Changing Technology or Behavior? The Impacts of a Behavioral Disruption

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Abstract: Transportation is a key factor in the fight against climate change. Consumer behavior changes in transportation are underrepresented in energy policies, even if they could be essential to achieve the fixed GHG emission reduction targets. To help quantify the role of behaviors in energy transition and their implications on the dynamics of an energy system, this study is conducted using the North American TIMES Energy Model, adapted to Quebec (Canada). A behavioral disruption scenario (an increase in carpooling) is introduced in the model's transportation sector and is compared to a massive electrification scenario. Our results highlight the fact that a behavioral disruption can lead to the same GHG emission reductions (65%) by 2050 as an electrification policy, while alleviating different efforts (such as additional electrical capacity and additional costs) associated with massive electrification. Moreover, the results are sensitive to behavior-related parameters, such as social discount rates and car lifetimes.

Keywords: TIMES model; low-carbon transition; behavioral disruption; private transport; carpooling; electrification

1. Introduction

1.1. The Pivotal Role of the Transportation Sector in the Energy Transition

In the fight against climate change, transportation is a key sector because of its share in total emissions and their evolution since 1990. Indeed, while many sectors have seen their emissions decrease, emissions from the transportation sector are mostly rising [1]. In Canada, passenger transportation emissions account for 53% of the total sector’s emissions. Between 1990 and 2018, emissions from cars have decreased by 17%, while total passenger transportation emissions have increased by 39%. This increase was caused by emissions from light trucks, which more than doubled. The growing preference of vehicle owners for light trucks over more fuel-efficient passenger cars has, therefore, played a major role in the increase in GHG emissions in Canada. If individual and collective preferences have evolved in this direction, they could, in principle, be reversed if adequate efforts are deployed.

1.2. The Limits of the Current Solutions

To address the need to decarbonize the transportation sector, many policies are being put in place and optimization models (such as TIMES energy models) are used to support them by quantifying solutions and dynamics within the energy system. However, as current policies and available technologies barely lead us to reach GHG emissions reduction targets [2,3], there is a growing agreement that modeling the decarbonization of transportation should be further developed [4,5]:
1. The quantification of the role of consumer behaviors in the energy transition needs to be further documented [5,6]. Historically, it was assumed that consumers had rational behaviors, so the role of consumers was not taken into account in the transition [7]. Recently, a lot of scientific approaches have been developed to quantify non-rational consumer behaviors and integrate them into models, either endogenously (in the form of behavioral variables) or exogenously (in the form of storylines) [8–11]. However, policies still often dissociate behavioral changes from the energy transition, focusing on the quantification of technological solutions [5,12]. In this sense, this study helps continue to document and quantify the role of transportation consumer behavior in decarbonization efforts.

2. The concept of disruption should also be developed, as there is only a small amount of literature integrating this concept in models [13,14]. To date, only very few papers have integrated disruptions into their models, which propose solutions with linear transitions [15]. However, if global warming is to be limited to 1.5 °C above pre-industrial levels [3], the transition must be both rapid and of large scale. The greater the climate urgency, the more the concept of disruption can be used as a key tool of how the energy system could change [16]. This study aims to explore the concept of disruption and its role in the energy transition.

1.3. Research Objectives and Contributions
Regarding the two gaps (quantifying behavioral impact in energy transition and including disruptions in models), the contribution of this study is threefold:
1. The quantification of the consequences of a behavioral disruption in the transportation sector is a useful contribution to decarbonization models, as it opens up their possibilities.
2. It is also an interesting way to “relax” model constraints while achieving the fixed GHG reduction targets.
3. Finally, the quantification of a behavioral disruption could also support transportation policies and provide an important complement to technological solutions, while producing other co-benefits, including human health benefits [17–19].

Given this context, the research question of this study is the following: What could be the contribution of a behavioral disruption in the private transportation sector? The objective of this study is to model (with a TIMES-type energy model) and quantify the contributions of a behavioral disruption in the transportation sector. Energy savings, GHG emission reductions, and cost impacts are compared to technology-only reduction scenarios. The behavioral disruption modeled here is a shift in the energy demand, made possible because of an exogenous rise in carpooling. This paper contributes to the understanding of the benefits and impacts of possible behavioral and lifestyle changes in transportation for decarbonization, using the context of Quebec, Canada.

