Article

How Many Electric Vehicles Are Needed to Reach CO₂ Emissions Goals? A Case Study from Montreal, Canada

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Abstract: In the province of Quebec, Canada where the electricity is nearly carbon-free, the road transport sector represents 35.6% of all emissions. As such, electric vehicles (EVs) have been proposed as a means to reduce such emissions. However, it is not clear how many conventional vehicles (CVs) would need to change to electric in order to meet the greenhouse gas (GHG) emissions reduction target of reducing 1990 CO₂ emissions by 37.5% by 2030 in the province. In fact, various considerations exist such as which vehicles will change and how those vehicles are used. This article addresses this issue in the case of Montreal, Canada. First, to create a baseline, direct emissions by all personal vehicles in Montreal in 2018 are calculated using data from the 2018 origin-destination (OD) survey and provincial vehicle registration. Next, five scenarios are studied to calculate the variations in the number of EVs needed in the fleet in order to achieve provincial targets. The most optimistic scenario shows that roughly 49% of the fleet would need to change. The most pessimistic scenario estimates that almost 73% of the fleet would need to be converted to EVs. It can be concluded that the strategy used can have a great impact on how many vehicles need to be replaced in the fleet. However, all simulations show that the necessary replacements are far from negligible. It must surely be coupled with other actions such as reducing veh.km travelled (vkm) or increasing public transport use.

Keywords: electric vehicles; vehicle ownership; GHG emissions; CO₂ emissions; emission targets

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1. Introduction

In the province of Quebec, Canada where electricity is produced through hydropower, the transport sector represents 44.8% of all emissions [1]. The road transport sector by itself represents 35.6% of all emissions. Drilling further down, personal vehicles represent 20% of total greenhouse gas (GHG) emissions in the province [1]. Personal vehicles in Quebec were responsible for the emission of 16 megatonnes of CO₂ equivalent in 2019. This accounts for approximately 20% of total GHG emissions in the province [2]. Thus, this sector is an important lever to achieve the target of reducing Quebec emissions by 37.5% compared to 1990 levels by 2030 [3].

One of the solutions to reduce vehicle emissions is to replace part of the provincial fleet's conventional vehicles (CVs; also called internal combustion vehicles (ICE)) with electric vehicles. Direct emissions from electric vehicles (EVs) are essentially zero, but the overall emissions related to electricity production can be higher. In the case of Quebec, its electricity was associated with roughly 34.5 gCO₂/kWh in 2017 [4]. To compare, electricity from Canada's largest province, Ontario, in 2008 (at the time, coal plants still functioned [5]) was associated with 201 gCO₂/kWh [6]. Another comparison can be made with the US, whose average gCO₂/kWh in 2019 was 417g [7]. The methods used to calculate these values vary from each other, but they can be used to get an overall idea of the differences between emissions in each region. As such, Quebec provides an example of a situation

where electricity generation has very limited GHG emissions, as compared to previous studies where this could only be assumed [8].

In a context such as Quebec's where GHG emissions for electricity are very low, the emissions associated to use could be much lower than in CVs. Assuming that an EV consumes 20 kWh/100 km (electric vehicles consume between 15 and 30 kWh per 100 km [9]), it would emit $34.5 \times 20/100 = 6.9 \text{ gCO}_2/\text{km}$ in this province which would be 25 times less than CVs (assuming $220 \text{ gCO}_2/\text{km}$). As such, EVs in Quebec provide the potential to significantly reduce transport-based and overall CO₂ emissions. However, vehicle emissions depend on other factors such as vehicle size and the distances driven and these are not constant over urban contexts [10]. As a result, it is not obvious what portion of the provincial fleet would need to convert to EVs to reach provincial emissions targets, or whether this would be feasible from a energy supply standpoint.

As such, this paper seeks to develop an estimate of the potential for EVs to contribute to CO₂ emission reductions in Montreal, Quebec, Canada. To do so, current GHG emissions of the Montreal personal vehicle fleet is first calculated to form a baseline. The baseline is then used to evaluate different EV-emission scenarios based on varying assumptions of CV to EV conversion to determine how many vehicles would need to change in order to achieve emissions reduction targets. The work focuses on the Montreal fleet for two key reasons: (1) it is the largest city in Quebec, with approximately half of the provincial population in 2018 [11]; and (2) granular data required to estimate use is available through its Origin-Destination survey (repeated every five years) along with complementary data.

The next section reviews existing methods to calculate GHG emissions and to analyze changes in vehicle fleets. Then the data used in this research will be presented. In the next section the methodology used to calculate Montreal's personal vehicle fleet emissions in 2018 and to determine how many vehicles would need to change in order to achieve the emissions reduction target will be explained. Afterwards, the results of the analysis will be presented, and the paper will be finished with a discussion of the results and concluding remarks.

2. Background

A lot of work has already been done on transport CO₂ emissions and EVs.

Some papers investigated the impacts of EVs on the international scale. For example Rietmann et al. [12] used data about previous sales from 2010 to 2018 in 26 countries including USA, Japan, China and Canada to forecast future EV sales and compare the results between the different countries. For Canada this study predicted that EVs would represent 19.6% of the market share in 2030. Sorrentino et al. [13] analysed the impacts of EVs on electricity grid and infrastructures, and on CO₂ emissions in Italy, Germany, France, USA, and Japan. The authors found that current energy mixes and expected EV market penetration were insufficient to reach CO₂ emission targets in these countries in 2050, except in France, because GHG emissions from electricity production in this country are around 4 times lower than the other countries studied. Hölt et al. [14] also studied EVs at a large scale in Europe. The authors found that 97% of EVs would be needed in the fleet by 2050 if car mobility continues to increase following current trends. Otherwise, only around half of the fleet would need to be composed of EVs if transport demand shifts to other modes.

At a lower scale, comparisons can be done between different regions in a single country. For example, Ribberink et al. [15] studied the provinces of Quebec, Ontario and Alberta using the PEV-CIM tool from Natural Resources Canada to calculate potential impacts of a change in fleet composition on GHG emissions at the provincial level. The conclusion of this article was that EVs can help reduce GHG emissions in the provinces of Quebec and Ontario, but not in the province of Alberta, where electricity production emitted 34 times more CO₂ than in Quebec, and 5.6 times more than in Ontario, according to this article. Kamiya et al. [16] compared the provinces of Alberta, Ontario, and British Columbia to estimate GHG impacts of EVs using different time frames. The authors found

that switching to EVs could reduce emissions by 78–98% in British Columbia, by 58–92% in Ontario and by 34–41% in Alberta. This type of article generally allows the authors to pinpoint the differences between zones whose electricity mix or EV share are different from each other.

Other papers study EVs on a national or regional level, focusing on a given region. For example, Propfe et al. [17] studied different possible governmental decisions to help EV diffusion in the German fleet. The authors found that German objectives regarding the number of EVs in the fleet wouldn't be reached without acting on external factors like increasing fuel prices or decreasing EV manufacturers' mark-ups. Kloess et al. [18] tried to estimate the market share of different types of vehicles in Austria from 2010 to 2050 under different policies. In this article, authors studied seven types of vehicle technologies, three different vehicle sizes and 3 possible user travel behaviour. The model they used proved that policy can help reduce GHG emitted. Wang et al. [19] used a four-step model to forecast trip behaviour in Maryland. The authors found that a high EV ownership scenario (43.14% of the fleet is made of EVs) would reduce CO₂ emissions by 16% from 2015 levels and would result in more balanced geographical distribution of emissions. A number of other articles [8,20,21] focused on the case of the United Kingdom. The first article [20] compared different integration scenarios for EVs and hybrid vehicles to determine which one would result in the lowest emissions, while the second [8] focused on national policies and the number of EVs in the fleet expected by the government. Both articles highlighted the fact that energy mix is really important when considering the replacement of CVs by EVs. The first [20] showed that a full EV scenario can reach national objective when coupled with the right energy mix, and the authors of the second [8] explained that replacing CVs by EVs is not the only solution that should be used to reach national GHG emissions reduction objective. The last one [21] analyzed the options available to reach a given GHG emission threshold in 2030. The authors of this last article suggested a lot of changes have to be made on transport and urban planning to achieve emissions goals. In these articles, the methodology used to calculate CO₂ emitted is similar and requires the same parameters: the size of the fleet, the proportions of the different vehicle technologies in it, CO₂ emitted per km by each vehicle technology, vehicle size or mass, and yearly km travelled. However, at this scale authors typically use averaged values for the zone studied.

