A global method for assessing energy and emissions for future mobility scenarios

Une méthode globale pour évaluer l'énergie et les émissions des futurs scénarios de mobilité

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ABSTRACT

The transport sector is one of the main energy consumers in developed countries and therefore a change toward less energy intensive forms of mobility is crucial for the success of any strategy aiming to use less energy. Electrification of vehicles promises to help in this respect but there are still several unknown on how this will be deployed and on its actual impacts on several levels. This project proposes an innovative methodology based on the integration of a particular class of transportation models, agent-based simulations, with life cycle assessment, in order to be able to get insight into the energy impact of innovative transportation solutions. This is a broader scope than the electrification of the transportation sector alone, but the many changes (strictly technological or enabled by new technology) that the transportation sector is experiencing now and is expected to experience even more in the future, call for an approach that can assess al such changes. Only such global, holistic view, allows a fair and complete assessment of future transportation scenarios. Such a model has been developed as part of this project and is described in detail in the document. In order to demonstrate its functioning and its suitability for the task at hand, three scenarios have been created and assessed: a baseline scenario representing the current situation (transportation system, travel demand) in the Montreal area, and two hypothetical scenarios that assume a large adoption of electric vehicles by the public and a larger carsharing system respectively. The finesse in the modeling proposed by this methodology makes it possible to calculate the impacts of the adoption of innovations in modes of travel by taking into account the diversity of uses made of them. Embedding life cycle analysis in such tool allows calculating complete impacts of different mobility solutions according to all phases of their life stages, This methodological contribution will make it possible to assess other mobility scenarios involving other innovations from an energy consumption perspective.

RÉSUMÉ

Le secteur des transports est l'un des principaux consommateurs d'énergie dans les pays développés et, par conséquent, un changement vers des formes de mobilité moins énergivores est crucial pour le succès de toute stratégie visant à utiliser moins d'énergie. L'électrification des véhicules promet d'y contribuer mais il reste encore plusieurs inconnues sur la manière dont elle sera déployée et sur ses impacts réels à plusieurs niveaux. Ce projet propose une méthodologie innovante basée sur l'intégration d'une classe particulière de modèles de transport, des simulations basées sur des agents, avec l'analyse du cycle de vie, afin de pouvoir avoir un aperçu de l'impact énergétique des solutions de transport innovantes. Il s'agit d'un cible plus large que l'électrification du secteur des transports à elle seule, mais les nombreux changements (strictement technologiques ou rendus possibles par de nouvelles technologies) que le secteur des transports connaît actuellement et connaîtra encore plus à l'avenir, appellent à chercher une approche qui peut évaluer tous ces changements. Seule une telle vision globale et holistique permet une évaluation correcte et complète des futurs scénarios de transport. Un tel modèle a été développé dans le cadre de ce projet et est décrit en détail dans le document. Afin de démontrer son fonctionnement et son adéquation à la tâche à accomplir, trois scénarios ont été créés et évalués: un scénario de référence représentant la situation actuelle (système de transport, demande de déplacement) dans la région de Montréal, et deux scénarios hypothétiques qui supposent un large adoption de véhicules électriques et d'un plus grand système d'autopartage respectivement. La finesse de la modélisation proposée par cette méthodologie permet de calculer les impacts de l'adoption d'innovations dans les modes de déplacement en tenant compte de la diversité des usages qui en sont faits. Intégrer l'analyse du cycle de vie dans un tel outil permet de calculer les impacts complets des différentes solutions de mobilité en fonction de toutes les phases de leurs étapes de vie. Cet apport méthodologique permettra d'évaluer d'autres scénarios de mobilité impliquant d'autres innovations du point de vue de la consommation d'énergie.

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LIST OF SYMBOLS AND ABBREVIATION

ABM	Agent-based Modeling
BEV	Battery Electric Vehicle
CMA	Census Metropolitan Area
CO	Carbon Monoxide
CO2	Carbon dioxide
EV	Electric Vehicle
SEV	Shared Electric Vehicle
GHG	Greenhouse gases
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
kW	kilowatt
kWh	kilowatt-hour
km	Kilometer

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MaaS	Mobility as a Service
MATSim	Multiagent transport simulation
NOx	Nitrogen oxide
SOx	Sulphur oxide
TtW	Tank-to-Wheel Energy

MODEL AND METHODOLOGY

Introduction

For decades, transportation, both in the urban and the interurban contexts, has been dominated by automobile. On the one hand, the automobile offers a flexible and relatively affordable transportation option for the population; on the other, it causes huge negative externalities being energy consumption, in the form of fossil fuels, and the consequent GHG and other toxic emissions among the most notable ones. Several novelties, however, has been introduced, or are starting to become popular, in recent years and are expected to substantially change the status quo.

Broadly, these can be put in two categories. The first, purely technological, is the transition of cars and vehicles, in general, from internal combustion units toward different power trains and in particular electric ones. In the second, technology enables new approaches to mobility and in particular, all forms of shared mobility (including autonomous vehicles in the future) and their integration into mobility as a service (MaaS) scheme. Electrification, assuming constant motorization rate and same mobility patterns, reduces direct emissions. Innovative mobility services, assuming same mobility and flexibility levels, reduce the global vehicular fleet and eventually also curb travel behavior toward less car dependent patterns. The logic for expecting such impacts may appear quite clear and simple; however, trying to quantify such impact is tricky. If we know that electrification reduces direct emissions, we need to take into account that electricity production will in general cause emissions. Moreover, it is known that manufacturing an electric vehicle is more energy and emission intensive than its internal combustion counterpart. Similarly, shared mobility promises to reduce the fleet necessary to offer a certain level of mobility, but vehicles will be used more intensively and therefore will need to have a quicker turnaround.

Transportation planning usually neglects such issues and transportation models in general are not particularly suitable to answer such questions. Looking at the whole life cycle of vehicles, or of whole transportation options (for example, carsharing, bikesharing, etc.) is a way to address such questions. However, their application typically tends to consider that demand level and mobility patterns would stay the same, but this is not expected to be true and even, it will vary depending on the kind of technologies and services introduced. All the above calls for integrating transportation models with LCA, and this is the main proposition of this project. The approach proposed has been operationalized and to demonstrate its functioning, two scenarios, one with a large use of electric vehicles, and another one with a moderate adoption of a carsharing system have been simulated.

Description of the model used

In this modeling exercise, Agent Based Modeling (ABM) and Life Cycle Assessment (LCA) were coupled to model the energy and environmental impacts of the transportation systems. In short, the transportation agent-based model simulates traffic flows at individual vehicles level taking into account how individuals are trading off among different mobility options. After the simulation, the ABM outputs are fed into the LCA model in order to calculate the energy and environmental impacts. The LCA exercise in itself, although being peculiar in some respects (the extension of its application to a complete transportation system, instead of a single vehicle) do not imply any special attribute of the model compared to more common LCA applications. Key in the modeling exercise is therefore the transport simulation and how it produces the input for the LCA. More details on both parts are given below.

MATSim: The agent-based simulation of the transportation system

The transportation model used in the project is an open-source multi-agent transportation simulation called MATSim. MATSim has been jointly developed over the last 15 years by two research groups at ETH Zurich and TU Berlin. The main idea behind multi-agent simulations is to represent individually the actors (agents) of the system that we want to model and give them specific behavioral rules. The latter define how they act in an artificial (computer simulated) environment and how they interact with other agents. The behavior of the system emerges from the simulation and from the behavior at the micro scale. Through ABM, researchers can conduct a wide range of virtual experiments to acquire new insights on complex systems. In MATSim, agents perform activities throughout the day, such as being at home or work, and going shopping. Agent needs to physically be at the locations where such activities are performed, and this leads to travel between such locations. MATSim's is based on a co-evolutionary algorithm. Agents, in order to optimize their plans, will make choices, such as mode choice, time choice, destination choice and route choice, as the same day is simulated iteratively until equilibrium in the system is reached. Its output provides, among other information, origin and destination, network distance, time, and mode for every trip of every agent while traveling between activities.

Additionally, MATSim allows users to add and customize extensions of their choice, thanks to its modular concept. In the electric vehicle module, for instance, MATSim can generate electricity consumption and auxiliary energy use for heating, cooling, etc.

The use of a transportation model implementing the agent-based paradigm is necessary for this project as it is the only class of models consistently maintaining the individual representation throughout the model. This is important because this allows having the kind of behavioral plausibility in the future scenarios that has a fundamental role in this project. Although other models can deal with individual travelers, usually they consider demand being completely exogenous, and/or they do not consistently represent individual travel constraints in the network assignment step of the model (trip-based assignment). **MATSim is unique as it is the most widely tested and used transportation agent-based simulation worldwide** and the one with the most already existing functional modules to simulate virtually all different kinds of innovative forms of mobility.

Travel demand

The transportation agent-based approach relies on the definition of a synthetic population for the study area. This population replicates the main socio-economic, activity and travel characteristics of the true population. As a result, synthetic agents are defined.