2. Materials and Methods
2.1. Case Study
The following study focuses on the case of Quebec (Canada). Quebec has its own objectives of reducing GHG emissions by 37.5% in 2030, compared to 1990 emissions levels; and by 80–95% in 2050, compared to 1990 emissions levels [20,21]. In Quebec, as with almost everywhere, one of the “hot spots” of the energy transition is the transportation sector. The transportation sector was the source of 43.7% of the region’s GHG emissions in 2016, and 97% of the energy consumed in the transportation sector came from petroleum products [22]. The energy transition of the transport sector will, therefore, be a major undertaking. As in many other countries, Quebec’s energy and GHG policies mostly focus on electrifying transportation. Millions of dollars of subsidies are spent on the electrification of transportation [23,24] and new legislation is voted to facilitate the deployment of electric vehicles [25]. In the transportation sector, decarbonization studies using optimization models are usually oriented, in the long-term, towards electric technologies. The arrival of
electric vehicles on the market is quantified, as well as the development of electric public transportation [8,26].

2.2. Model General Specifications
The NATEM-Quebec model is used in this study because it allows the dynamics of the considered energy system to be represented and a broad point of view of the consequences of a disruption. NATEM (North American TIMES Energy Model) is a North American TIMES-type optimization model [27], and NATEM-Quebec is the portion of NATEM representing specifically the Quebec region [28]. TIMES-type models were developed about forty years ago as part of the IEA-ETSAP (Energy Technology Systems Analysis Program of the International Energy Agency). TIMES-type models are powerful tools used to support long-term decision making in the energy sector. The main strength of TIMES-type models is their ability to provide a detailed representation of the technological, economic, and environmental dimensions of a system and their ability to represent the intersectoral dynamics of the energy market. NATEM’s hypothesis and functioning are detailed in different key papers [27–29]. NATEM-Quebec is a bottom-up energy system optimization model. It is defined as bottom-up because it goes from 2415 technological processes and 501 interconnected commodities, up to the 73 end-use energy demands of the different energy sectors (residential sector, transportation sector, agricultural sector, industrial sector, and commercial and institutional sector). It is cast as an optimization model because it determines the optimal energy system to meet energy demand, at the lowest cost, and over the chosen time horizon. The optimization considers the physical resources and the constraints set by the user while minimizing the net total cost of the energy system through the objective function. Cost minimization includes the investment costs of each technology, as well as operation and maintenance costs, activity costs, and end-of-life costs. Minimizing the objective function is equivalent to maximizing the sum of the consumer and producer surpluses, thus seeking market equilibrium. NATEM-Quebec is calibrated for the base year of 2011, but up-to-date data are constantly integrated, as they become available. It is divided into eight multi-annual periods up until 2050, four seasons (spring, summer, autumn, winter) and four daily periods (day, night, and two peak periods). NATEM-Quebec assumes perfect foresight (i.e., all investment decisions are made in each period based on known future assumptions) and perfect market competition. It optimizes horizontally (in all sectors of the energy market) and vertically (in all periods for which the limit is imposed). The discount rate is fixed at 5%. The assumptions for GDP and population growth are based on the data of Vaillancourt et al. [28].

2.3. Environmental Impacts
TIMES-type models generally account for emissions associated with fuel combustion and fugitive sources (emissions related to the extraction, processing, and delivery of fuels) [30]. In NATEM, all GHG emissions from all sectors are included (except Land-Use, Land-Use Change, and Forestry—LULUCF). This includes the three main GHG emissions (carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O)) as well as all GHGs, from fuel combustion, fugitive sources, industrial processes, agriculture, and waste. These greenhouse gases are then aggregated into a single amount of carbon dioxide (CO2eq), using 100-year global warming potential characterization factors. NATEM thus covers all GHG emissions related to Quebec’s energy sectors and non-energy-related emissions. In the individual transportation sector, emissions are associated with the combustion of fossil fuels (e.g., gasoline, diesel, natural gas) and are added to the emissions associated with the production and distribution of energy (e.g., pipeline transport, gasoline production, etc.). Emissions are accounted for at the generation source, i.e., where fuels are burned, or processes are used. Sometimes, there are no direct emissions associated with the use of the energy but only emissions further in the product chain. For example, no emissions are linked to electricity or hydrogen usage. However, emissions are associated with some
processes that supply electricity or hydrogen (natural gas extraction, natural gas burned in power plants, pipeline transportation, etc.).