The smallest scale that seems to have been studied is the scale of a city [22–26]. These papers often use Origin-Destination surveys so as to more accurately represent travel behaviour within the city. Two main equations emerge from these articles to calculate GHG emissions for a given trip. The first, taken from Waygood et al. [23] is straight-forward (Equation (1)). It requires distance traveled (d), energy efficiency per km (f), a factor to convert kWh to CO₂ emitted (k) and the time that a vehicle has sat still in order to calculate the cold start impacts.

$$GHG = d \times f \times k \quad (1)$$

Total GHG emitted is the multiplication of these three terms. However, calculating the energy efficiency per km (f) would require knowing the energy used by all transport modes studied (9 in this case) and the average passenger rates for each.

The second, used in more papers [22,24,25] is based on disaggregate data on personal vehicles and an average value for buses (Equation (2)).

$$GHG = \frac{FCR \times SCF \times EF \times D}{NP} \quad (2)$$

Total GHGs emitted is the multiplication of the average fuel consumption rate (FCR) of the vehicle used, a speed correction factor (SCF), an emission factor (EF) and the distance of the trip (D). This total is also divided by the number of people in the vehicle during the trip (NP) because the objective is to give an emission value for a given person. The formula can vary across articles. For instance, Yang et al. [25] were able to know which part of the trip was done with a motorized mode and which part was not. They replaced the total

distance (D) in Equation (2) with the motorized trip distance during the trip. However, these studies do not typically consider electric vehicles, their uptake, and how they might help achieve reduction targets.

The studies presented in the previous paragraph only took into account tailpipe GHG emissions, to better understand emissions at a local scale. However, it is possible to perform a complete life cycle assessment to have a better insight on global impacts. Both articles [13,18] chose this approach. A life cycle analysis was carried out by Kloess et al. [18] to calculate the associated emissions of each type of vehicle studied. As mentioned above, the model they used proved that policy can help reduce GHG emitted. Sorrentino et al. [13] even took into account EV operating cycles and technical features like battery technology and battery energy capacity to better estimate the impact on grid and infrastructures. As mentioned above, the authors found that current energy mixes and expected EV market penetration were insufficient to reach CO₂ emission targets in Italy, Germany, USA, and Japan in 2050.

When studying possible future impacts of EVs, other authors have focused on estimations of the future sales of EVs. A review of the methods available for this has been done by Al-Alawi et al. [27]. That study divided previous work into three groups: agent-based models, consumer choice models, and diffusion rate and time-series models. Agent-based models estimate the travel choices of a population that has to meet given needs under given constraints. This method was used by Propfe et al. [17] for example. Consumer choice models use utility measures and logit models to predict people's choices like in article by Kloess et al. [18]. Finally, diffusion rate and time-series models predict the evolution of markets in a more macroscopic scale. Articles [8,12] used this approach. It is the method used when knowing data regarding previous sales.

Some work has been done to try to translate government policies or emission reduction strategies into changes in fleet or travel behaviour and see the associated impacts on CO₂ emitted [8,17–20,22]. Article by Zahabi et al. [22] studied the transition to hybrid buses, electric trains, or more fuel efficient cars and compared these strategies. Authors found that the two most efficient strategies to reduce GHG emissions are the continuous improvement of fuel efficiency of cars and the improvement of transit supply. Scenarios developed by Propfe et al. [17] followed different possible governmental decisions to help EV diffusion. The authors found that German objectives regarding the number of EVs in the fleet wouldn't be reached without acting on external factors like increasing fuel prices or decreasing EV manufacturers' mark-ups. In addition to factors like fleet growth and yearly driving distance, the global approach by Kloess et al. [18] took into account political and economic decisions to forecast future GHG emissions. Wang et al. [19] studied the Maryland Department of Transportation projections, coupled with different scenarios regarding fuel prices and taxes. As mentioned above, the authors found that a high EV ownership scenario would reduce CO₂ emissions by 16% from 2015 levels and would result in more balanced geographical distribution of emissions.

Unlike papers described in the previous paragraphs, a different approach can be followed: fixing an objective and creating one or more scenarios to reach this objective. This backcast approach was followed by [14,21]. For example, Hölz et al. [14] sought to find solutions to decrease European transport emissions by 60% compared to 1990 levels, acting either on car ownership, shift rate to EVs, or energy mix. As mentioned above, one article [21] suggest that a lot of changes have to be made on transport and urban planning to achieve emissions goals, and the other [14] showed that different travel behaviours and car ownership trends could lead to different fleet compositions to reach emission objectives.

Other research does not focus on EVs but investigates factors that have an impact on GHG emissions. For example, articles [10,22,23,25,26,28] studied the link between urban form and CO₂ emissions. Some of them also investigated socio-economic factors, transit supply, and distance to downtown. Yang et al. [25] also took into account the purpose of trips in the structural equation model approach they used. The findings of these articles were similar. They found that GHG emitted are influenced by land use mix, population

density and transport supply. The number of workers and retirees in a household also play a role in GHG emitted. Emissions were also found to be higher during weekdays. More populated households emit less and richer ones emit more. In addition, Zahabi et al. [26] showed that variations of household emissions among neighbourhoods is much greater than among cities. The trend is actually the same for all cities: less emissions in the center and more in the periphery.

As can be seen in the previous paragraphs, GHG emissions and electric vehicle ownership have been the topic of a lot of studies. Some aim to calculate CO₂ emissions in a given area. Others try to predict electric vehicle market evolution. Still others assess the effects on GHG emissions of modifications of vehicle fleets. Nevertheless, estimating how many EVs would be necessary to meet government objectives to reduce GHG emissions taking into account that vehicle emissions and use varies across urban development does not seem to have been examined. In other words, previous work that compared GHG emissions evolution with government objectives did so at a macroscopic scale, often using average values regarding km travelled and vehicle emissions. Given that other studies showed that transport based emissions vary spatially within a city and depend on the built environment, and that typically larger, less efficient vehicles are found in the more suburban areas where people drive more, it is important for policy makers to know how this would affect the percentage of vehicles that would need to change to meet reduction targets. That would also allow them to have a better insight on the possible differences in the number of CV that would need to be replaced between possible replacement methods.

This article will thus investigate this question. The following work is divided into two steps:

- calculating the 2018 the current emissions of the Montreal fleet of personal vehicles based on all registered personal vehicles and likely distances travelled by municipal sector;
- calculating the composition of the fleet necessary to achieve Quebec provincial government GHG reduction objectives based on five different fleet replacement scenarios.

As the province of Quebec mostly relies on hydro-power to produce its electricity, carbon emitted during energy production is very low in this region (34.5 gCO₂/kWh in 2017 [4]). Thus, this case can be seen as a reference situation where no efforts are needed to change energy mix as opposed to various previous studies where assumptions had to be made to forecast future energy mix [12–14,20,21]

3. Data Used

Three main different datasets were used in the analysis for this report. The 2018 origin-destination (OD) survey was used to provide information about the number and length of trips by Montrealers [29]. This survey investigates personal vehicle trips made by 147,200 respondents from 73,400 households to draw a portrait of Montreal mobility. 3.89% of total households answered the survey and this sample represents all 4.4 million people on the 9840 km² area covered by the survey [30]. A total of 357,800 trips from 5 September to 20 December inclusive were recorded in the database. These are trips made by respondents in the 24-h period before they answered the survey. However, week-end trips were not recorded. Therefore, the origin-destination survey for Montreal uses a fall day to make estimations of people's travel behavior. Some countries such as Sweden use a rolling survey so as to capture different travel patterns by season [31]. However, in the case of the province of Quebec, Canada, only travel data on a random fall day is gathered. The assumption being that people have established their general travel pattern after summer holidays and the start of the new school year (which starts in September). Future surveys should aim to gather data from all periods of the year to make estimations of yearly travel more accurate. The OD survey is done with a stratified random sample: the 158 municipalities in the area are gathered into 113 municipal sectors, which is the stratum. A municipal sector is a geographic area the size of a small city whose population typically is around 100,000 people, but can vary between 3000 and 140,000 people.

Among other variables, the survey provides the origin and destination coordinates of the trips made by respondents. The combination of modes used is also available. For example one can know if a person took the bus, then the metro, then was picked up by someone with a car. Junction coordinates indicate where the person switched between a private mode and public mode of transport. Finally, household expansion factors were available that allow the sample to be expanded to be representative of the actual population.

Although the OD survey is very detailed, it does not include the characteristics of household vehicles like their average CO₂ emissions per km. This value has to be averaged at the municipal sector level and was based on the vehicle registration database and data provided by Natural Resources Canada.