To this end, research has investigated various methodologies (Müller and Axhausen, 2010). In this research, we use a reconstruction method called **Hierarchical Iterative Proportional Updating** (HIPU) (Ye et al., 2009; Konduri et al., 2016). The basic idea of HIPU is to combine rich but small sample data (survey data for example) with more complete but less detailed data (census data for example). The HIPU scales up the sample population using expansion factors computed from census data. Individual expansion factors are computed for each record in the sample data to match the total population of the study area.

The HIPU has two main advantages:

1. It accounts for both persons and households to compute expansion factors.
2. It allows for different data sources with different spatial resolutions to be used.

HIPU requires two data sources: (i) population census data; (ii) Household Travel Surveys (HTS).

To attach daily activity plans and travel details to synthetic agents, a statistical matching algorithm, i.e., k-Nearest Neighbor (KNN) is performed. For each synthetic agent, this method looks for the closest HTS record and assigns its activity plan to the agent.

Travel supply

To perform their daily activities, agents need to travel from one place to another. In this research, most conventional travel modes are included: car, transit, bike and walk. The routing of these modes requires various information on the network, like the speed limit or the number of lanes of a road or the transit schedule. These data are obtained from several sources detailed in the section Data Accessibility (Table 1).

Calibration

In MATSim, agents learn how to optimize their decisions. The learning process is based on a genetic algorithm that favors “optimal plans” on the expense of “bad” ones. Each agent decides which travel mode to choose, which network route to take, and at what time to start a specific activity. At the end of each simulation day, agents score their daily routines and choose the optimum plan for the next day. For a specific study area, one needs to calibrate the scoring function parameters in order to replicate the observed behaviors and the aggregate dynamics of the mobility system. This operation is called calibration.

Simulation of electric vehicles

Electric vehicles (EVs) are subject to discharging and recharging constraints. Energy consumption of EVs is attributable to two main sources:

1. The vehicle traction system
2. The auxiliary energy consumption

Energy consumption by the traction system is computed according to (Ohde et al., 2016). Auxiliary energy consumption is due to onboard gadgets, lights, heating or air-conditioning. When activated, heating or air-conditioning accounts for most auxiliary energy usage. In this regard, auxiliary energy consumption is dependent on the outdoor temperature. **Our methodology allows to set this parameter to match any local or seasonal weather conditions**.

In MATSim, EV drivers schedule their trips and routes considering the state of charge of the EV battery and the expected energy consumption of the trip. If the current state of charge is insufficient to cover the whole trip, agents add a charging stop in their daily trip plan to recharge the EV battery. In this case, agents are assumed to fully recharge their EVs. The time spent recharging the battery is considered as a penalty. The higher the penalty of the trip the less likely the agent continues to use the EV as a travel mode for that specific trips. In this case, agents can use other travel modes, if available.

Simulation of electric shared cars

The use of shared electric cars requires the possession of a carsharing membership. This membership can give access to all carsharing services or to only some of them. These services are of three types:

1. One-way cars
2. Two-way cars
3. Free-floating cars

One-way cars can be picked up at a station and dropped-off at another 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 the carsharing service area.

As in the case of EVs, Shared EVs (SEV) are subject to discharging and recharging constraints.

Life Cycle Assessment

LCA is used to quantify the environmental impacts of a product based on a cradle-to-grave concept. This may include emissions, energy use, water use, impact on marine life and human life, among others. Such assessment is made throughout the product lifetime stages, from raw material extraction to operation, and to disposal as described in ISO 14040 and ISO 14044 (ISO Standard, 2006). In the project, two types of powertrain were considered: internal combustion engine vehicle (ICEV) and battery electric vehicle (BEV). As no other forms of electric vehicles (for instance Hybrid Plug-In Vehicles) are considered, for the sake of simplicity, we will simply refer to the latter as EV in the rest of this document. Similarly, only gasoline-fueled vehicles were considered as ICEV. Passenger car is the only vehicle type considered in the LCA. In this project, it was looked at the full lifecycle stages as it enables accounting for the indirect and direct upstream processes of the vehicle.

The elements of this LCA include the production of vehicle (glider and powertrain), use phase (exhaust and non-exhaust emission), energy chain (electricity and fuel production), energy storage, maintenance, end-of-life treatment, construction and maintenance of road infrastructure. Additionally, it was assumed that batteries from electric vehicles and most vehicle components are scrapped at the end of service; however, the impact of recycling material used in a production of new vehicle is not considered.

Functional Unit

In LCA, the functional unit describes the quantitative function of a studied system according to a reference flow (Baumann and Tillman 2004). The functional unit of an LCA depends entirely on the type of product system as well as the goal and its system boundary. A common unit to describe the environmental burden of a vehicle is potential impact per passenger-kilometers or vehicle-kilometers over lifetime (Hawkins et al. 2012). However, these units are not able to provide an effective assessment of the impact of a service or a transport system as a whole (Guyon 2017; Chalaka Fernando et al. 2020). To overcome this limitation, Chalaka Fernando (2020) suggested defining a functional unit for the impact of transportation systems that can represent usage pattern of a whole service rather than a product. For this LCA exercise, the functional unit is defined as **potential impacts of mobility scenario for a single day in 2021**.

Life Cycle Inventory

Life cycle inventory (L) collects the necessary input and output information for the studied system for all life cycle stages (ISO, 2006). Data for manufacturing, maintenance, and end-of-life phases is obtained from ***ecoinvent 3.7*** for both powertrains. The input and output data of the use phase for ICEV also relied on the same ***ecoinvent*** database. To reduce bias on assumptions of key parameters (e.g., vehicle driving mass, etc.), we used an uncertainty analysis method with Monte Carlo simulation to generate a possible range of input values.

Other LCI key parameters are retrieved from the simulation results:

*Tank to Wheel Energy***:** EV energy consumption by the traction and auxiliary energy use for Tank-to-Wheel energy (TtW energy) are retrieved from electricity consumption per vehicle in MATSim outputs. The energy consumption by the traction depends on vehicle characteristics, distance travelled, congestion and even driving habits (eco-driving for example) and is computed according to (Ohde et al., 2016).

*Lifetime mileage***:** Lifetime mileage for both powertrains is derived from the driving distance in the simulation. For instance, if a vehicle travels 41 km in the simulation, it is assumed that this is the average distance that will be driven over 10 years of lifetime (i.e., 41 km per day x 365 days x 10 years, where 10 year represent the lifespan assumed for the vehicle). For electric vehicle in carsharing scenario, a new assumption is applied regarding lifetime mileage, which is derived from (Greenblatt and Saxena 2015).

Manufacturing, maintenance, use phase and end-of-life require electricity: Depending on the location and energy source, electricity production can result in different environmental footprints. **In this project, electricity was modeled from the grid system of Quebec. Most of its energy comes from renewable sources**. Share of energy source in the electricity mix is assumed to be consistent throughout the day, therefore, hourly electricity mix is not taken into account.

Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is an important part of the LCA that translates all environmental loads from inventory such as CO, CO2, NOx, SOx, etc. into an environmental impact category such as, for example, climate change or acidification (Baumann and Tillman 2004). This translation process in LCIA is known as characterization method. This study uses *Carculator*, a python package developed by (Sacchi et al. 2020) for life cycle assessment, to implement LCI and LCIA. Results are presented as characterization results instead of inventory results because they are more comprehensible and easier to communicate. The ReCiPe 2008 method is used to characterize the inventory results (ReCiPe 2008). LCIA results provide among other, primary energy use (renewable and non-renewable), and midpoints impact categories (i.e., Climate change, Acidification, Smog formation, Formation of fine particle).

ABM-LCA Simulation Steps

Coupling ABM to LCA brings more complexity, as all elements for the assessment are broken down to the individual vehicle level, but the bottom-up approach of ABM is helpful for the simulation of adaptive social processes.

Concretely the coupling of ABM-LCA is implemented based on the following steps:

Step 1: A vehicle inventory is built (weight, aerodynamic force, drivetrain efficiency, rolling drag coefficient, etc.) based on existing car models. Once the car models are created in the inventory, their specification information is applied.

Step 2: Agents perform activities according to their daily plans and decide on the optimal mode, route, and time. Travel behavior is constrained by the traffic conditions, and particularly if EVs are used, range and charging. The simulation is carried out over a series of iterations. MATSim records the information of charging time and energy use, which are available at the vehicle level. Based on this information, TtW energy for each vehicle is derived by summing electricity use, auxiliary use, and energy loss (15% loss based on Sacchi et al. 2020) as detailed above. TtW energy of simulated vehicles are then applied to build the LCI for the use phase of vehicle.

Step 3: TtW energy is used as the final demand vector for LCI at the use phase of EV. Other life cycle stages (i.e., manufacturing, maintenance, energy storage, road, end-of-life) rely on the inventories collected from ***ecoinvent***. LCI is constructed for each vehicle and once it is created, LCIA is performed for each vehicle using their respective LCI.

Step 4: LCIA calculation provides impact factor (i.e., emission factor) for the chosen impact categories and energy consumption factor for primary energy consumption. These calculated values are then multiplied by the kilometer-travelled distance of all individual agents and aggregated to determine impacts equivalent per day according to the chosen functional unit.

