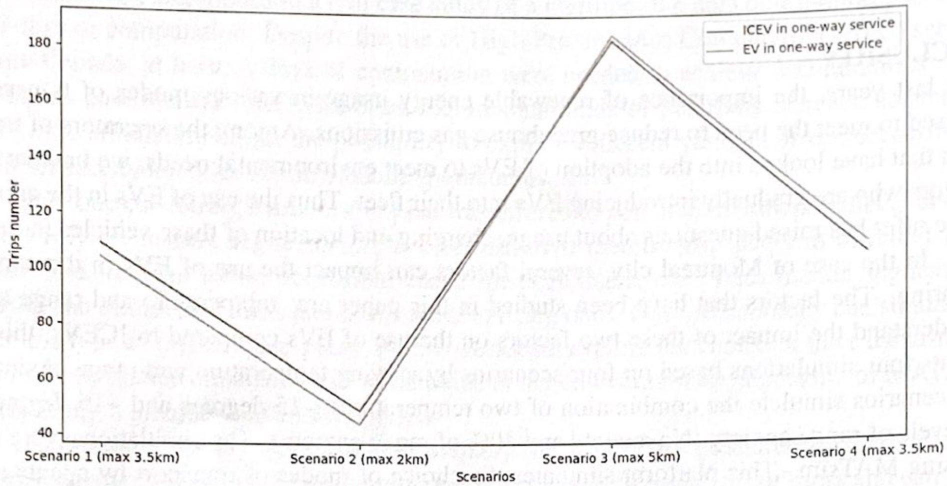
The impact of users choice on the number of trips performed by vehicle type in each scenario is shown in figure 18. We can notice that the number of trips performed by EVs using one-way service are higher (orange line) when temperature is higher (scenarios 3 and 4). However, the number of EV trips is lower than ICEV trips in these scenarios. Having this kind of information, carsharing operator can decide the number of vehicles to be positioned in various stations depending on temperature and users anxiety.



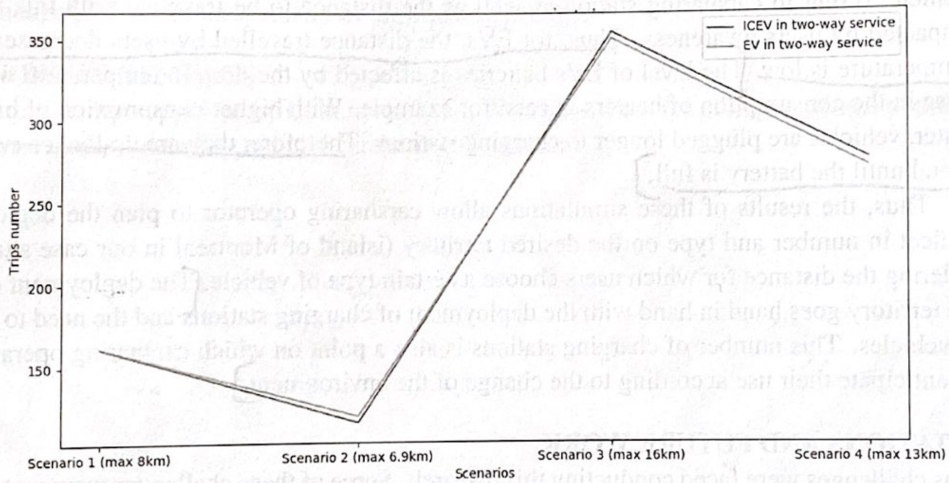
↳ could be useful to identify scenarios throughout (in earlier figures)

FIGURE 18: Trips number per simulated scenario using carsharing vehicles

Regarding distance factor, carsharing operator can choose to substitute an EV with an ICEV and vice versa depending on the scenarios, as shown in figure 19. For one-way service 19a, carsharing operator can interchange the availability of vehicle types that perform trips with distances of at most 3.5km for scenario 1, 2km for scenario 2, 5km for scenario 3 and 3.5km for scenario 4. Similarly for two-way service 19b, carsharing operator can interchange the availability of vehicle types that make trips with distances of at most 8km for scenario 1, 6.9km for scenario 2, 16km for scenario 3 and 13km for scenario 4.