The vehicle registration database for the province is maintained by the Société de l'assurance automobile du Québec (SAAQ; English: Quebec Automobile Insurance Company) [32]. Emission statistics of vehicle models was obtained from Natural Resources Canada [33] and this was used to calculate CO₂ emissions. The first gives the year, make, model, number of cylinders and engine size of each vehicle in the province. The second gives the corresponding CO₂ emissions in grams per km.

These two databases were combined to get the CO₂ emission profile of personal vehicles in the province. Vehicles with similar emissions were then gathered into ten emission categories using a k-means clustering method. Only their CO₂ emission values were taken into account to measure the distance between them. The distance measurement used is the square of the emission difference between vehicles.

Figure 1 shows the distribution of emission values for all vehicles in the province obtained with this method. The vertical lines present the boundaries between the emission categories. Table 1 gives more information about the average emissions and the number of vehicles per category in the Greater Montreal area. One category (category 0) was dedicated to EVs. They were assumed to emit 6.9 gCO₂/km. This value is the estimation made in Section 1 of the CO₂ emitted during the production of electricity needed to power the vehicle in Quebec. This category is a bit different from the others, that is why the boundary between it and category 1 does not appear in Figure 1.

Figure 1. Distribution of emission values for the province's fleet.

A request was made to the provincial licensing authority to obtain a dataset with the number of vehicles in each emission category at the dissemination area level (slightly smaller than the US block group). This data was aggregated to the municipal sector level afterwards. Aggregated values had to be used for confidentiality reasons. The number of emission categories was set to 10 to respect data confidentiality.

Table 1. Emission values and number of vehicles for the 10 emission categories.

Emission Category	Emissions (gCO ₂ /km)	Number of Vehicles
0	6.9	12,576
1	47.6	55,843
2	170.2	895,852
3	190.8	1,036,725
4	210.5	691,539
5	234.5	693,929
6	263.3	618,897
7	291.6	428,870
8	331.2	248,867
9	375.9	96,092

Table 2 shows what was obtained at the end of that process. For instance 2317 vehicles belong to emission category 2 in the peripheral city center.

Table 2. Overview of the data obtained from the provincial licensing authority.

Emission Category	Montreal: City Center	Montreal: Peripheral City Center	Montreal: Southwest
0	34 (0.5%)	66 (0.4%)	53 (0.2%)
1	175 (2.9%)	347 (2.3%)	327 (1.4%)
2	863 (14.1%)	2317 (15.8%)	4509 (19.0%)
3	1169 (19.1%)	2881 (19.6%)	5418 (22.8%)
4	1112 (18.2%)	2600 (17.7%)	3880 (16.3%)
5	1180 (19.3%)	2608 (17.8%)	3811 (16.0%)
6	807 (13.2%)	1941 (13.2%)	2954 (12.4%)
7	517 (8.4%)	1276 (8.7%)	1859 (7.8%)
8	160 (2.6%)	425 (2.9%)	683 (2.8%)
9	95 (1.5%)	186 (1.2%)	252 (1.0%)

For the second part dedicated to changes in the fleet, additional data was used. Population estimates for Montreal were taken from two sources. The first is the population census for Montreal [34]. It provides population estimates every 4 years from 1996 to 2016. It is the only one which provides data for the year 1990. This is why it was used to calculate 1990 CO₂ emissions. The other source is Quebec's provincial institute of statistics (ISQ) [11]. Data from the ISQ is available at the municipal level for every year between 2011 and 2018, thus it was used for the vehicle ownership growth calculations.

To estimate 1990 emissions, population data for the province was taken from annual demographic estimates by Statistics Canada [35]. Emission values for the province by Delisle et al. [1] were also used.

To create the hypothetical fleet, vehicle data from the SAAQ [32] for the years 2011 to 2018 was used. Population growth forecasts for 2030 were obtained from reference scenario values by the ISQ [36].

4. Methodology

The article will follow a backcast approach as in Hörtl et al. [14]. An overview of the methodology used is given here first. A detailed explanation of each step will then follow.

- Estimation of 2018 emissions in Montreal (Section 4.1)
- Definition of the emission level that needs to be reached in 2030 (Section 4.2)
- Creation of the business as usual baseline until 2030 (Section 4.3)
- Creation of the different scenarios followed to reach the objective from the baseline situation (Section 4.4)

Once these are discussed, the implications for the ability to meet emission targets through the electrification of the private vehicle fleet will be discussed as well.

The code used for this study can be found in a public GitHub repository at <https://github.com/Pierre-C-M-Laffont/How-Many-EVs-are-Needed-to-Reach-CO2-Emissions-Goals-A-Case-Study-from-Montreal-Canada>, last accessed 10 December 2021.

4.1. Estimation of 2018 Emissions

To calculate Montreal's personal vehicle fleet CO₂ emissions in 2018, the equation used by [22,24,25] was applied. In this case, Equation (3) was used.

$$GHG_{2018} = \sum_p \sum_{t_p} \frac{D_{pv} \times EF_{veh}}{NP} \quad (3)$$

In this equation, p is the number of people in Montreal, t_p the number of trips made by person p in 2018, D_{pv} the distance traveled using a private vehicle during the trip, EF_{veh} the emission factor in gCO₂/km of the vehicle used for the trip, and NP the number of people in the vehicle. It should be noted that the fuel consumption rate, the speed correction factor, and the emission factor from Equation (2) were combined into the emission factor in Equation (3).

Disaggregate data from the OD survey was aggregated to the municipal sector level. This data also represents the travel behavior for an average fall day (the survey was carried out from September to December). Therefore, Equation (3) has to be modified to be used with the available data. The equation used given this constraint is presented in Equation (4).

$$GHG_{2018} = \sum_{p_{OD}} \sum_{t_{p_{OD}}} \frac{D_{pv} \times EF_{veh_{MS}}}{NP} \times f_{exp_{OD}} \times f_{exp_{annu}} \quad (4)$$

Here, the sum is calculated across the trips made by the expanded respondents (p_{OD}). The emission factor is now average CO₂ emissions per km for all vehicles in the municipal sector MS where the respondent lives ($EF_{veh_{MS}}$). It was obtained using Table 2. Two new terms are added in the equation. The first accounts for the household expansion factor ($f_{exp_{OD}}$) and the other is a factor to annualize (i.e., to give a yearly amount) the results ($f_{exp_{annu}}$). The following paragraphs will explain how these variables were calculated.

4.1.1. Distance Calculations

To calculate the distance of automobile trips, the shortest path between the origin, destination and the given junctions of the trip were estimated using the OSRM API [37]. As this route calculation server only works for trips within Canada, the distance of trips whose origin or destination were outside of Canada (0.5% of the total number of trips) was calculated with the HERE API [38].

Since the purpose of the study was to examine only how the vehicle fleet would need to change if reductions were made with private electric vehicles, not all modes were retained. Only trips where one part was car-driver, car-passenger, taxi or motorbike modes were used. Those using metro, bike, plane, train or interurban bus modes were not used in the calculation.

The results of the two APIs were checked for plausibility and some unusual results were found. For example the distance between origin given and origin returned (or destination given and destination returned) by the requests were more than 5 km. These 2902 trips were ignored as most of them had one of their coordinates equal to zero. Among these trips, only two had coherent X, Y values, but they did not seem to use the road network.

4.1.2. Average Emissions by Municipal Sector

As it was explained in Section 3, vehicles from the original database of the provincial vehicle licensing authority (SAAQ) [32] were sorted into 10 categories of emissions.

One category was dedicated to EVs. Emissions for all other vehicle types in a given emission category represented the average emissions of all vehicles in the category.

The average emissions of vehicles from a given municipal sector were calculated using Equation (5).

$$EF_{veh_{MS}} = \sum_c \frac{n_c \times EF_c}{n_{tot}} \quad (5)$$

In this equation, c is the vehicle emission category, n_c the number of vehicles in this category in the municipal sector, n_{tot} the total number of vehicles in the municipal sector and EF_c the emission factor whose calculation was explained in the previous paragraph.