Data accessibility and data sources used

Table 1: Database and source of database used in the modelling exercise

Data	Description	Provider	Access	Access/information link
HTS	Household Travel Survey data	ARTM	Restricted	https://www.artm.quebec/enqueteod
Census	Population census	Statistics Canada	Open access	https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E
Real estate	Characteristics of buildings	MAMOT	Restricted	https://www.mamh.gouv.qc.ca/fileadmin/publications/evaluation_fonciere/documentation/role_evaluation_contenu.pdf
Networks	Car, bike, and walking networks	OSM	Open access	https://www.openstreetmap.org
Transit network	Transit routes and schedules	GTFS	Open access	http://www.stm.info/en/about/developers
Carsharing stations	Location of carsharing stations	Communauto	Open access	https://www.reservauto.net/Scripts/Client/Ajax/Stations/ListStations.asp?CityID=59&LanguageID=1&BranchID=1
LCA-Background inventory	Life Cycle Inventory Database	Ecoinvent	Open access via Carculator	https://carculator.psi.ch https://www.ecoinvent.org/
LCA-Foreground inventory	Life Cycle Inventory Database	Ecoinvent	Open access via Carculator	https://carculator.psi.ch https://www.ecoinvent.org/

Scenario development process and formulation of underlying assumption

For this modeling exercise, three scenarios for the study area of Montreal are used. Two hypothetical scenarios of a large adoption of electric vehicles (EV) and a moderate adoption of an electric carsharing system. Both scenarios are compared to a business-as-usual (BAU) or baseline scenario.

Baseline scenario

The Census Metropolitan Area (CMA) of Montreal has a population of nearly 4 million persons (Statistics Canada, 2016). 47% of this population lives in the island of Montreal (fig. 1). For this research, we prepared a synthetic population summarizing the main activities and travel characteristics of the population of Montreal on an ordinary working day. Different data sources are used to prepare this population: census data (Statistics Canada, 2016), Household Travel Survey (HTS) (MTQ, 2013), car ownership data (SAAQ, 2016), and real estate data (MAMOT, 2014).

To keep computation times reasonable, a 5% random sample of the synthetic population is retained, resulting in 202,387 agents and 86,174 households. The downsampling of the population and network capacities has no significant impact on the outcomes of this research.

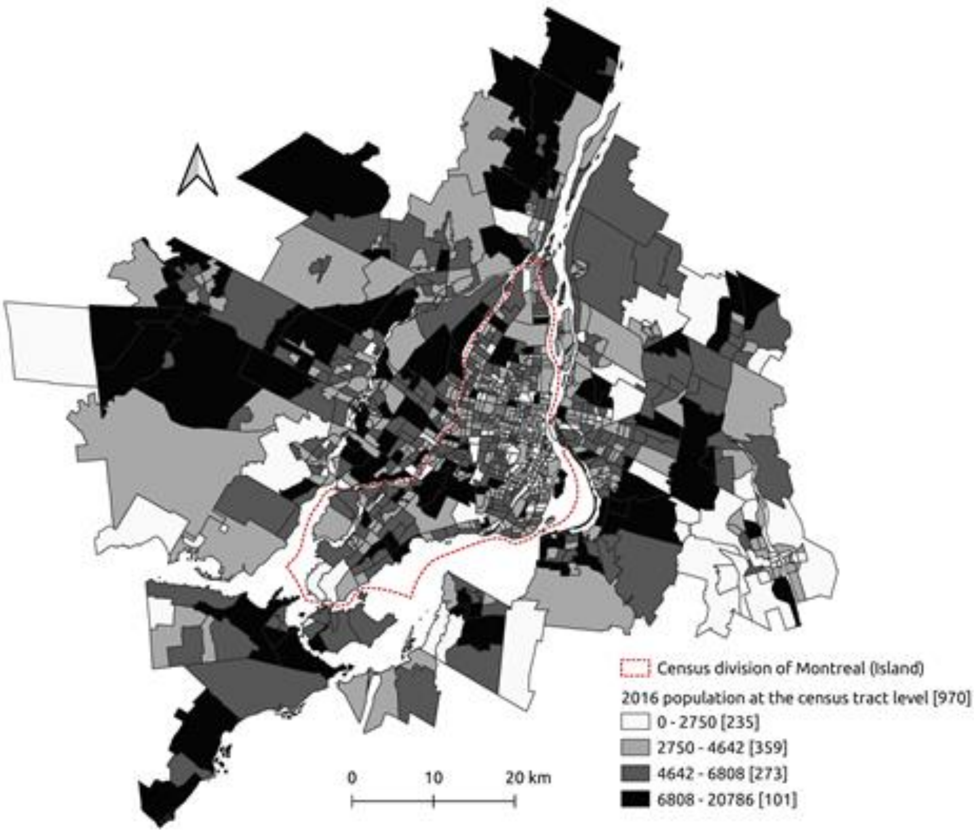

Figure 1: Population of the census metropolitan area of Montreal

The baseline scenario is introduced as a reference point to which the two hypothetical scenarios are compared. This scenario includes all conventional travel modes: car, transit, bike and walk. Neither electric vehicles nor carsharing are included in this scenario. The BAU scenario has been calibrated to reproduce observed travel mode shares (fig. 2).

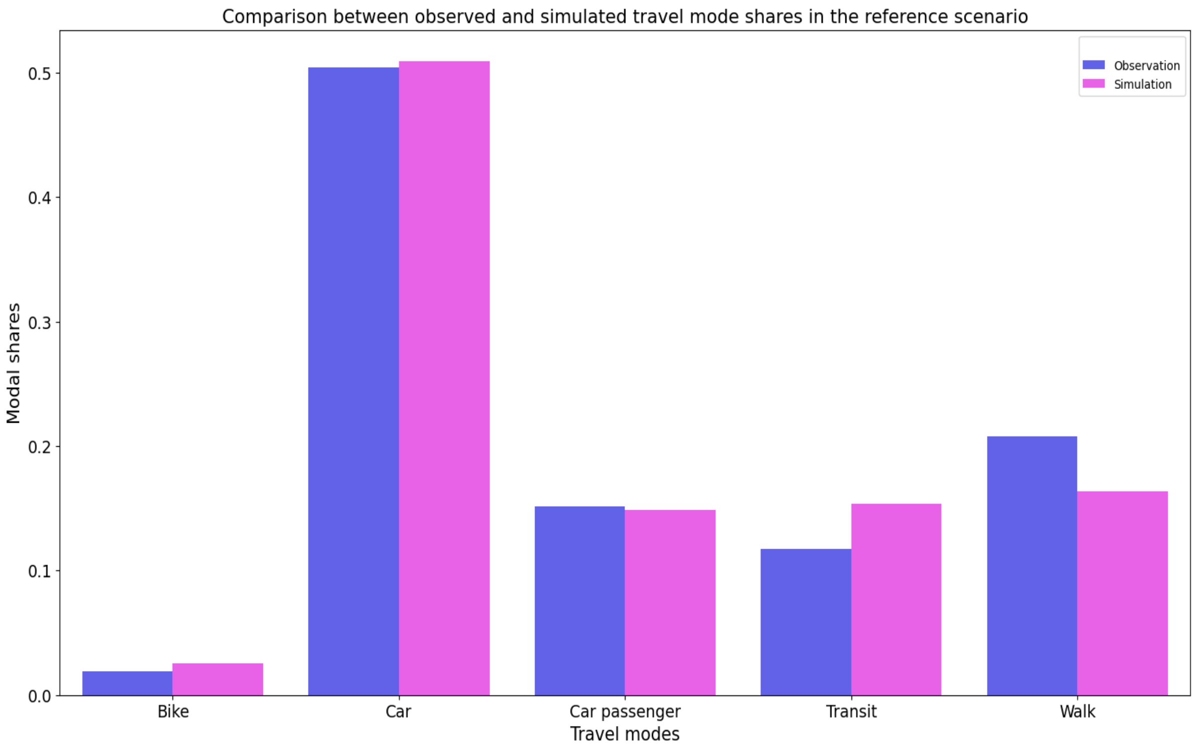

Figure 2: Calibration of the baseline scenario

Electric vehicle scenario

The EV scenario of Montreal, hereafter referred to as the EV scenario, is introduced to assess the impacts of a **high penetration rate of full battery electric vehicles** in the Census Metropolitan Area (CMA) of Montreal. **The EV scenario is built upon three main assumptions**:

1. Penetration rate of EVs: how many EV adopters?
2. Characteristics of the EV fleet: which EV for which agent?
3. Charging stations: how many stations and where are they located?

In practice, the EV scenario is built upon the BAU scenario by introducing electric cars as a new travel mode, in addition to the conventional other modes. In comparison with fuel-powered cars, EVs are subject to discharging and recharging constraints. The routing, recharging and discharging operations are handled by two models: MATSIM and the MATSIM EV contribution (Horni et al. 2016; Waraich and Bischoff, 2016).