(a) Maximum distances for each scenario in one-way service



(b) Maximum distances for each scenario in two-way service

FIGURE 19: Maximum distances for which carsharing operator can interchange vehicle types (with 5 trips as a maximum difference between trips using ICEVs and those using EVs)

Another point that carsharing operator can use to plan the deployment of these cars on the territory is the number of charging stations that the operator could make available to users of the system. Taking the example of energy consumption described in figure 15 and areas where used EVs are dropped, carsharing operator can choose where to put charging stations and in which carsharing stations. In terms of battery consumption and charging stations in carsharing stations, the results obtained would give the operator indications on the number of chargers and the stress they should withstand depending on the outside temperature and the use of EVs for the desired trips.

CONCLUSION

In the last years, the importance of renewable energy usage in various modes of transport has increased to meet the need to reduce greenhouse gas emissions. Among the operators of transport modes that have looked into the adoption of EVs to meet environmental needs, we find carsharing operators who are gradually introducing EVs into their fleet. Thus the use of EVs in the carsharing service offer has raised questions about usage, charging and location of these vehicles in the city.

In the case of Montreal city, several factors can impact the use of EVs in the context of carsharing. The factors that have been studied in this paper are: temperature and range anxiety. To understand the impact of these two factors on the use of EVs compared to ICEVs, this paper presents four simulations based on four scenarios by varying temperature and range anxiety. The four scenarios simulate the combination of two temperatures (-15 degrees and +15 degrees) and two levels of range anxiety (No anxiety and 30% of range anxiety). The simulations were carried out using MATsim. This platform simulates the choice of modes of transport by agents and the impact of the environment on this choice. The evolution of the temperature as well as its impact on the behaviour of agents were simulated. As presented in the results section, carsharing users consider the temperature and the state of charge available to achieve their trips. The choice of the vehicle to rent in carsharing station as well as the distance to be travelled with this vehicle are impacted by users awareness. Thus, for EVs, the distance travelled by users decreases when the temperature is low. The level of EVs batteries is affected by the drop in temperature with the increase in the consumption of heaters in cars, for example. With higher consumption of batteries in winter, vehicles are plugged longer to charging stations. Therefore, they are ~~no longer available~~ for rental until the battery is full.

is this explanation supported?

Thus, the results of these simulations allow carsharing operator to plan the deployment of its fleet in number and type on the desired territory (island of Montreal in our case study) by considering the distance for which users choose a certain type of vehicle. The deployment of EVs on the territory goes hand in hand with the deployment of charging stations and the need to charge these vehicles. This number of charging stations is also a point on which carsharing operator can act to anticipate their use according to the change of the environment.

does this go here?

LIMITATIONS AND FUTURE WORK

Various challenges were faced conducting this research. Some of these challenges were met, others were obviated by relying on simplification assumptions. These simplifications are limitations that can be addressed in future work.

A noteworthy limitation relates to the calibration of the utility parameters of carsharing. For lack of specific data on mode choice behaviour of carsharing users, and especially on the distribution of the value of travel time (VOT), we assume that car and carsharing have the same value of travel time. The same goes for the value of walking times to and from carsharing stations, that is taken equal to transit access and egress walk time. The VOT is likely to be distributed in the population depending on characteristics of agents (income, age, etc.). Future work is required to refine the calibration of carsharing parameters. In this regard, revealed or stated preferences data can be used.

VOT for carsharing unknown

Simulation computation times were a serious limitation to this research. The simulation of the adoption and use of e-carsharing using an integrated simulation framework with endogenous demand and competing modes in a real case study of a metropolitan area of 4 million people takes several days of computation. Despite the use of High Performance Computation (HPC) servers of Compute Canada, at least, 6 days of computation were needed to achieve 300 iterations. In real and complex case studies, MATSim often requires hundreds of iterations of reach convergence. Cumbersome simulations limit the possibility to explore different variants of our scenarios or to conduct sensitivity analysis on the modelling outcomes.

computing limitations

Only one carsharing membership plan was offered to potential members. Often, carsharing operators rely on market segmentation to offer different membership plans to different market segments like frequent users, occasional users, off-peak users, etc. With market segmentation, carsharing can attract new users and better serve existing ones. Our methodology can simulate any number and type of membership plans. Future work cam explore the choice of the carsharing plan by agents. This choice dimension can be included in the co-evolutionary algorithm of MATSim or predicted using a membership choice model.

potential future exploration with different carsharing plans

Carsharing members were assumed to query the availability of shared cars exclusively in the nearest carsharing station. This assumption limits the search perimeter of users and can underestimate the demand for carsharing in the case where users are willing to walk to more remote stations with available cars. Future work can address this limitation by extending the search perimeter to more distant stations. However, this improvement should be considered in conjunction with the refinement of calibration, especially of the walking penalty.

ACKNOWLEDGEMENTS

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