4.1.3. The Other Factors of Equation (4)

- The number of people in the vehicle (NP) was not always reported in the OD survey (i.e., if the trip was not made by the respondent), such missing values were replaced by the average value calculated using trips for which the number of passengers was given. This assumes that the number of people in cars does not vary spatially, and that the time and purpose of the trip do not have any influence on it. Studying the link between these factors and the number of people in cars would have made the calculation more precise.
- The household expansion factor ($f_{exp_{OD}}$) was taken from the OD survey results.
- The factor $f_{exp_{annu}}$ used to annualize the results was set to 335 for all trips. This value was chosen following research on how to annualize the values from an OD survey in Montreal [39] and was calculated using trip data by the ministry of transport in this region. This factor can obviously be questioned, even if it has already been used in another study. In fact, annualized OD survey results are risky, because such surveys only register trips made during weekdays for one. Other values have already been used in previous work: 290 was used by Morency et al. [40] and was calculated according to counts in public transport. This value focuses on public transport, and only takes into account weekdays. The value of 250 accounts for the number of working days in a year, and was used by Jeanjacquot [41].

It can be further noted that the time of the trips was not taken into account. This implies that vehicles emit as much during peak hours than during the other times of the day. Taking time of day into account would therefore increase precision. Tradeoffs between precision and feasibility are required in all such studies.

4.2. Definition of the Emission Level That Needs to Be Reached

The objective of this article is to determine how many CVs need to be replaced by EVs in order to reduce Quebec emissions by 37.5% compared to 1990 levels by 2030. Thus, Montreal's personal vehicle fleet GHG emissions in 1990 need to be estimated.

A different approach was necessary to calculate the Montreal private vehicle fleet emissions for the year 1990. Data was only available about the emissions of cars for the whole province in 1990 [1], along with the population of the Montreal census metropolitan area [34] and the total population of the province [35]. Comparable data was also available for the year 2018.

In order to come up with comparable emissions between 1990 and 2018, the following approach was used. The difference in emissions per person between Montrealers and the rest of the province has been assumed to remain constant over time. This was the most appropriate approach given the available data, and knowing that previous research found that people in more densely-populated areas drive less and emit less than others [23,24].

$$\frac{Em_y}{Pm_y} = \alpha \times \frac{Eq_y - Em_y}{Pq_y - Pm_y} \quad (6)$$

In Equation (6), the emissions (E) of Montreal (m) over its population (P) for a given year (y) equals a constant (α) times the emissions of the rest of the province (the difference

between the emissions of the province of Quebec (q) and the emissions of Montreal (m) over the population. With this equation, α could be calculated using 2018 values for the province's and Montreal's population, as well as emissions for the province. Montreal's 2018 emissions come from the results of the first step of this research described in Section 4.1.

From Equation (6), CO₂ emissions of the personal vehicle fleet in Montreal in 1990 were approximated by Equation (7).

$$Em_{1990} = \frac{\alpha \times Eq_{1990} \times Pm_{1990}}{(Pq_{1990} - Pm_{1990}) + \alpha \times Pm_{1990}} \quad (7)$$

This method assumes that Montrealers' emissions varied at the same rate as the emissions by other people of the province. Further, socio-demographics were not analyzed. Taking this into account could have modified the results.

After 1990 levels were estimated, the 2030 CO₂ emission objective was set to 37.5% of this value.

4.3. Creation of the Business As Usual Baseline Until 2030

Before calculating the number of vehicles that need to be replaced in order for the provincial GHG emission target to be reached, the composition and size of the 2030 private vehicle fleet for each municipal sector needed to be created assuming that business as usual trends were followed. Previous studies have tried to forecast vehicle ownership, for example with discrete choice models [42]. The article by Lansley et al. [43] focused on the type of vehicle used by households, at a fine geographical scale. Since this study focused on vehicle type and distances travelled on the municipal sector level, population forecasts by Quebec's provincial statistics institute (the ISQ) [36] were first used to predict the population of the entire area covered by the OD survey in 2030.

Two methods were then applied to estimate how many vehicles would make up the fleet in 2030. The first was a naive solution: multiply the number of all vehicles of each category of each municipal sector by the rate of population increase. In other words, this method assumes that all new vehicles from 2018 to 2030 will be sorted in to the 10 emission categories according to the 2018 distribution. This is a very strong assumption as it involves an increase in the number of the most emitting vehicle categories even though these categories are largely made up of old vehicles, which will be retired by 2030. However, the method is quick and easy to implement. This method is illustrated in Figure 2.

Figure 2. Creation of the hypothetical 2030 fleet with the naive method.

For the second method, population predictions for 2030 from the reference scenario values from the ISQ [36] were first used. Then, vehicle ownership was estimated using these predictions and both vehicle [32] and population [11] data from 2011 to 2018. Next, the proportions of the 10 vehicle categories were estimated with the same method. Linear regressions were used to predict the 2030 values. Finally vehicles were allocated to municipal sectors according to their 2018 ratios. This method is illustrated in Figure 3.

Figure 3. Creation of the hypothetical 2030 fleet with the complex method.

The linear regression for vehicle ownership only takes into account the number of vehicles per person per year. Similarly, vehicle category regressions take into account the percentage of vehicles of each emission category per year to predict the 2030 values. Equation (8) was used for these regressions and Table 3 shows all the regressed parameters.

$$V_{year} = A * year + B \quad (8)$$

In Equation (8), V is either the number of vehicles per person, or the percentage of vehicles in a given emission category (depending on whether we look at car ownership or the size of the different emission categories in the fleet). A and B are the regressed parameters.

Table 3. Regressed parameters.

Regression	A	B	R ²
Vehicle Ownership	0.00361	−6.769	0.915
Emission category 0	0.000859	−1.730	0.881
Emission category 1	0.00310	−6.257	0.962
Emission category 2	0.00965	−19.296	0.974
Emission category 3	0.00638	−12.651	0.984
Emission category 4	−0.00317	6.555	0.895
Emission category 5	−0.00306	6.332	0.992
Emission category 6	−0.00446	9.130	0.995
Emission category 7	−0.00531	10.814	0.996
Emission category 8	−0.00251	5.103	0.996
Emission category 9	−0.00147	2.998	0.999

For the emission category regressions, only the years 2015 and higher were taken into account because the trend changed significantly after this year for emission categories 2 and 3. To improve the estimation, further factors that influence vehicle emissions such as socio-demographics could be used. Whelan et al. [42] used a discrete choice model with parameters such as household income, employment, license holding, car purchase and use costs to forecast future vehicle ownership. The method used in the current study is much simpler but it can at least give some insight on the future evolution of the 10 emission categories.

An estimation of veh.km travelled (VKMT) in 2030 is needed to estimate the emissions linked to this situation. Kilometers travelled per vehicle within a given municipal sector were assumed to remain constant from 2018 to 2030. This was felt to be reasonable as vehicle kilometers travelled seem to have been relatively stable in Canada for the past two decades according to Shenstone et al. [44]. As the timeline is short (10 years), we then also assumed that individual behaviour will remain relatively stable in the near future.

One means to increase accuracy would be studying the evolution of travel behaviour. This would allow for a more refined calculation of the estimated veh.km travelled in 2030.

4.4. Changes in the Fleet

The scenarios allowing CO₂ emissions (Section 4.3) to meet the reduction target are described in this section. Vehicles in the different categories shown in Table 2 were replaced with electric vehicles (category 0) following rules based on five scenarios. Vehicles were replaced following the rules until the emissions reduction target was met. The rules are as follows :

- 1st scenario (Random): Replace vehicles randomly
- 2nd scenario (Efficient): Replace vehicles that have the highest emissions per km first (i.e., the least efficient motors and the biggest vehicles)
- 3rd scenario (Optimistic): Replace vehicles that emit the most during a year first (both emissions per km and veh.km travelled in municipal sectors are taken into account)
- 4th scenario (Inefficient): Replace vehicles that have the lowest emissions per km first
- 5th scenario (Pessimistic): Replace vehicles that emit the least during a year first

The first scenario, *Random*, could be interpreted as resulting from electric vehicles purchase incentives without targeting specific vehicles. The second, *Efficient*, could be interpreted as incentives targeting vehicles which emit the most per km. The third, *Optimistic*, can be seen as focusing on both the use and efficiency of the vehicle. The second to last, *Inefficient*, relates to people who already seek out energy-efficient vehicles, replacing their vehicles with EVs. The last one, *Pessimistic*, is the situation where perhaps environmentally concerned individuals who already own efficient vehicles and do not use them frequently are the people that replace their vehicles.

4.5. Summary of the Main Assumptions

A number of assumption have been made to adapt to data availability and complexity of calculations. Table 4 lists the main assumptions authors needed to make to carry out this study.

Table 4. Main factors, their assumptions, and justifications.