Penetration rate of EVs

The EV scenario assumes that all car owners of the CMA of Montreal who travel less than **150 km a day own an electric vehicle (EV)**. The 150 km is an arbitrary threshold used to filter out car owners who travel long daily distances. These car users are less likely to adopt the EV technology, given the current battery capacity limitations. This threshold can be set to any value depending on local observations or current or future capacity projections of EV batteries. Given this 150 km threshold, nearly 99% or 1,559,560 Montrealer car users are assigned an EV.

EV fleet characteristics

Agents with varying characteristics, like income, household size, or daily travel distance, can have varying preferences for EV models. The agent-based framework proposed in this research can account for taste variability. To this end, data on individual or grouped preferences of EVs are needed. In the EV scenario of Montreal, we assume that all EV owners have the same preferences, i.e., no taste heterogeneity. All EV owners are assigned the same EV model: a **Nissan Leaf model with a battery capacity of 60 kWh**. It should be noted that, although, only one EV model is considered here, the approach naturally allows accounting for different models as every single vehicle is simulated.

Charging stations

The recharging of EVs can be either performed at home or at a charging station. Home charging is assumed to be performed after the latest out-of-home activity involving a car trip. This is mostly done by night. Recharging at out-of-home stations can be performed all-day. All EVs are assumed to start their day with a full state of charge battery.

The charging supply of the CMA of Montreal is resized to meet the hypothetical EV demand. The characteristics of the charging station system are defined in accordance with the new EV demand. The number and spatial distribution of these stations are defined using the density of car trip ends. Charging stations are assigned to zones with high density of car trip ends as they are more likely to be used.

14,680 charging stations are introduced in the CMA of Montreal, most of them are located in the island of Montreal (fig. 3). All charging stations deliver the same power of **100 kW** and have **5 charging plugs.**

For the auxiliary energy consumption of EVs, an outdoor temperature of 15 degrees Celsius is assumed. **Our methodology allows to set this parameter to any other outdoor temperature.**

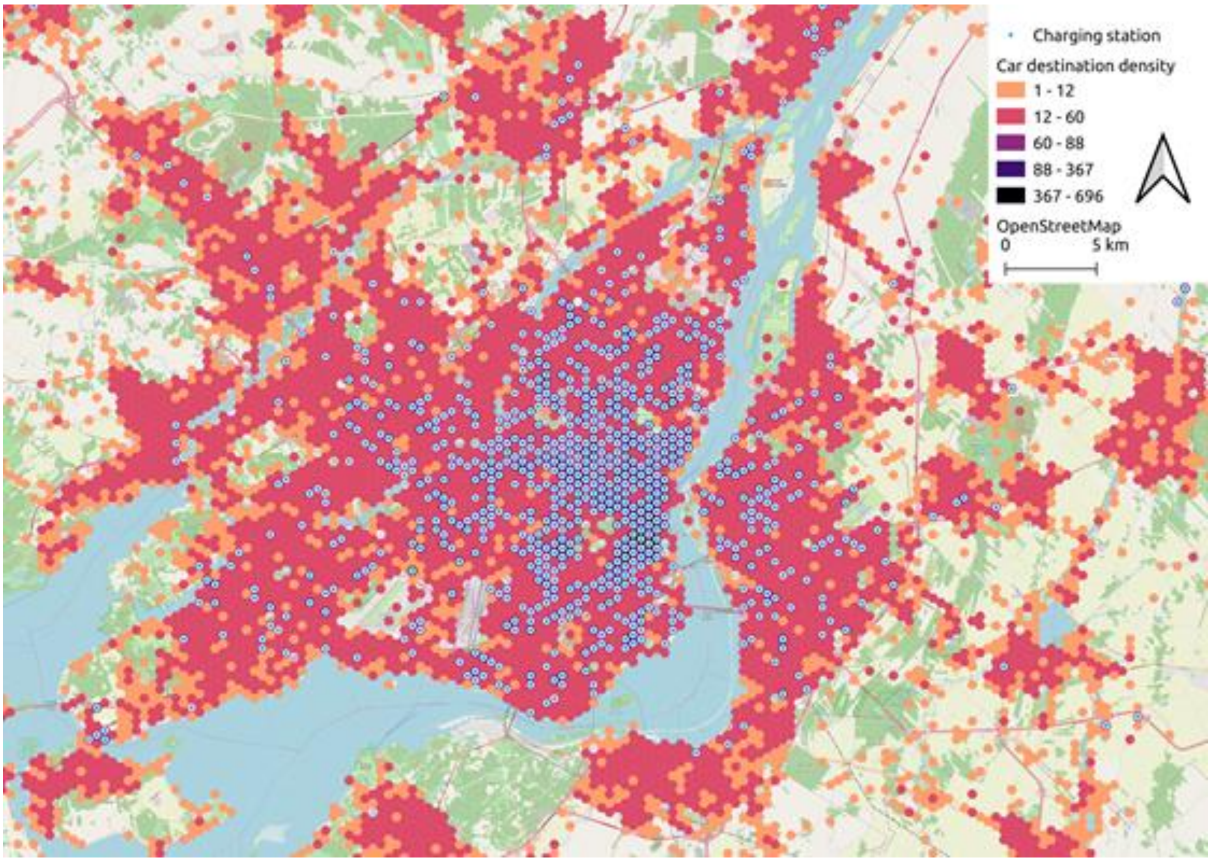

Figure 3: Spatial distribution of the charging stations in the CMA of Montreal

Carsharing scenario

The carsharing scenario, hereafter referred to as e-carsharing, is a hypothetical scenario of a moderate adoption of a carsharing system based on EVs in the CMA of Montreal, Quebec. **The EV-Carsharing scenario is built upon the following assumptions**:

1. Carsharing membership: members of the carsharing system
2. Carsharing supply: location of carsharing stations and their shared vehicles

Carsharing membership

In the e-carsharing scenario, **10% of the population is given a carsharing membership**. This share is to be compared with 4%: the actual share of carsharing members in the CMA of Montreal. The selected agents are randomly drawn from the total population. This results in nearly 400,000 agents.

Our methodology allows for other membership assignment strategies to be used. Memberships can be assigned, for example, based on a threshold distance from carsharing stations, or based on car ownership or a mix of both criteria.

Carsharing supply

11,460 carsharing stations are introduced in the CMA of Montreal (fig. 4). **Each station offers 6 vehicles for reservation**: 3 two-way EVs and 3 one-way fuel-powered cars. This results in 68,760 shared vehicles, of which 34,380 are EVs. Shared EVs are assumed to have a **battery capacity of 100 kWh**. This capacity is greater than that of personal EVs (60 kWh).

Communato data (Table 1) are used to infer the spatial location of carsharing stations. Each station contains 6 charging plugs delivering a power of **25 kW**. **The recharging of shared EVs is only allowed at carsharing stations.**