2.4. Modeling the Private Transportation Sector

In this study, we focus more specifically on the individual passenger transportation (private transport) sector. The individual transportation sector is divided into three car classes (small cars, large cars, light trucks) and two travel options (short and long-distance). The database for the individual transportation sector has been revised for the Quebec region. Vehicle cost and efficiency data are based on Quebec data and are detailed below. Vehicle efficiencies are derived from the fuel consumption guide [31,32]. Vehicle availability and inventory (annual mileage) come from the comprehensive energy consumption database [33]. The costs are broken down into investment costs, fixed costs, and variable costs. We assume in this study that variable costs include maintenance (oil change, brake change, tire change) and repair costs. They are expressed in CAD/km and come from different Quebec organizations [34,35]. The fixed costs correspond to the annual registration and insurance costs [34,36,37]. Small gasoline-powered cars are characterized in the database by data from a Honda Civic, large gasoline-powered cars are characterized in the database by data from a Toyota Camry, and light gasoline-powered trucks by data from a Chevrolet Equinox. Small plug-in hybrid cars are characterized in the database by data from a Ford C.-Max, large plug-in hybrid cars are characterized in the database by data from a Hyundai Ioniq (50 km range) and a Chevrolet Volt (100 km range), and plug-in hybrid light trucks by data from a Mitsubishi Outlander. Small electric cars are characterized in the database by data from a Chevrolet Spark and Ford Focus, large electric cars are characterized in the database by data from a Hyundai Ioniq (150 km range) and a Nissan Leaf and Bolt EV (300 km range), and electric light trucks by data from a Kia Soul EV (150 km range) and a Hyundai Kona EV (400 km range) [34–37]. These cars are currently on sale in Quebec and are representative of the Quebec market. The technologies’ efficiency and costs are detailed in Appendix A.

2.5. The Scenarios

Four scenarios are defined: a reference “business as usual” scenario, a GHG emissions reduction scenario, a massive individual transport electrification scenario, and a behavioral disruption scenario (carpooling scenario). The description and the main assumptions for each scenario are detailed below.

2.5.1. Reference Case

The reference scenario corresponds to our “base case scenario” It is a scenario in which no energy policy is added to those already in place in 2020. The main assumptions of this scenario are based on the policies already in place through the Climate Change Action Plan, the Transport Electrification Plan [24,38,39] and the renewable fuels strategy [40], and can be detailed as follows:

- A carbon market is already in place in Quebec (with California) and represented in the model through a tax on carbon, representing the (minimum) carbon price on the market. The lowest price per ton of CO2eq is expected to increase by 5% per year (from CAD 10 per ton of CO2 in 2012 up to CAD 66 per ton in 2050) [38,39,41].
- A minimal number of electric vehicles is imposed in the transportation sector: a minimum of 6%, (i.e., 100,000 electric or hybrid vehicles in Quebec in 2020) and 20% in 2030 (i.e., 1,000,000 electric or hybrid vehicles in Quebec in 2030) [24]. This objective was adjusted in November 2020, increasing it to 1,500,000 electric vehicles [23].
- All gasoline vehicles run on a minimum of 5% ethanol and 2% biodiesel for diesel vehicles, a policy implemented in 2010 [39].
- Vehicle manufacturers must comply with the corporate fuel average economy (CAFE). Vehicles therefore have a minimum energy efficiency [28].
2.5.2. GHG Emissions Reduction (GHG80)

In this scenario, the model is required to achieve 2030 and 2050 GHG reduction targets [42,43] without additional constraints to guide the transition. In addition to the measures considered in the baseline scenario, the only constraint of the model is to reduce the total GHG emissions. To meet the government’s targets (i.e., 80% GHG reduction in 2050 relative to 1990, see Table 1), the use of carbon capture and storage (CCS) is needed. In this study, the CCS potential is limited by the geological potential of Quebec. Quebec’s total geological potential is estimated at 890 Mt CO$_2$eq. This assumption is made without accounting for social acceptability issues, the reliability of geological sequestration, or the maturity of CCS technologies [44]. With limited use of CCS (2.5 Mt CO$_2$/year [44]), only a 65% reduction can be achieved in 2050 (see the results of a 65% GHG emissions reduction scenario in the Supplementary Materials). No specification is provided to the model as to the technologies to be used.