Factor	Assumption/Value Chosen	Justification
2018 emissions		
Vehicle emissions in municipal sector	average value for each municipal sector	Vehicle type is found to vary by built environment [10,28,45]
Annualization factor	335	[39]
1990 emissions		
difference in emissions per person between Montrealers and the rest of the province	no change over time	[23,24]
business as usual baseline		
Population rate of increase	1.1025	calculated using population predictions by [36] for this area
Vehicle ownership (naive method)	no change over time	naive method
Vehicle ownership (complex method)	linear regression	following annual current trends
Distribution of vehicles in emission categories (naive method)	no change over time	naive method
Distribution of vehicles in emission categories (complex method)	linear regressions	following annual current trends
yearly km travelled by vehicle	no change over time	[44]

5. Results

Montreal's 2018 personal vehicle fleet emissions and the emission level that needs to be reached will be described first. Then the business as usual scenario for the 2030 fleet will be presented. Finally, the five scenarios on the replacement of CVs with EVs will be presented.

5.1. 2018 Emissions

In 2018 there were 2.3 million vehicles in the OD region of Greater Montreal and their division between emission categories is given in Figure 4.

Figure 4. Vehicle emission categories in the 2018 Montreal fleet.

Category 0 represents electric vehicles, whose emissions are set to 6.9 gCO₂/km, while category 1 is largely made of hybrid electric vehicles, whose emissions values were averaged at 47.6 gCO₂/km based on dataset described in Section 3. The other categories contain only conventional vehicles whose emission values vary from 170.2 gCO₂/km (category 2) to 375.9 gCO₂/km (category 9).

Figure 5 represents average emissions per veh.km by municipal sector. People in the suburbs generally use vehicles that emit more. However, areas with high average emissions per veh.km can be seen around the center of the island too. This may be due to higher income, previously associated to higher vehicle emissions [24].

Figure 6 shows average km traveled per vehicle and Figure 7 shows CO₂ emitted per vehicle in municipal sectors. It can be seen that people from suburban areas use their car more, and given that their vehicles emit more per km, the total emissions per vehicle are the highest in the region. This geographical difference is supported by the conclusions of [22–24,26] about the built environment, and especially [26] which pointed out the increase in emissions when households were far from the city center.

Figure 5. Average CO₂ emissions (grams, g) per veh.km in Greater Montreal in 2018.

Figure 6. Kilometers per vehicle per day (km/veh/day) traveled in Greater Montreal in 2018.

Figure 7. Tonnes of CO₂ emissions per vehicle per year.

Table 5 shows key values concerning CO₂ emissions and distances traveled by Montrealers in 2018. Note that gCO₂/km is the average emission factor of vehicles by municipal sector. This estimation finds that in total Montreal's personal vehicle fleet emitted in total 5.52 MtCO₂ in 2018. That represents 2.35 tCO₂ per vehicle and 1.28 tCO₂ per person. It should be noted that tCO₂ per person only includes people aged 5 years or over, because that age group is not counted in the OD survey.

Table 5. Overview of results per municipal sector.

	gCO ₂ /km	km/pers/day	km/veh/day
mean	220.4	20.1	33.0
std	6.4	8.5	8.4
min	212.5	6.6	16.2
25%	216.8	13.3	26.3
50%	219.2	20.2	3201
75%	222.7	25.5	3800
max	265.1	44.2	59.1
	tCO ₂ /pers/year	tCO ₂ /veh/year	tCO ₂ /MS/year
mean	1.5	2.4	48,882.6
std	0.7	0.7	30,813.9
min	0.5	1.4	2742.3
25%	1	1.9	25,604.7
50%	1.5	2.4	45,038.9
75%	1.9	2.8	67,982.9
max	3.4	4.5	155,356.8

1990 emissions were estimated to be 3.7 MtCO₂. That means emissions would have to be lower than 2.31 MtCO₂ in 2030 to achieve provincial objective (reduction of 37.5%). As

such, Montreal 2018 emissions estimated here (5.52 million metric tons) would have to be reduced by 58.2%.

5.2. Description of the Business as Usual Baseline for 2030

Before calculating the number of vehicles which need to be replaced in order to reach the emission target, different methods for estimating Montreal's 2030 fleet were used. Changes include the number of total vehicles in the fleet and the distribution of vehicles among the emission categories. The first method (naive solution) resulted in the same composition of the fleet but with 2.6 million vehicles in total due to population growth. The composition of the fleet using the second method is given in Figure 8. The number of vehicles with this method increased to 2.9 million due to both population and vehicle ownership growth (as combined vehicle ownership and population growth is greater than population growth only). It can be seen in Figure 8 that there would be more vehicles in categories 2 and 3 in 2030 than in 2018 which follows a trend of increasing vehicle efficiency.

Figure 8. Estimated fleet composition according to vehicle emission category in Montreal in 2030.

5.3. Scenario Results

Table 6 shows the result of all replacement simulations on both 2030 fleets described in the previous paragraph, in terms of the number of vehicles and in the percentage of the total fleet. It can be noted that randomly changing vehicles would require the replacement of nearly two thirds of the fleet by EVs, and only the most optimistic scenario (replacing the highest total CO₂ emitting vehicles first) results in less than half of the fleet being replaced by EVs. It can be seen that the replacement of more than 100,000 vehicles could be avoided by focusing on total emissions rather than just on emissions per km. Finally, the difference in the number of vehicles changed between the best and the worst scenarios reaches 687,000 vehicles (23% of total vehicles). It can also be seen that the results do not vary much (<4%) between methods used to estimate the composition of the fleet.

Table 6. Number of vehicles which need to be replaced in order to reach the emission target.

	Million Vehicles Changed	Percentage of the 2030 Montreal Fleet
S1: random	1.762 naive: 1.652	61.5% naive: 63.8%
S2: efficient	1.531 naive: 1.417	53.5% naive: 54.7%
S3: optimistic	1.395 naive: 1.315	48.8% naive: 50.8%
S4: inefficient	1.972 naive: 1.879	68.9% naive: 72.6%
S5: pessimistic	2.082 naive: 1.960	72.7% naive: 75.7%

Note on Electricity Supply

In the hypothetical fleet used for the scenarios described in the previous section, around 40,000 vehicles were electric, while there were only 7870 EVs in 2018. The scenario requiring the replacement of the largest number of vehicles (replacing lowest total CO₂ emitting vehicles first) forecasts requiring 2 million new EVs in 2030, added to the 40,000 already in the fleet. Naturally, the number of vehicles provides an estimate of overall electricity that would be required to power the vehicles in 2030. In addition to demand, its useful to compare such demand with the amount of electricity potentially available in the province in 2030.

The two million vehicles of the pessimistic replacement scenario, traveling the average distance calculated in this research (33 km/day equivalent to 11,000 km/year), and consuming 20 kWh per 100 km, would consume 4.4 TWh a year. This is equivalent to the electricity consumption of 237,600 households (using the equivalence from [46]). This same report states that current electricity production capacity exceeds the provincial needs by more than 40 TWh. As such, it is amply sufficient to provide electricity for a 2030 fleet that could meet provincial personal vehicle emission targets. However, further analysis may want to predict the impact on electricity demand during peak hour to recharge the batteries.

5.4. Sensitivity Analyses

Sensitivity analyses were carried out regarding two factors in this study: the factor used to annualize the OD data ($f_{exp_{annu}}$ in Equation (4)) and the emissions values for EVs (mentioned in Table 1).

Table 7 shows how the results would vary for three different annualization factors: 335 (used in this study), 290 (used by [40]) and 250 (used by [41]).

Table 7. Sensitivity of the results to the annualization factor.

Annualization Factor Used	335	290	250
Variation		−13%	−25%
Emissions in Montreal in 2018 (in million metric tons)	5.5	4.7	4.1
Variation		−13%	−25%
Proportion of vehicles replaced randomly	61.5%	61.9%	62.2%
Variation		+0.7%	+1.1%
Proportion of vehicles replaced with the optimistic scenario	48.8%	49.2%	49.5%
Variation		+0.8%	+1.4%

Results show that annual emissions are proportional to the chosen factor. This can be proven using Equation (4). It can be further noted that when the emission factor decreases,

the number of CVs that need to be replaced by EVs to reach provincial objective increases. However, the variation in the number of vehicles to be replaced is much lower than the variation in the emission factor value.

Table 8 shows result variations for three different possible EV electricity consumption values: 20 kWh/100 km (6.9 gCO₂/km in the province of Quebec) accounts for the Tesla model S and was the value used in this study, 30 kWh/100 km (10.35 gCO₂/km) accounts for the Jaguar i-Pace and 15 kWh/100km (5.175 gCO₂/km) accounts for the Hyundai IONIQ.

Table 8. Sensitivity of the results to the emission value for EVs.