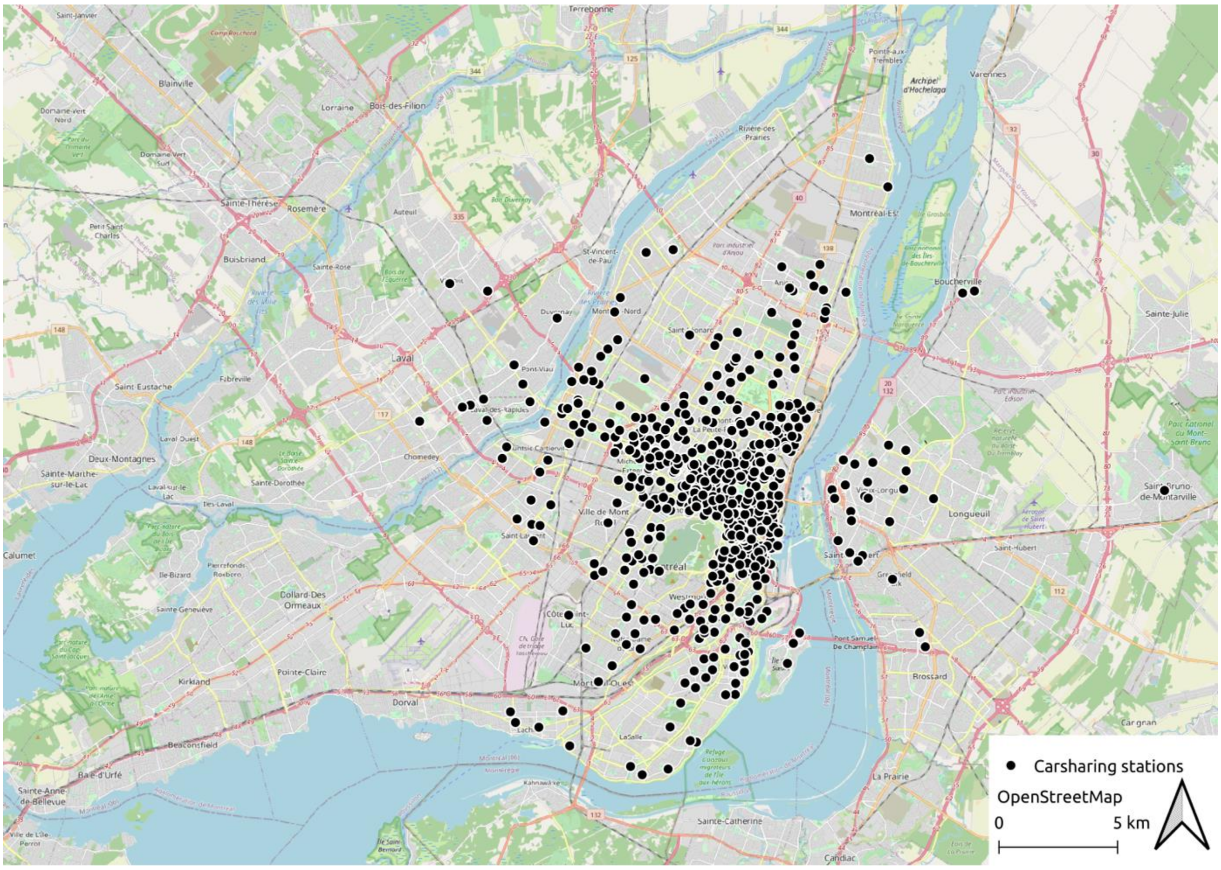

Figure 4: Spatial distribution of the carsharing stations in the CMA of Montreal

MODELLING RESULTS AND ANALYSIS

The project investigates two scenarios related to the transition of the transportation sector toward electrification. The main contribution of the project is methodological. In this respect, it is more relevant to discuss the nature of the results delivered by the proposed methodology than the numbers as such. As explained in more detail in the first section of this report, it is also important to put such an exercise in the correct context. The expected transformations of the transportation sector render necessary the creation of new tools that would: (a) allow the modeling of all potential transformations; (b) allow assessing the whole transportation systems based on different paradigms in a fair way. To demonstrate how our methodology achieves these two objectives, we show the results of three scenarios described in detail in the previous section. These are: a reference scenario that reproduces the current situation in Montreal, and two future hypothetical scenarios that consider, for one, a high penetration of EVs among private vehicles, and for the other, a moderate adoption of a carsharing system with EVs. **The future scenarios are two examples among many others that can demonstrate the added value of the proposed methodology.**

LCA outcomes

Based on the travel mode and travel distance computed by MATSim for each agent in the population, it is possible to calculate the total energy consumption during driving as the sum of the energy consumed to move the vehicle and the auxiliary energy it uses. As expected, the **EV scenario reduces significantly the driving energy consumption** in comparison to the baseline scenario (fig. 5). This reduction is totally attributable to the introduction of EVs. The reduction of energy consumption by the e-carsharing scenario is not significant. **This is expected as the adoption of shared cars is limited (< 1%)**, even when 10% of the population has a carsharing membership.

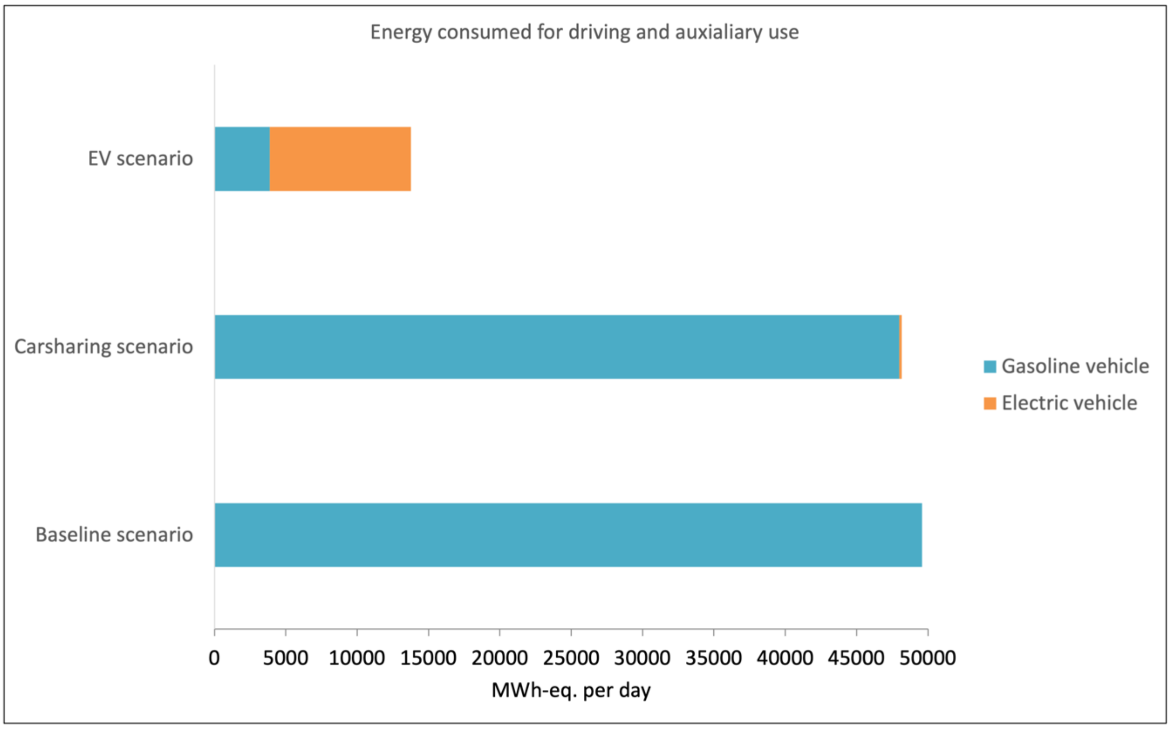

Figure 5: Total energy consumed for driving and auxiliary use per day

The impact of the introduction of EVs and shared cars goes beyond the reduction in energy consumption while driving. **One major contribution of this research is to assess the lifetime impacts of these technologies** by using the life-cycle assessment. In this regard, the life cycle impacts of each technology can be assessed at two levels:

1. Technology level: life cycle impacts of one vehicle of a specific technology (Gasoline vehicle, EV, SEV)
2. Scenario level: computed for the overall fleet

At the technology level, the primary energy usage for the three technologies is compared in figure 6. **Over their lifetime**, the energy impact of EVs and SEVs is half that of the conventional gasoline car. Moreover, 40% of this impact is attributable to a renewable energy source.

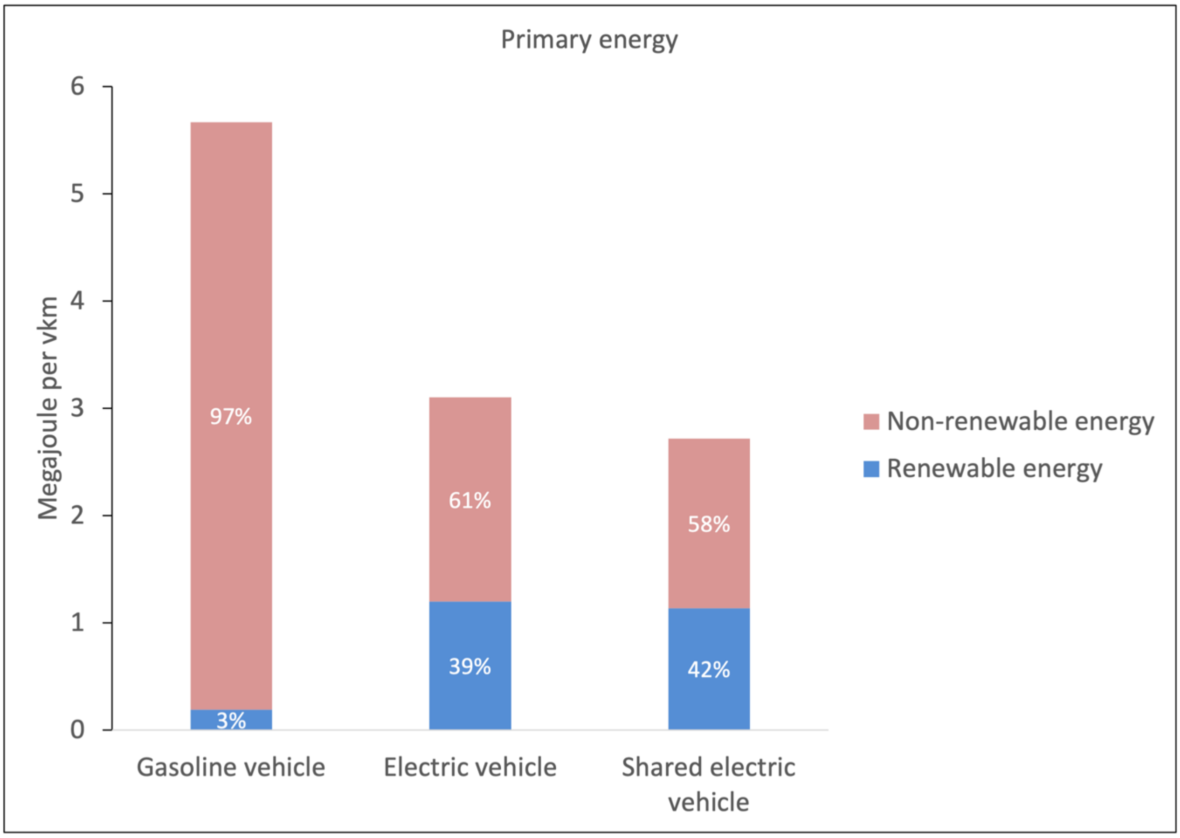

Figure 6: Life cycle primary energy consumption of Gasoline vehicle, Electric vehicle, and Shared electric vehicle

The non-renewable energy impact of the three technologies can be further traced back to their sources. Over the lifetime of a gasoline car, the energy chain (petrol extraction, transportation, and distribution) and chassis production account for most of its energy impact. For EVs and SEVs, chassis production and road construction are the main sources of non-renewable primary energy impacts (fig. 7).