Table 1. Quebec 2030 and 2050 GHG emissions reduction targets.

| Year | Reduction (Compared to 1990) | Emissions (Mt CO$_2$eq) |
|------|-----------------------------|-------------------------|
| 1990 | -                           | 86.5                    |
| 2030 | −37.5%                      | 52.9                    |
| 2050 | −80%                        | 16.9                    |

2.5.3. Massive Electrification (Electrification)

The third scenario corresponds to a scenario of massive electrification of the personal transport sector. This scenario is based on the constrained penetration of electric vehicles (EV) to meet the GHG emission targets. In addition to the assumptions taken from the reference scenario and the GHG reduction scenario, it is assumed in this scenario that 100% of the passenger car sales will be electric from 2025. The fleet and future sales of individual vehicles are projected from the Comprehensive Energy Use Database [33]. From these projections, the penetration of the electric vehicle stock on the total fleet of individual vehicles is calculated. These data are detailed in Table 2.

Table 2. Electric vehicles market share by 2050 and by vehicle class (small cars, large cars, light trucks) for the massive electrification scenario (sales of fully electric individual vehicles starting in 2025 in Quebec).

| Vehicle Class   | 2025 | 2030  | 2050  |
|-----------------|------|-------|-------|
| Small cars      | 6.0% | 31.0% | 100%  |
| Large cars      | 6.0% | 31.0% | 100%  |
| Light trucks    | 9.4% | 46.9% | 100%  |

1 Small cars: 0–3115 L; large cars: 3115–4530 L; light trucks: 2722–3856 kg. See Appendix A for more details about the transportation sector’s segmentation.

2.5.4. Behavioral Disruption Scenario: Carpooling Development

The fourth scenario considered is a behavior disruption scenario. In addition to considering the assumptions of the reference scenario and the constraints of the GHG reduction scenario, the idea is to integrate a significant behavioral shift. This scenario puts in place a rapid increase in carpooling over medium and long distances, by doubling the average number of passengers per car and by eliminating car use for distances below 1 km. Such behavioral disruption takes effect between 2020 and 2025. As the exact timing of the behavior change does not have a substantial impact on our results (but would simply delay or accelerate GHG reductions), this scenario follows the Quebec government’s ambitious timeline for short-term investments (2021–2026), with the addition of a disruptive behavior change [23]. As a sensitivity analysis, a different timeframe scenario is presented in Appendix B. The scenario modeled here is based on the 2017 Canadian Statistical Addendum to estimate the current number of passengers per vehicle
in Quebec [45]. In NATEM, this scenario is modeled as an exogenous demand shift, the demand for passengers being expressed in passenger km. While it is beyond the scope of this paper to investigate how such a shift could happen, we should mention that a lot of researchers study ways to implement behavioral changes, including the increase in carpooling. Studies agree that behavioral changes in transportation could reduce energy consumption, GHGs emission, and traffic, especially during peak hours, and strategies to implement carpooling are examined in [18,46,47]. With our hypotheses, the total decrease in demand due to the development of carpooling could reach 58.24%. This number can seem hard to reach, but is not out of reach when we see that, against all expectations, 13 states in the United States have reduced their number of cars per inhabitants between 1998 and 2018, without drastic policy shift [48]. In Massachusetts, the decrease was even by 15%, from 837 to 707 vehicles. These numbers show that car ownership can decrease—especially if adequate policies (in remote working, public transit, car sharing, carpooling, and active transportation) are put in place. The decrease in these 13 states illustrates that moderate change can happen without significant policies. Well-designed policies could accelerate the trend, and with the current developments in real-time carpooling platforms, price incentives (such as road or parking pricing), and education, it is conceivable to experience such accelerated behavioral changes. Of course, we do not claim that these changes would be easy, and the authors agree that the carpooling scenario may seem complicated to implement, especially in a world where behavioral changes are not contemplated, let alone in the form of disruption. Table 3 shows the detailed shift in demand.