EV Electricity Usage (kWh/100 km)	20	30	15
Emission value for EVs (in gCO ₂ /km)	6.9	10.35	5.175
Variation		+50%	−25%
missions in Montreal in 2018 (in million metric tons)	5.5	5.5	5.5
Variation		+0%	+0%
Proportion of vehicles replaced randomly	61.5%	62.8%	61.0%
Variation		+2.1%	−0.8%
Proportion of vehicles replaced with the optimistic scenario	48.8%	49.9%	48.3%
Variation		+2.3%	−1.0%

Results first show that the EV electricity consumption value has a negligible impact on 2018 emissions because only 0.3% of the Montreal's fleet was electric in 2018. As it could be expected, when EV emission value increases, more CVs need to be replaced in order to reach a given GHG emission threshold because the emission difference between vehicles is lower. However, variations in emissions are low compared to variations in EV emissions.

6. Discussion

6.1. Intermediate Results

This study first showed that instead of decreasing, overall CO₂ emissions of the Montreal fleet increased by 49% from 1990 to 2018. The 2018 Montreal fleet is also characterized by a low number of low-emission vehicles. In fact, vehicles from category 0 and 1 account for only 1.7% of the current fleet.

Results at the municipal sector scale show that people from suburban areas not only travel more than others, but also have vehicles with higher emissions per km. This result is coherent with the findings of Chen et al. [10]: neighbourhoods with high densities in population and employment own smaller vehicles. Therefore, total emissions vary from around 0.5 tCO₂ per person per year (1.4 kgCO₂ per day) in some municipal sectors on the island of Montreal to more than 3 tCO₂ per person per year (8.5 kgCO₂ per day) in the most emitting suburban areas. However, one must be careful about these results. First sensitivity analyse showed that the 2018 emissions are proportional to the factor chosen to estimate the yearly emissions based on one day's observed travel (i.e., annualizing the result). Using another value could have reduced total CO₂ emissions by 25%. In addition, real-world emissions can be very different from the values contained in the Natural Resources Canada dataset due to driving speeds or temperature for example. This fact can cause the final Montreal's 2018 emissions to have been underestimated. Despite that, results by [23,24] suggest the final results of this paper are coherent. Emissions per person are a bit higher than the values calculated by [23] for Osaka, which vary from 0.12 tCO₂ per person per year in "older single households" living in highly commercial areas to 1.13 tCO₂ per person per year in "all adult households" living in rural areas. On the contrary, they are lower than the values calculated by [24] for Quebec, which vary from 4.3 kgCO₂ per person per day in the city center to 9.7 kgCO₂ per person per day in peripheral areas. The fact that

it falls between a less car-centric urban area (Osaka) and a more car-centric urban area (Quebec City), the results seem reasonable.

Differences in average vehicle emissions per km between municipal sectors are minimal. This might be due to the aggregation level. A more disaggregated study would be more precise and would better find areas where emission reduction solutions should be focused. Such an approach was not possible in this study because the population was sampled at the municipal sector level for the OD survey. Therefore data was not reliable if studied at the dissemination area level.

According to the results, vehicles studied in this paper travelled around 11,000 km in 2018. It is a bit less than the value from the 2007 annual Canadian vehicle survey [47]. That survey estimated that the average Canadian vehicle travelled 15,797 km per year. At this date this was the lowest annual value. It is possible that the value calculated in this study is lower because it focuses on an urban area with some of the highest public transport use in Canada [48]. Unfortunately, average distances are not estimated by that earlier study [47] since 2009.

Between the two methods used to estimate the 2030 fleet, the composition of the 2030 fleet is quite different. Following the trends from previous years would result in a clustering of vehicles in categories 2 and 3 whose emissions per km vary from 108 gCO₂/km to 200 gCO₂/km. There would also be more vehicles in category 0 and 1 which emit the least. Despite these differences, the numbers and proportions of vehicles to be changed in the first fleet (naive method) are not so far from the second. In fact, the fleet resulting from vehicle replacement is really different from the initial 2030 fleet for both methods: 50% of vehicles have to be replaced with the most optimistic scenario. Therefore the composition of the fleet one works on does not seem to be that important. If the emission threshold was not this low, differences in results between the two methods would have been probably more visible. Therefore, it might not be so unrealistic to approximate the 2030 fleet by assuming the distribution of vehicles in emission categories is the same in 2030 than in 2018 in this study, as it was done with the naive method. Thus, despite the relatively small differences between the two methods, we would recommend the more detailed method.

6.2. Number of Vehicles That Need to Be Replaced

In this study, following the estimation of vehicle emissions in 1990 and 2018, a reduction of 58.2% by 2030 from the 2018 is necessary. It is almost the same objective as a previous study for Europe [14], whose objective is to decrease emissions by 60%.

The five replacement scenarios results are very different, but first, it can be noted that at least half of the fleet should be replaced by EVs to reach provincial objectives. Even if Quebec's electricity production emit a low amount of CO₂, the effort required is far from being negligible. Results by Logan et al. in the UK [20] describe a higher EV share in the fleet: even with the 100% EVs scenario, national objectives may not be met, depending on the future energy mix. Hörtl et al. [14], using a backcasting approach to investigate the potential of behaviour change, EV share and energy mix to decrease emissions by 60% from 1990 levels, showed that without acting on energy mix or travel behaviour (the assumptions that were made in this Montreal case), 97% of the fleet would need to be electric in Europe in 2050. In Montreal where the carbon content of electricity is already quite low, even the most pessimistic scenario would lead to the replacement of 75.7% of the fleet by EVs in 2030. This confirms that the Montreal case can be seen as a reference scenario as it already has an optimal energy mix.

The gap in the number of vehicles that have to be replaced by electric ones between the best and the worst scenario is high too. It means the impacts of two distinct policy choices could have significantly different repercussions: the pessimistic scenario would lead to the replacement of 49% more vehicles than the optimistic scenario.

Overall the results suggest that a targeted vehicle replacements policy rather than just supporting EV sales seems more important than the choice of the method used to replace vehicles itself.

Results are quite robust regarding annualization factor and EV emission value used. The first sensitivity analyse showed that the factor chosen to annualize the results has a much lower impact on the number of vehicles that need to be replaced to reach the provincial objective than on 2018 emissions. The other sensitivity analyse suggests that the type of vehicle chosen has not much importance on total CO₂ emissions either, as long as it is an EV, but it must not be forgotten that the study carried out in this paper only focuses on tailpipe emissions, and does not take into account the whole life cycle like articles [13,18].

Finally, the fact that vehicles CO₂ emissions per km values come from laboratory-based test results could have an impact on the number of vehicles that need to be changed but the results of the second sensitivity analysis suggest that this assumption would not have a significant influence on the number of vehicles that would need to be replaced. In addition, results showed that the method chosen to estimate the composition of the 2030 fleet has a great impact on the dominant vehicle categories in the fleet. However, the percentage of vehicles that need to be changed from the two different 2030 fleets are not very different. This other point also suggests that the precision level on the initial fleet CO₂ emissions has not much influence on the final results.

However, it must not be forgotten that the geographical area studied and the time can influence the results through carbon intensity of power generation. For example, if the study was carried out in Ontario in 2008, electric vehicles would have indirectly emitted almost 6 times more CO₂ than in this study as the carbon intensity was roughly 6 times larger [4,6]. If it was carried out in the United States of America, EVs would have indirectly emitted 12 times more (electricity carbon intensity is around 417 gCO₂/kWh in the US [7]). The scenarios results may be very different if they were carried out in these areas. For example, even with replacing all CVs by EVs with the same energy mix as USA, provincial objectives would not be met.

The values obtained via this simulation can be compared to other forecasts. The first is the electric vehicle association of Quebec's (AVEQ) 2026 objective [49]. By 2026, they would like 600 thousand vehicles to be on the roads of the province. The second is the government objective [50]: 1.5 million electric vehicles by 2030. The last one is the Hydro-Quebec estimate taken from their report [46]. That report stated that 11% of the fleet in 2029 might be electric, which would require an additional energy supply of 2.3 TWh [46]. It can be seen that the 1.5 million vehicles objective for the whole province is just enough to reach the emission reduction target just for Montreal following the optimistic scenario (1.395 million vehicles replaced). As Montreal represents only 49.1% of the provincial vehicle fleet according to the SAAQ database, it suggests that this would be insufficient without significant changes in travel behavior. It can be concluded that the provincial objective regarding the number of vehicles to be replaced should at least be coupled with other strategies to reduce veh.km travelled or to change the modal share in the province, to reach the emission reduction objective for the whole province. Results for the different scenarios show that at least 50% of the Montreal's fleet would need to be replaced by EVs to reach emission goals. That value is much higher than the 11% estimate by Hydro-Quebec. The results of this study suggest that the previous estimates were not ambitious enough.