Figures 6 and 7 show that SEVs have a lesser energy impact than EVs. This is due to the underlying assumption regarding the total mileage over the lifetime of the vehicles. **SEVs are assumed to be more intensively used than EVs**. **This assumption has two implications**. The first implication is the average total mileage of SEVs at the end of their lifetime should be greater than that of EVs. The second implication of the intensive use of SEVs is their shorter life span in comparison with EVs or gasoline cars. This implies frequent vehicle replacement and maintenance. **The frequency of these operations depends on the carsharing operator strategy.**

Given these two implications, **SEVs should have a lesser energy impact than EVs when they are compared over their corresponding lifetime** (fig. 7). However, **over the same period, 10 years for example, SEVs have a greater energy impact than EVs** (fig. 8) as they need to be replaced and maintained more often. This impact depends on the lifetime (abbreviated as LT in Figure 8).

Figure 8 assesses the sensitivity of this impact with a varying SEV life span ranging from 2 to 5 years. **In the case of a short life span of 2 years, SEVs are found to have a higher energy impact than gasoline cars.**

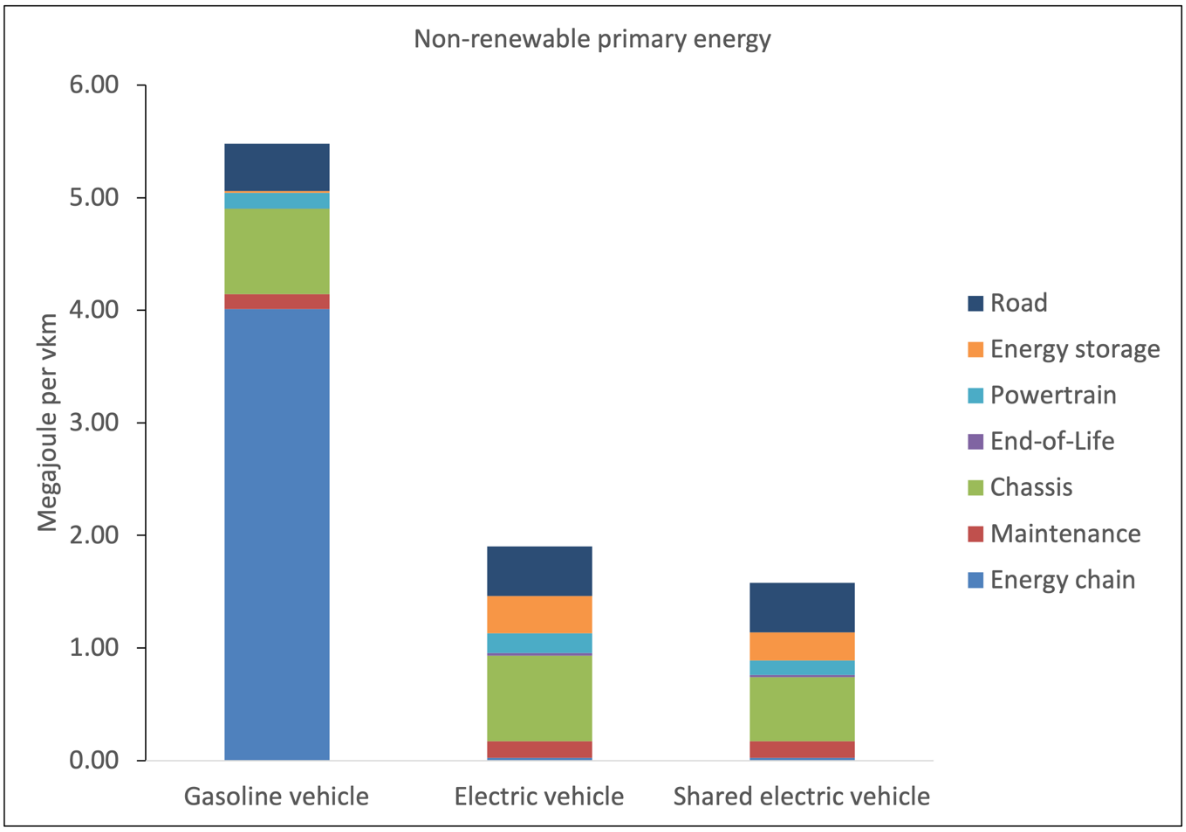

Figure 7: Life cycle consumption of non-renewable primary energy of Gasoline vehicle, Electric vehicle, and Shared electric vehicle

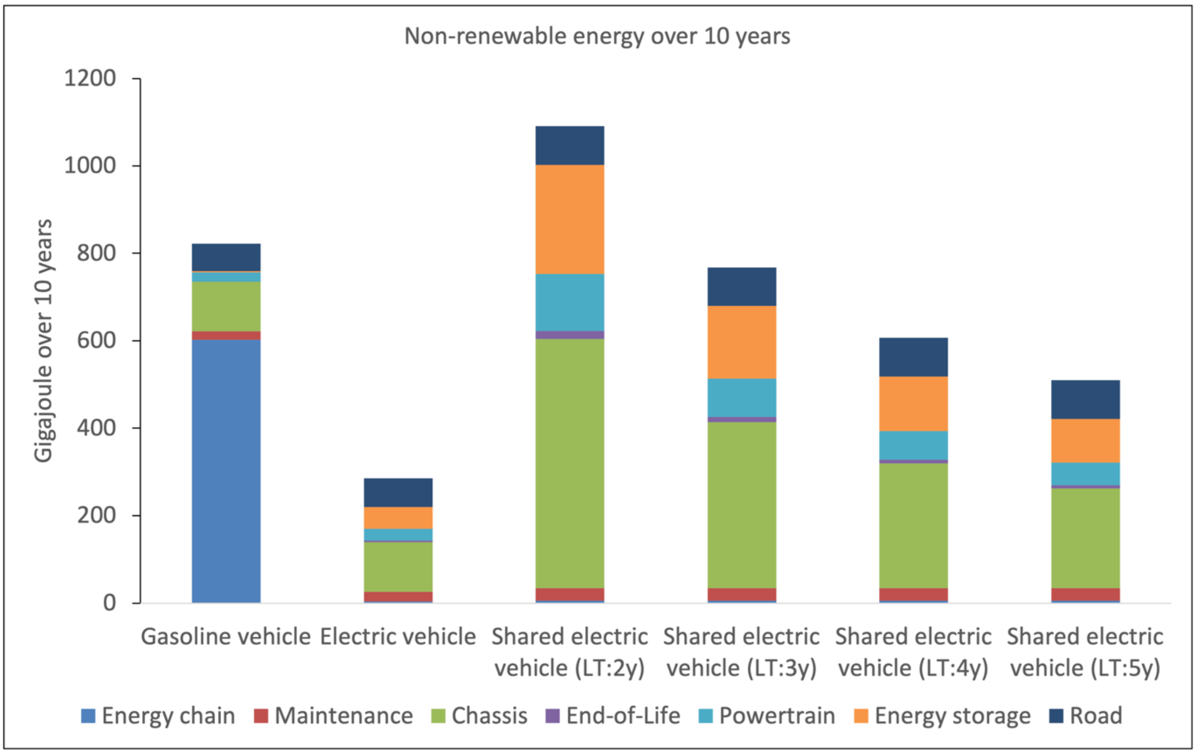

Figure 8: Comparison of non-renewable primary energy consumption over 10 years

The adoption of the three technologies has an impact on climate. **At the vehicle level** and with comparison to the gasoline car, EVs and SEVs reduce the life cycle impacts on climate by nearly 67%. For the conventional gasoline car, most of the climate impact is attributable to direct exhaust emissions, chassis production and energy chain. For EVs and SEVs, chassis and battery production are the main source of the impact on climate.