Table 3. The detailed shift in demand that could occur in Quebec with a carpooling scenario.

| Distance (Km) | Number of Passengers per Vehicle (Carpooling Scenario) | 2017 Number of Passengers per Vehicle | Total Demand (%) | Shift in Demand (%) |
|---------------|--------------------------------------------------------|---------------------------------------|------------------|---------------------|
| <1            | n.a. (individual cars are not used)                    | 1.2                                   | 23.6             | −20.0               |
| 1–11          | 3.0                                                    | 1.5                                   | 53.1             | −26.6               |
| 12–50         | 3.6                                                    | 1.6                                   | 20.2             | −10.1               |
| 51–100        | 3.6                                                    | 1.8                                   | 2.2              | −1.1                |
| >100          | 3.6                                                    | 2.1                                   | 1.1              | −0.44               |

2.5.5. Carpooling Scenario Discussion

Carpooling is certainly complicated to implement, especially in a world where behavioral changes are not often contemplated, let alone in the form of disruption. However, some authors are beginning to write about the fact that radical changes will be necessary and inevitable in the future [49,50]. It is therefore a deliberate choice to propose a “shock” scenario, almost doubling the number of passengers per vehicle, to explore the concept of disruption. This paper simply illustrates possible outcomes to better inform policy decisions. This decision to introduce a behavioral disruption may appear too radical (doubling the number of passengers per vehicle), but can be supported by the following arguments:

- A behavioral shift will be required in any case. While a behavioral shift is very hard to achieve, so is the deep decarbonization of the economy by 2050. Thinking that deep decarbonization can happen only with technology and no behavioral change is not credible. The cost of new technologies required to achieve decarbonization would itself require some behavioral change, as there are not enough resources to have carbon-free technologies without changing some consumption patterns, under our already debt-laden governments. Behaviors will have to change either because of severe climate change, because of financial restrictions due to the required investments, or because of pro-active policies to minimize the cost of decarbonization. In all cases, some hard-to-do behavioral changes will happen.
- The COVID-19 pandemic illustrated that drastic behavioral changes happen in crisis situations. The climate crisis could justify and potentially lead to some important
behavioral shifts. It is better to plan these shifts than having individuals being con-
strained or forced to make them—under extreme climate or financial circumstances.

As a sensitivity analysis on this scenario, two other disruptions—one with a different
timeframe and one with a different shift in demand—are presented in Appendix B.

2.6. Sensitivity Analysis

In a sensitivity analysis, the influence of two behavioral parameters is studied: dis-
count rate and car lifetime. These two parameters appear to represent the main barriers to
the implementation of electric vehicles (EVs) [26,46]. These two parameters are applied to
each of the scenarios detailed above (reference, ghg80, electrification, carpooling).

2.6.1. Discount Rate Variations

Discount rates represent an individual’s attitudes toward the future and risk [46].
A high discount rate for a product means that the consumer puts more weight on the
present value of the product, rather than on its future value. In the case of EVs, or any
other innovative technological change, consumers will have in mind the risk they take
by investing in new technology and less the future gains they will benefit from. Many
studies have been carried out to determine a “social discount rate” and, in particular,
that of Haq et al. (2018), which estimates the social discount rate for consumers between
17 and 21% in the transport sector [48]. For our sensitivity analysis, we will apply a specific
discount rate of 20% on EVs only.

2.6.2. Cars Lifetime Variations

A shorter car lifetime results in a rapid turnover of the vehicle’s fleet. The average
age of an individual vehicle in Quebec is estimated at 8.2 years for small and large cars
and 6.9 years for light trucks in 2018 [51]. The available data for the 2013–2018 period also
confirm a relatively stable age of the fleet in Quebec [51]. While the model left vehicles on
the market until the end of the life of the technology (20 years), we choose here to reduce
the life of vehicles down to 11 years.

3. Results and Discussion

3.1. Electric Vehicles Market Shares

Figure 1 shows the penetration of electric and hybrid vehicles from 2015 to 2050 under
the investigated scenarios.