7. Conclusions

This paper explored the possible evolution of CO₂ emissions by personal vehicles in Montreal by focusing on electric vehicle ownership. Current emissions have been estimated at 5.52 MtCO₂ in 2018 which represents a growth from an estimated 3.7 MtCO₂ in 1990. To reach the 37.5% decrease from 1990 levels by 2030, the Montreal's personal vehicle fleet has to reduce its 2018 transport emissions by 58.2%. The 2018 fleet included only 1.7% of low emission vehicles, and in this fleet, the largest GHG emitters are located in the suburban areas of the Montreal region.

A number of policy-relevant points have been highlighted here: (a) considerable changes to the fleet would need to occur in a very short time; (b) a general incentive that would result in random replacement would require over 60% of the fleet to be replaced;

(c) if the most polluting vehicles were targeted, just over half of all vehicles would need to be replaced; (d) if vehicles that are both inefficient and high use were replaced, just under 50% of vehicles would need to be replaced; on the other hand, (e) individuals in central areas are more likely to have smaller, more efficient vehicles and typically drive them less, and following this trend two-thirds to three-quarters of all vehicles would need to be replaced. However, despite the difference between the results of the five scenarios, it can be concluded that changing only the number of vehicles planned by the government or Hydro-Quebec will not be enough to reach the emission reduction objective, if replacing CVs by EVs is the only reduction strategy.

Provincial and federal governments can benefit from this policy-relevant work as they will be better informed about policy approaches to reduce emissions from transport. As seen at COP26 [51], the promotion of EVs as a solution was common, but the extent to which the vehicle fleet must change is not really known, and as it is shown there is considerable variation depending on use. This case can then be seen as a reference case given that Quebec's CO₂ emissions by electricity production are very low.

This model can be also be applied to another urban context where similar data is available.

This research focused on one parameter to reduce emissions: the number of electric vehicles in the fleet. Changing the km travelled per vehicle or the mode used would have influenced the results. However, the purpose of this analysis was to demonstrate the extent to which changes would be required in the fleet over a short period in order to meet reduction targets if a “business-as-usual” approach were taken towards car ownership and use.

The results of this study could be improved if simplifying assumptions of this study were replaced with more sophisticated models. This could be the next step for this topic in a number of ways in future studies. For example, more research could be done on vehicle occupancy for trips where a value was not given, on the factor used to annualize CO₂ emissions, and on the evolution of travel behaviour over the years and across all age groups of the population. Some recent trends suggest that people may not be buying vehicles at the same rates [52], though it could be that vehicle purchase is simply delayed [53]. Urban sprawl and socio-demographic analysis that would have helped us better understanding travel behaviour could be taken into account in a future study.

The results could also be improved if the research was carried out at a more disaggregated scale, and if a survey gathered more detailed information on the type of vehicle owned. The enlargement of the area of study to the whole province could also provide more interesting data, but emissions would be probably more difficult to estimate. Finally, a life cycle assessment approach would enable a better overall insight on the overall climate impacts. The analysis carried out by [54] illustrates this idea: the report shows that around 90% of total GHG emissions of an EV in the province of Quebec is due to the construction process, which was not taken into account in this study. As emissions are a global issue, this is an important point to consider. In the current study, only point of origin (i.e., tailpipe) emissions are considered as this directly relates to how emissions are associated to regions.

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References

1. Delisle, F.; Leblond, V.; Paradis, J.; Rioux, C.; Lacroix, O.; Lamarre, S.; Leblond, V.; Normandin, A.; Rousseau, P.L.; Turcotte, V. *Inventaire Québécois des Emissions de Gaz à Effet de Serre en 2018 et Leur Evolution Depuis 1990*; Technical Report; Ministère de l'Environnement et de la Lutte Contre les Changements Climatiques: Quebec City, QC, Canada, 2020.
2. Whitmore, J.; Pineau, P.O. *État de l'énergie au Québec 2021*; Technical Report; Chaire de gestion du secteur de l'énergie, HEC Montréal: Montreal, QC, Canada, 2021.
3. *Cible de Réduction D'émissions de Gaz à Effet de Serre du Québec pour 2030—Document de Consultation*; Technical Report; Ministère du Développement Durable, de l'Environnement et de la Lutte Contre les Changements Climatiques: Québec, QC, Canada, 2015.
4. Levasseur, A.; Mercier-Blais, S.; Prairie, Y.; Tremblay, A.; Turpin, C. Amélioration de la précision de l'empreinte carbone de l'électricité: Estimation des émissions de gaz à effet de serre des réservoirs hydroélectriques. *Renew. Sustain. Energy Rev.* **2021**, *136*, 110433. [\[CrossRef\]](#)
5. *The End of Coal*; Technical Report; Ministry of Energy: ON, Canada; 2021. Available online: <https://www.ontario.ca/page/end-coal> (accessed on 20 May 2021).
6. Mallia, E.; Lewis, G. Life cycle greenhouse gas emissions of electricity generation in the province of Ontario, Canada. *Int. J. Life Cycle Assess.* **2013**, *18*, 377–391. [\[CrossRef\]](#)
7. U.S. Energy Information Administration. How Much Carbon Dioxide Is Produced Per Kilowatthour of U.S. Electricity Generation? 2020. Available online: <https://www.eia.gov/tools/faqs/faq.php?id=74&t=11> (accessed on 20 May 2021).
8. Hill, G.; Heidrich, O.; Creutzig, F.; Blythe, P. The role of electric vehicles in near-term mitigation pathways and achieving the UK's carbon budget. *Appl. Energy* **2019**, *251*, 113111. [\[CrossRef\]](#)
9. Jasmin, D. Électricité 101: La Consommation des Véhicules Électriques. 2019. Available online: <https://roulezelectrique.com/electricite-101-la-consommation-des-vehicules-electriques/> (accessed on 30 January 2021).
10. Chen, N.; Akar, G.; Gordon, S.I.; Chen, S. Where do you live and what do you drive: Built-environmental and spatial effects on vehicle type choice and vehicle use. *Int. J. Sustain. Transp.* **2021**, *15*, 444–455. [\[CrossRef\]](#)
11. Estimations de la Population des Municipalités Selon le Groupe D'âge et le Sexe, Québec, 1er Juillet 2001 à 2020. Institut de la Statistique du Québec. 2021. Available online: <https://statistique.quebec.ca/fr/fichier/excel-estimations-de-la-population-des-municipalites-selon-le-groupe-dage-et-le-sexe-quebec-2001-2020.xlsx> (accessed on 20 April 2021).
12. Rietmann, N.; Hügler, B.; Lieven, T. Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions. *J. Clean. Prod.* **2020**, *261*, 121038. [\[CrossRef\]](#)
13. Sorrentino, M.; Rizzo, G.; Sorrentino, L. A study aimed at assessing the potential impact of vehicle electrification on grid infrastructure and road-traffic green house emissions. *Appl. Energy* **2014**, *120*, 31–40. [\[CrossRef\]](#)
14. Höltl, A.; Macharis, C.; De Brucker, K. Pathways to Decarbonise the European Car Fleet: A Scenario Analysis Using the Backcasting Approach. *Energies* **2018**, *11*, 20. [\[CrossRef\]](#)
15. Ribberink, H.; Entchev, E. Electric vehicles—A 'one-size-fits-all' solution for emission reduction from transportation? In Proceedings of the 2013 World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, Spain, 17–20 November 2013; IEEE: Barcelona, Spain, 2013; pp. 1–7.
16. Kamiya, G.; Axsen, J.; Crawford, C. Modeling the GHG emissions intensity of plug-in electric vehicles using short-term and long-term perspectives. *Transp. Res. Part D Transp. Environ.* **2019**, *69*, 209–223. [\[CrossRef\]](#)
17. Propfe, B.; Kreyenberg, D.; Wind, J.; Schmid, S. Market penetration analysis of electric vehicles in the German passenger car market towards 2030. *Int. J. Hydrogen Energy* **2013**, *38*, 5201–5208. [\[CrossRef\]](#)