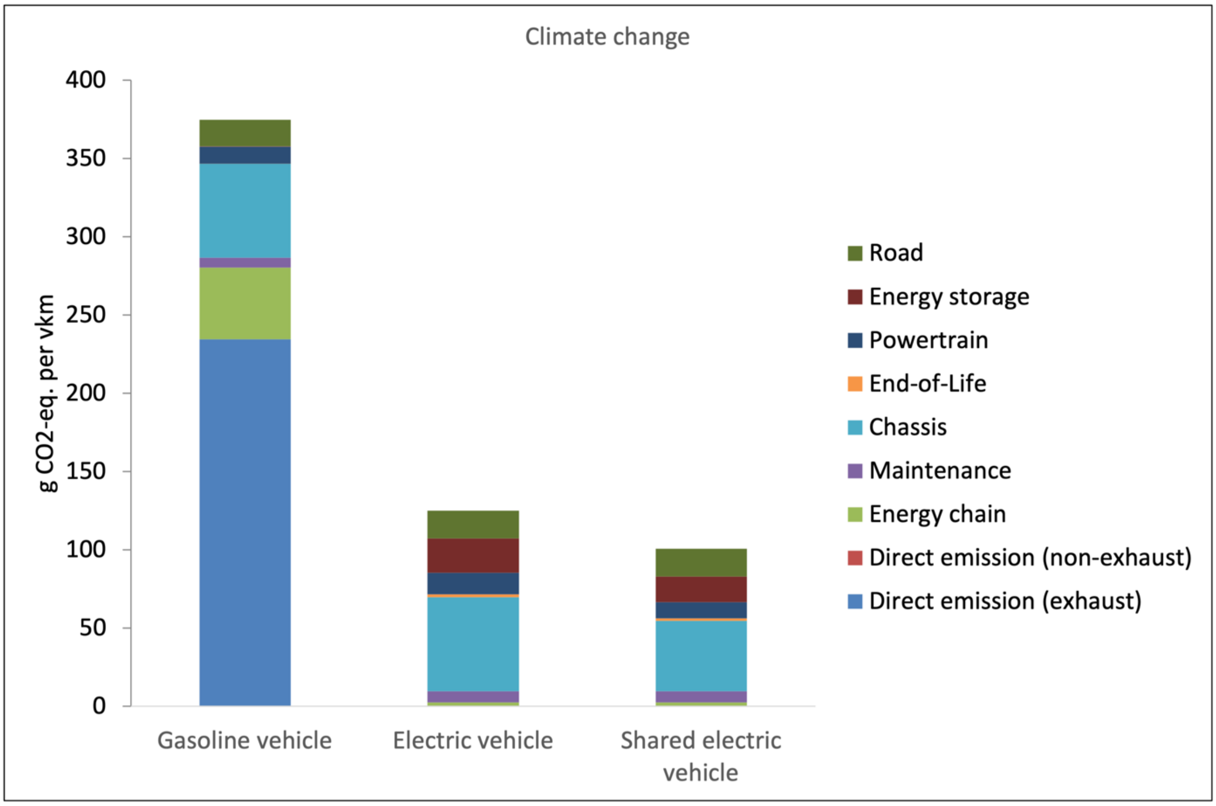

Figure 9: Life cycle impact of climate change of Gasoline vehicle, Electric vehicle, and Shared electric vehicle

Over a period of 10 years, SEVs can have varying climate impacts depending on their life span. **With frequent vehicle replacement strategies, the impact of SEVs is greater than that of a gasoline car** (fig. 10).

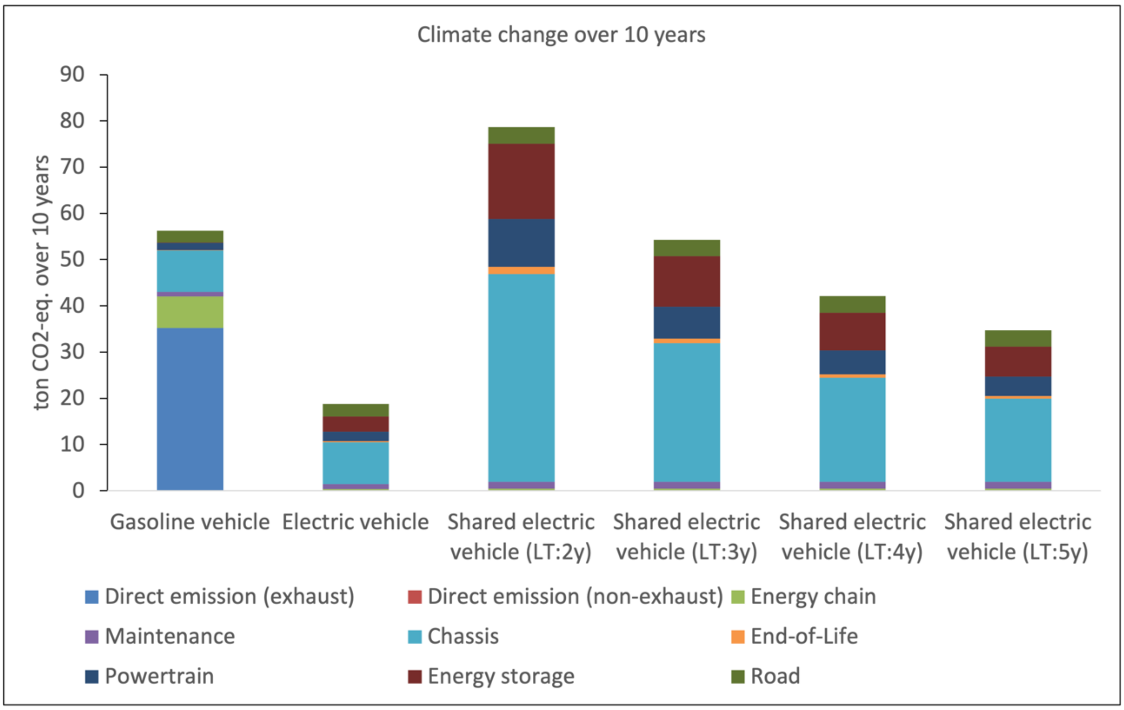

Figure 10: Comparison of life cycle impact of climate change over 10 years

Figure 11 compares the contribution of the two scenarios: wide adoption of EVs and moderate adoption of shared electric cars in Montreal. The contribution is computed relatively to the baseline scenario. **The EV scenario has the greater reduction of the negative externalities of the transportation system**. The electrification of private cars in Montreal can help reduce non-renewable energy usage and climate change impacts. **Comparatively, the e-carsharing scenario has a limited impact**. This is mainly due to the limited usage of this system as a travel mode.

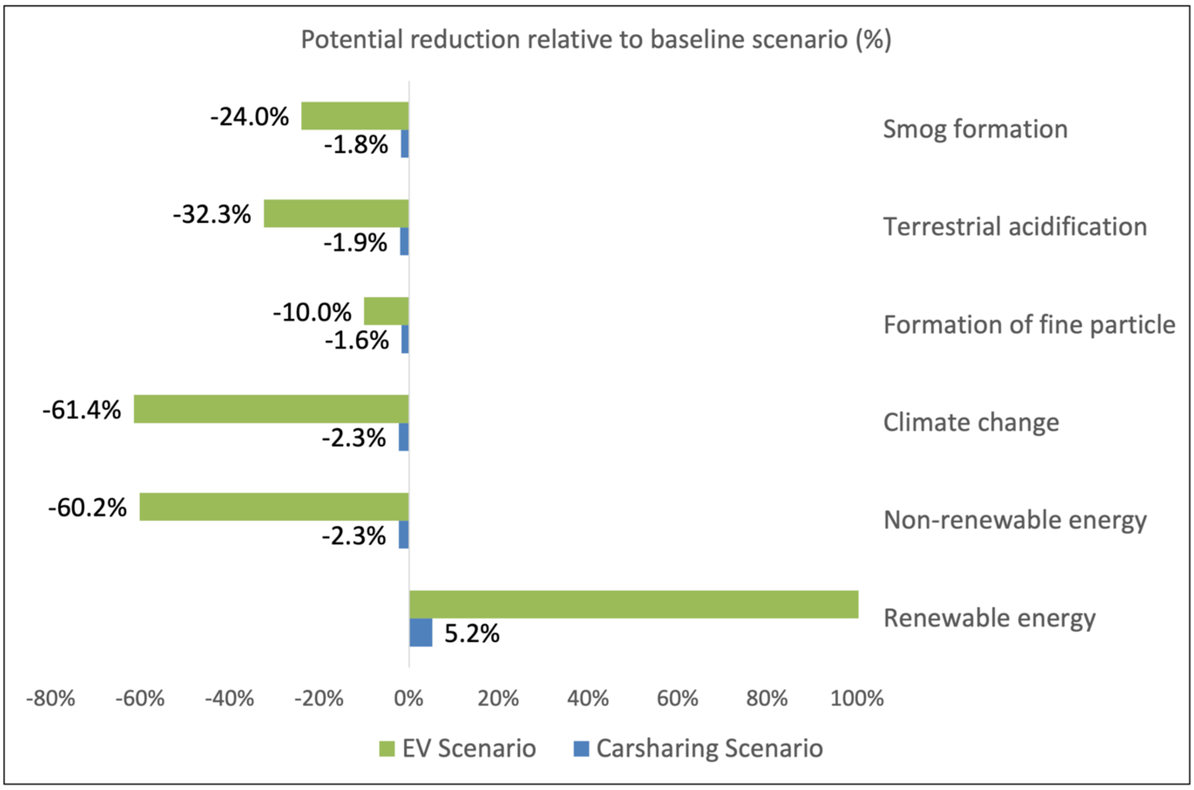

Figure 11: Comparison of potential benefits of EV scenario and Carsharing scenario relative to baseline scenario

Discussion on how those can contribute to electrification and decarbonization pathways

The results presented are a demonstration of how the combined ABM-LCA framework works. The global and holistic view proposed here allows for a fair and complete assessment of future transportation scenarios. It is fair because it takes into account the implication of a possible larger diffusion of shared services (that may be, or not under the umbrella of a MaaS system). The vehicles composing such systems will be used more intensively than private cars and will have therefore a shorter lifetime, as it is today already with carsharing vehicles. If this difference is not accounted for, the wider impacts of shared mobility solutions would be biased, with unfortunate implications for public policy.