Figure 1. Annual penetration of electric vehicles in the individual transportation sector, depending on the car class (small
cars, large cars, light trucks) and the scenarios considered (reference, ghg80, electrification, carpooling). BEV: battery electric
vehicles; PHEV and HEV: plug-in hybrid and hybrid electric vehicles; FFV and BFV: fossil fuel vehicles and biofuel vehicles.
3.1.1. Implementation of EVs without Additional Policy (Reference Scenario)

The combination of several factors, namely the decrease in battery costs, the expected increase in gasoline prices, and the increase in the range of electric vehicle batteries, are decisive in the introduction of electric vehicles in Quebec. Figure 2 shows that, as a result of these factors, and even without additional political and financial incentives (reference scenario), consumers have a financial interest in investing in electric vehicles starting in 2030 with smaller cars, as these EVs are already quite well developed. Light trucks and large cars are currently less available on the market because their investment cost makes them less affordable. Light trucks are also used outside urban areas and over long distances and require good autonomy. Given these considerations, their implementation would be later, after 2040, if the economic interest of vehicles alone is considered.

Figure 2. Fuel consumption of the individual transportation sector in Quebec considering the four assessed scenarios.

Our results show, for all vehicle classes combined, a total of 54% electric vehicles and 15% plug-in hybrid vehicles in 2050. These results seem a little optimistic when compared to the 11% penetration of electric vehicles projected in 2050 in the United States for the reference scenario [52]; the 5% penetration of electric vehicles in Europe [53], or the 27% of electric and hybrid vehicles projected in the Quebec reference scenario [44]. These results depend mainly on the assumption that electric car investment costs decrease until they reach the same investment cost as internal combustion vehicles in 2050.

3.1.2. Optimal Response to a Reduction in GHG Emissions (GHG80 Scenario)

First, it should be noted that achieving the regional GHG reduction targets of an 80% emissions reduction implies almost total decarbonization of the passenger transport sector. The introduction of 15% of plug-in hybrid vehicles in all vehicle categories is directly related to the current electrification policy [23]. According to our optimization, the electrification of the passenger transportation sector is essential to achieve our GHG reduction objectives. Electrification of the sector is expected to begin in 2020 to reach large proportions in 2030 (28% of EVs) and 2040 (71% of EVs). These results are comparable to those published by [44] in the GHG emission reduction scenarios.

3.1.3. Impacts of a Transport Electrification Policy

A massive electrification policy for transportation has a significant impact on Quebec’s vehicle fleet. Indeed, if companies are forced to sell only electric vehicles from 2025 onwards,
the penetration of electric vehicles into the entire fleet is fast. By 2030, about half of the private car fleet becomes electric. Having 100% electric sales from 2025 onwards also makes it possible to achieve a 100% electric fleet by 2050. This scenario is comparable to the “high electricity consumption in the United States” scenario in which electrification of the transport sector begins in 2017, reaching nearly 80% in 2030 [52].

3.1.4. Impact of a Behavioral Shift Scenario

The main advantage of the behavioral shift scenario is to halve the number of vehicles in the fleet. However, half as many car purchases also involve a slightly slower penetration of electric vehicles when the demand disruption occurs (between 2020 and 2030). After 2030 (after the demand shift), demand resumes, and the electrification of the transport fleet begins. The horizontal step of the carpooling scenario (Figure 1) is directly related to the assumption of a demand disruption in the private passenger transportation sector. Indeed, with the demand disruption expected in 2025 in the carpooling scenario, there is a small window during which the demand for individual transport decreases, before resuming its growth in 2025. This shift in demand delays the penetration of electric vehicles (this is the observed step) because the model can meet its emission reduction targets without new technologies—that is, as shown in Figure 1, without replacing standard vehicles with electric vehicles.

3.2. Energy Supply and Demand

Figure 2 makes a link between the penetration of EVs from Figure 1 and the corresponding fuel consumption.