18. Kloess, M.; Müller, A. Simulating the impact of policy, energy prices and technological progress on the passenger car fleet in Austria—A model based analysis 2010–2050. *Energy Policy* **2011**, *39*, 5045–5062. [\[CrossRef\]](#)
19. Wang, Z.; Erdogan, S.; W Ducca, F. Evaluating the Efficacy of Zero-Emission Vehicle Deployment Strategies: The Maryland Case. *Sustainability* **2019**, *11*, 1750. [\[CrossRef\]](#)
20. Logan, K.G.; Nelson, J.D.; Hastings, A. Low emission vehicle integration: Will National Grid electricity generation mix meet UK net zero? *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2021**. [\[CrossRef\]](#)
21. Hickman, R.; Banister, D. Looking over the horizon: Transport and reduced CO2 emissions in the UK by 2030. *Transp. Policy* **2007**, *14*, 377–387. [\[CrossRef\]](#)
22. Zahabi, S.A.H.; Miranda-Moreno, L.; Patterson, Z.; Barla, P.; Harding, C. Transportation Greenhouse Gas Emissions and its Relationship with Urban Form, Transit Accessibility and Emerging Green Technologies: A Montreal Case Study. *Procedia Soc. Behav. Sci.* **2012**, *54*, 966–978. [\[CrossRef\]](#)
23. Waygood, E.O.D.; Sun, Y.; Susilo, Y.O. Transportation carbon dioxide emissions by built environment and family lifecycle: Case study of the Osaka metropolitan area. *Transp. Res. Part D* **2014**, *31*, 176–188. [\[CrossRef\]](#)
24. Barla, P.; Miranda-Moreno, L.F.; Lee-Gosselin, M. Urban travel CO2 emissions and land use: A case study for Quebec City. *Transp. Res. Part D* **2011**, *16*, 423–428. [\[CrossRef\]](#)
25. Yang, W.; Wang, S.; Zhao, X. Measuring the Direct and Indirect Effects of Neighborhood-Built Environments on Travel-related CO2 Emissions: A Structural Equation Modeling Approach. *Sustainability* **2018**, *10*, 1372. [\[CrossRef\]](#)
26. Zahabi, S.A.H.; Miranda-Moreno, L.; Patterson, Z.; Barla, P. Impacts of built environment and emerging green technologies on daily transportation greenhouse gas emissions in Quebec cities: A disaggregate modeling approach. *Transportation* **2017**, *44*, 159–180. [\[CrossRef\]](#)
27. Al-Alawi, B.M.; Bradley, T.H. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies. *Renew. Sustain. Energy Rev.* **2013**, *21*, 190–203. [\[CrossRef\]](#)
28. Bhat, C.R.; Sen, S.; Eluru, N. The impact of demographics, built environment attributes, vehicle characteristics, and gasoline prices on household vehicle holdings and use. *Transp. Res. Part B Methodol.* **2009**, *43*, 1–18. [\[CrossRef\]](#)
29. Mobilité des personnes dans la région de Montréal Enquête Origine-Destination 2018, Version 18.2b; Autorité Régionale de Transport Métropolitain (ARTM); Processing: Pierre Laffont. Available online: <https://donnees.artm.quebec/> (accessed on 20 June 2020).
30. Enquête Origine-Destination 2018, La mobilité des personnes dans la région métropolitaine de Montréal; Technical Report; Autorité Régionale du Transport Métropolitain: Montreal, QC, Canada, 2020.
31. Liu, C.; Susilo, Y.O.; Karlström, A. Investigating the impacts of weather variability on individual's daily activity–travel patterns: A comparison between commuters and non-commuters in Sweden. *Transp. Res. Part A Policy Pract.* **2015**, *82*, 47–64. [\[CrossRef\]](#)
32. Véhicules en Circulation 2018. Société D'assurance Automobile Québec (SAAQ). 2020. Available online: <https://saaq.gouv.qc.ca/donnees-ouvertes/vehicules-circulation/Vehicule-en-circulation-2018.csv> (accessed on 20 June 2020).
33. Fuel Consumption Ratings, Natural Resources Canada, Contains Information Licensed under the Open Government Licence—Canada. 2021. Available online: <https://open.canada.ca/data/en/dataset/98f1a129-f628-4ce4-b24d-6f16bf24dd64> (accessed on 20 June 2020).
34. Profil Sociodémographique Recensement 2016, Région Métropolitaine de Recensement de Montréal; Technical Report; Ville de Montréal: Montreal, QC, Canada, 2018.
35. Statistics Canada. Table 17-10-0005-01 Population Estimates on July 1st, by Age and Sex. 2020. Available online: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000501> (accessed on 10 March 2021).
36. Perspectives Démographiques du Québec et des Régions, 2016–2066, 2019th ed.; Technical Report; Institut de la statistique du Québec: Québec, QC, Canada, 2019.
37. OSRM API Documentation. 2021. Available online: <http://project-osrm.org/docs/v5.5.1/api/> (accessed on 10 February 2021).
38. HERE API Documentation, © 2021 HERE. Available online: <https://developer.here.com/documentation> (accessed on 20 February 2021).
39. Rapport de Quantification des Emissions de Gaz à Effet de Serre Évitées par le Transport Collectif Dans la Région Métropolitaine de Montréal; Technical Report; Société de transport de Montréal et Comité de Pilotage pour la Quantification des émissions de GES évitées dans la région de Montréal: Montreal, QC, Canada, 2016.
40. Morency, C.; Verreault, H. Réduction des gaz à effet de serre: Le télétravail peut-il y contribuer? *Vecteur Environ.* **2020**, *53*, 30–33.
41. Jeanjacquot, C. Évaluation de L'intermodalité à Montréal. Master's Thesis, École Nationale des Travaux Publics de l'État (ENTPE), Lyon, France, 2011.
42. Whelan, G. Modelling car ownership in Great Britain. *Transp. Res. Part A Policy Pract.* **2007**, *41*, 205–219. [\[CrossRef\]](#)
43. Lansley, G. Cars and socio-economics: Understanding neighbourhood variations in car characteristics from administrative data. *Region. Stud. Region. Sci.* **2016**, *3*, 264–285. [\[CrossRef\]](#)
44. Shenstone-Harris, S.; Rivers, N.; Paterson, M. Have we reached peak driving? A 25-year decomposition of vehicle trends in Canada. Master's Thesis, University of Ottawa, Ottawa, ON, Canada, 2016.
45. Metin, S.; Ryuichi, K.; Jamilah, M. Residential location, vehicle ownership and travel in Asia: A comparative analysis of Kei-Han-Shin and Kuala Lumpur metropolitan areas. *Transportation* **2009**, *36*, 325–350. [\[CrossRef\]](#)
46. Portrait des Ressources Énergétiques d'Hydro-Québec; Technical Report; Hydro-Québec: Québec, QC, Canada, 2019.

47. *Enquête sur les Véhicules au Canada: Annuelle*; Technical Report; Statistics Canada: Ottawa, ON, Canada, 2007.
48. *Commuting to Work, National Household Survey (NHS)*; Technical Report; Statistics Canada: Ottawa, ON, Canada, 2011.
49. Morissette, J.F.; St-Laurent, F.; Rioux, S.P. Statistiques SAAQ-AVEQ sur L'électromobilité au Québec en Date de 31 Mars 2021. 2021. Available online: <https://www.aveq.ca/actualiteacutes/pre-a-publier-statistiques-saaq-aveq-sur-lelectromobilite-au-quebec-en-date-du-31-mars-2021-infographie> (accessed on 20 April 2021).
50. *Plan Pour une Economie Verte 2030*; Technical Report; Gouvernement du Québec: Québec, QC, Canada, 2020.
51. United Nations Climate Change. COP 26 Speeches and Statements. 2021. Available online: <https://unfccc.int/cop26/speeches-and-statements> (accessed on 10 November 2021).
52. Belgiawan, P.F.; Schmöcker, J.D.; Abou-Zeid, M.; Walker, J.; Lee, T.C.; Ettema, D.F.; Fujii, S. Car ownership motivations among undergraduate students in China, Indonesia, Japan, Lebanon, Netherlands, Taiwan, and USA. *Transportation* **2014**, *41*, 1227–1244. [CrossRef]
53. Rérat, P. A decline in youth licensing: A simple delay or the decreasing popularity of automobility? *Appl. Mobil.* **2021**, *6*, 71–91. [CrossRef]
54. Roy, P.O.; Ménard, J.F.; Fallaha, S.; Samson, R. *Analyse du Cycle de vie Comparative des Impacts Environnementaux Potentiels du Véhicule Electrique et du Véhicule Conventionnel Dans un Contexte D'utilisation Québécois*; Technical Report; CIRAIG: Montreal, QC, Canada, 2016.