It is complete because LCA accounts for all the phases of the life cycle of the vehicles and not only for operations. This is important in order to compare different technologies. In the case at hand, ICEV, EV, and SEVs are very different in terms of consumed energy during the phases of their lifecycles. Not accounting for such phases beyond operations means ignoring such differences and again having a biased assessment.

Another point that should be stressed again here is that the approach proposed is based on realistic, behaviorally sound transportation scenarios. They are realistic because the approach allows to explicitly represent individual constraints and preferences and because all transportation modes, and the trade-offs among them given their specific implementations are also explicitly represented. This is particularly important because in complex systems it is not possible (per the definition of complex system itself) to predict the behavior of the system simply by knowing the main principles that govern it. In other words, it is not possible to predict the behavior of the system as a whole, because we do not know how all the individual impacts of a certain change in the system or of a new policy will sum up at the system level. However, if such principles are implemented at the individual level, the macro-behavior will emerge from the simulation.

Such a tool should, therefore, play a crucial role in designing and evaluating transformation pathways in the transportation sector. The kind of results delivered here, specifically, provides a precise picture of impacts of different systems and help defining the most desirable futures. It does not necessarily provide, a simple one-scenario-is-better-than-the-other assessment. In the examples provided it is no surprise that the ICEV based scenario (baseline) is the one with the largest impacts in all categories.

Between the scenarios with large EV fleet and EV carsharing, the EV scenario is the one that performs better. Then again, although this was not made here, if one accounts for the substitution effect of carsharing cars for private cars, the carsharing scenario could be the one that performs better. At the same time, it also imposes more limitations to the users, possibly limiting somewhat the mobility of individuals. This aspect can be directly observed and measured in the transportation side of the model (MATSim). This shows, therefore, that the methodology proposed represents all possible trade-offs and provide the information necessary in order to decide how to deal with them.

Specificities of the model making it best adapted to that task

Most of the specificities of the model have been mentioned already in previous sections. The first specificity worth noting is that the model is multidisciplinary in nature. It marries two techniques, agent-based modeling, and life cycle assessment, coming respectively from transportation planning (note that this is referred to the specific implementation and not to agent-based models as such that are used in many disciplines) and ecology. This allows capturing all the relevant elements in transportation related energy consumption. In other words, and this is another specificity of the model, it contributes providing a holistic view of the transportation sector beyond the fact that MATSim already models all transportation modes (which is already a holistic approach as compared to other transportation models). The bottom-up approach, with specific rules governing the actions of and interactions among single individuals and single vehicles is another specificity of the model.

Information delivered by the model

In terms of the information delivered by the model the fact of modeling single individuals and vehicles, although their impacts are then synthetized in the LCA exercise, implies having the results at any desired aggregation level in terms of individual groups (for example age groups) or in spatial and temporal terms. Additionally, as the information covers way more than what is necessary as input for the LCA, the main output, the energy and emissions footprint of a particular scenario, can be integrated with essentially any possible key performance indicator of the transportation system. As explained in the section regarding the contribution of the results presented to electrification pathways, this helps providing more complex, but also more complete evaluations.

The modelling gaps it fills

In a typical LCA exercise all environmental effects generated by products and services are analyzed by quantifying all inputs and outputs of material flows and assessing how these material flows affect the environment. It is more commonly applied to compare single products. A transportation model typically delivers transportation demand, given a certain planning situation that usually accounts for changes in the supply (i.e. new infrastructure, introduction of new modes, new pricing, etc.) or for the introduction of new policy measures. With the new transportation paradigms their application need to be reversed somewhat, as the outputs needed are the nature and size of the supply in order to offer a certain level of service. To our best knowledge, worldwide, LCA applications to whole transportation systems are sparse and the coherence in terms of travel behavior is not guaranteed as averages and/or no behavioral changes are assumed (which in turn is not possible if on the transportation side an aggregate model is used). In fact, only an extremely limited number of research efforts went on a similar path, and none put the same kind of emphasis on the plausibility of the future transportation scenarios. This is the main gap covered by this research.

DISCUSSION

Accessibility and transparency of the model

The model is accessible to everybody as it is based on open-source models. The agent-based model MATSim, in particular, is a long-term project of two universities (ETH Zurich and TU Berlin) and the large community worldwide that currently uses it, guarantees its further development and maintenance. This is a crucial aspect as open-source academic models sometimes are for many different reasons (lack of funding, lack of further interest) can be abandoned and not maintained anymore and therefore represent a risk factor in being included in a modeling landscape as the one targeted by EMI. This risk is rather as distance as it can be, given the context, in this case. Additionally, the resources invested over time by the two universities to provide a complete documentation (www.matsi.org), and the abundant literature existing on the model's application thanks to the large community, provide all the necessary transparency. Finally, if we intend transparency in a more technical way, the parameters of the model are also very well documented (Horni et al., 2017) and this guarantees an transparent (although not necessarily easy or straighforward) access to the model.

Usability for policy design

The nature of the model, its multidisciplinary and ability to deal with complexity, all make it an ideal tool for policy design. At the same time, it is also a complex model, that implies long calculation times and that is only possible to use by expert users. Additionally, the bottom-up architecture, with individuals explicitly represented in the model, allows for the integration of information that could be relevant and available for specific policy tasks (say for example a survey based behavioral model of potential reactions by the public to a specific policy). Moreover, it should be noted here that, as already mentioned, the approach will create realistic and detailed pictures of several scenarios and all the information to assess them according to any metrics. At the same time, for the very same reasons, as already mentioned previously, it will not provide simple answers (like one capture-all metric) and indicate univocal solutions but rather offer a deep understanding of the transportation-energy system.

This does not always bode well with policy makers or with some kinds of policy design. Given all this, the modeling approach of this project is particularly suitable for strategic planning and for the design of policies that are expected to have an impact over longer spans of time. Nevertheless, such an approach contributes to guide modeling effort and addresses several of the Federal Budget 2020 issues, and especially the future of transportation. At a more local level, several policies (City of Montreal's Climate Plan, Quebec's Sustainable Mobility Policy) are working to identify strategies to reduce the negative impacts of transport, in particular GHG emissions, and this requires being able to accurately estimate the impacts of these strategies with all the implied trade-offs as the model proposed does.

Benefits from being integrated in a national modelling platform

Before saying that integrating such a model into a national modeling platform brings benefits, it should probably be mentioned that it is in a way natural to do so. Although MATSim is a transportation simulation, at its core it simulates human activities in a computer simulated world that mimics closely the geography and the socio-demography of the real one. From this point of view, it is easy to envision how it could be coupled with other energy systems and other types of models as human activities, directly or indirectly, are determining energy consumption. Therefore, integrating the combined approach ABM-LCA in a national platform can be beneficial especially for considering the further extension of the model to different components of the energy sector beyond that of transportation. Some additional aspects of this potential further development are provided here below.

Current state of development and envisioned future work on how this model could be further developed or adapted to increase transparency

The model is already fully functional, but its development is still in its infancy. However, the potential of extension of the project is endless and, in a way, even more interesting for the EMI initiative at long term than the proposed modeling exercise itself. An agent-based simulation like MATSim simulate, although in a very simple manner, the chaining of individual activities. Considering that all kinds of energy consumption is related to human activities, the approach could be used as the backbone of a modeling tool that would simulate any aspect of energy consumption with a human centered perspective and at any spatial and temporal scale. In the assessment of future scenarios, this can be a crucial feature as it provides a natural way to account for preferences and behavioral change.

This potentially game changing approach, though, comes with several challenges. Having MATSim transportation as the only focus, activities are overly simplified and summarized in a limited number of categories that tell little about the energy consumed for it. A more sophisticated modeling of such activities will come with a need for very detailed data for such activities. Although some data of this kind exists, expanding the behavioral dimensions of the agents well beyond the current ones, means also the necessity to take into account new correlation patterns among behavioral models for certain activities (how does correlate the travel behavior with the appliances bought by a certain individual?) and little is known about that. This should be addressed with the integration of new data sources, like mobile phone data, social networks, etc., which come with a whole set of challenges in itself. But the possible long-term development of the modeling approach is a “digital twin” of a study region that would allow getting insight on all the aspects of the energy system considered.

Issues with access and availability of data; how it jeopardizes model usage and development

The data used, described in the dedicated section is data usually available to researchers and therefore there is no specific issue to report regarding data access or availability, at least for any application to the Canadian territory (things may be, and sometimes actually are different in other countries).

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