Assuming that electric vehicles are about three times more efficient (depending on the vehicle models, see Appendix A) than fossil fuel vehicles, investment in electric vehicles reduces the energy consumption of the passenger transport sector by two-thirds. This relationship can be seen in the reference scenario: when there is an investment in EVs, the consumption is reduced (from about 125 PJ in thirty years), even if the overall passenger demand continues to increase. Consequently, the GHG reduction and the electrification scenarios lead to energy consumption in 2050 that is half as small as in 2015. It is also interesting to note that the reduction in electricity consumption (in the range of 33 PJ) in the carpooling scenario can be significant, especially when placed in a larger electrification context (electrification of the residential, industrial, or commercial sectors). On the contrary, the increase in electricity consumption in the massive electrification scenario leads not only to an increase in electricity capacity but also to larger imports of electricity during certain time slots (see Supplementary Materials for the hourly demand increase). The total electrical capacity required for Quebec is shown in Figure 3. It should be noted that the data used for investment in new electrical infrastructure are detailed in the Supplementary Materials.

Massive electrification of the transport sector (combined with a reduction in GHG emissions in other sectors) implies an increase of about 23 GW in 2050 relative to the reference scenario, divided into 10,000 MW of supplementary hydropower, 12,000 MW provided by wind farms, 11,000 MW provided essentially by roof-mounted solar panels and solar farms and 2000 MW provided by biomass. The carpooling scenario avoids the construction of 3.5 GW of wind capacity in 2050 compared to the massive electrification scenario. Reducing GHG emissions, whether or not coupled with massive electrification of the transport sector, is a major challenge not only in terms of energy consumption but also in terms of electricity infrastructure. These results could be amplified if they were taken in the context of peak hour demand or if a renewable energy constraint was imposed.
3.3. Environmental Impacts

Figure 4 shows GHG emissions breakdown in the transportation sector due to the assessed policies.
Our results confirm, with the assumption that no direct emissions are associated with electric vehicles, that total electrification of the passenger transportation fleet would achieve a GHG reduction of 22.9 Mt of CO2eq in 2050, compared to the 2015 GHG emissions level (Figure 5). This is the case in 2050 for the total electrification scenario. Under the same assumption, the GHG emissions of the reference scenario are also decreasing, due to the partial electrification of the transportation fleet. It is also interesting to note that the forced electrification scenario (sales of electric vehicles imposed from 2025) takes fifteen years to reduce emissions significantly, where a behavioral shift can halve the emissions in five years (Figure 4)—under the assumption that rapid progress is made through carpooling. According to our model, the effects of a massive electrification policy would avoid between 5.1 and 10.7 Mt of GHG emissions per year from 2030 relative to the reference scenario. The reduction in GHG emissions would be immediate in 2025 in a behavioral disruption scenario (32.6% of reduction in just five years relative to the reference scenario, between 2020 and 2025). If we want to seek a drastic reduction in GHG emissions, a behavioral shift is technically easier to implement than a turnover of the transportation fleet, and its effects are immediately measurable. Furthermore, as detailed in the next subsection, a behavioral disruption has significant cost benefits.

![Figure 5](image_url)

**Figure 5.** Annual investment in the region’s electrical infrastructure (Quebec) according to the different scenarios (reference, GHG80, electrification, carpooling).

### 3.4. The Cost of the Transition

Figure 5 shows the annual total investment in new electric infrastructure and the operation and maintenance costs and the activity costs of the existing infrastructure. The new electricity infrastructure would lead to a range of investment between 1.2 and 5 additional billion CAD per year between 2040 and 2050 in a massive electrification scenario, relative to the reference scenario. A carpooling scenario would avoid the investment
of 700 million per year relative to the massive electrification scenario, while complying with the same GHG emission reduction constraints. By way of comparison, the last dam built in Quebec and started in 2009 (La Romaine complex) cost around 6.5 billion CAD [54]. It can be pointed out that massive investment in infrastructure would cause problems of social acceptability (just as the construction of the last large dam caused in Quebec), which are not considered into the optimization. Just as the difficulties of changing habits with carpooling are not considered, the social resistance to large investments is not integrated into the model either.

Consumers’ interest is often focused on cost. Figure 6 shows the total expenditures per household for all vehicle types combined. This cost is not necessarily the cost paid by the consumers but should be analyzed as the total cost of owning a vehicle.

By way of comparison, it is estimated that each Quebec household spent approximately 8000 CAD in 2012 on its own vehicle [36]. Some European studies have shown that electric vehicles would still be more expensive by about 1000 CAD to own in 2050 [26,55], while in California, electric vehicles have reportedly already been cost-effective since 2015, based on their lifecycle costs [56]. Note that the results presented in Figure 6 should be put into perspective since all the costs are minimized, particularly vehicle activity costs (the model seeks to optimize energy costs and thus to reduce the activity costs). However, the trends remain interesting to analyze. Since the reference scenario is not subject to any additional political constraints, the costs calculated in the reference scenario represent the minimum costs that a household should have to spend on personal transportation, i.e., between 4675 CAD/year in 2030 and 4698 CAD/year in 2050. This cost can be converted into 0.33 CAD/km and compared to 0.30 CAD/km estimated by the Canadian government [57]. In comparison, with a transport electrification policy, annual household investments could increase by an average of 100 CAD per household per year. This cost increase is linked to the fact that electric vehicles remain more expensive to invest in, even with the savings on operating costs. Maintenance costs here are dominated by insurance costs, which eliminate savings on electric vehicle maintenance costs. Figure 6 also brings up one of the most
important points of this study, namely the fact that a behavioral change is much cheaper for consumers than a technological change, from a purely financial perspective. By simply doubling the number of people per car, household transport expenditures are reduced by 52.5% in 2050.

Figure 7 shows the increase in the marginal cost of CO$_2$ in the given scenarios. The marginal cost corresponds to the cost paid for the last ton of CO$_2$ equivalent (CAD/tCO$_2$eq), in a given scenario. As the model optimizes according to the costs and first chooses the least expensive options, the marginal cost here is the highest cost per ton of CO$_2$eq among the reductions in GHG emissions considered.

![Figure 7. The marginal cost of CO2 in the four scenarios considered.](image)

The reference scenario leads to 132 CAD/tCO$_2$eq in 2050. Since the marginal cost represents the cost of the whole energy sector, the constraint of reducing the GHGs emissions by 80% in 2050 leads to a common marginal cost for all the concerned scenarios, reaching 1150 CAD/tCO$_2$eq in 2050. The behavioral disruption scenario leads to an average of 10% reduction of the marginal cost of CO$_2$ between 2030 and 2050, compared to the electrification scenario. A decrease in the marginal cost does not only mean a decrease in costs emissions generated to reduce GHGs but also increased flexibility to reduce GHG emissions even more.

3.5. Sensitivity Analysis

Finally, Figure 8 presents the sensitivity of the results to the two behavioral parameters detailed. Each parameter has been applied to each scenario. The results in Figure 8 show that the two behavioral parameters considered (high discount rate and car lifetimes) do not change the trends in the results in the cases where the GHG emissions reduction constraint is in place (GHG80 scenario, electrification, and carpooling).

3.5.1. High Discount Rate

Scenarios with a 20% discount rate on electric vehicles illustrate the attitude of consumers valuing more the present than the future or towards what they consider a higher risk. With a discount rate of 20%, consumers place more value on current cost than on future gain, and therefore prefer to limit their investment in electricity, as electricity represents a greater risk than fossil fuel vehicles already on the market. Without additional constraints (reference scenario), consumers choose not to invest at all in electric vehicles, other than through the obligation of current policies. In the other scenarios, a high discount rate delays the arrival of electric vehicles on the market. In the electrification scenario, consumers still
must invest at some point in electric vehicles; while without the electrification constraint, consumers will choose other options in the other sectors to reduce the GHG emissions. We can see that without the electrification constraint, the model will prefer hybrid vehicles compared to plug-in hybrids or electric vehicles. The solutions to reach the GHG emissions reduction are then chosen elsewhere. Such a high discount rate may actually better reflect real consumers’ attitude towards spending in vehicles and consumption in general [48].

Figure 8. Sensitivity analysis of the penetration of electric vehicles in the Quebec passenger fleet until 2050, according to two types of variations: resistance to change (discount rate) and acquisition of new vehicles (lifetime of cars). Reference: baseline scenario; electrification: electrification scenario; carpooling: carpool scenario; discount rate 20%: scenario + discount rate of 20%; lifetime 11 years: vehicle lifetime of 11 years instead of 20 years. BEV: battery electric vehicle; PHEV: plug-in hybrid vehicle; FFV + BFV: fossil fuel vehicle and biofuels vehicle.

3.5.2. Cars Lifetime

If instead of making cars last 20 years as technologically planned, consumers start changing cars more regularly and make their vehicles last only 11 years, the consequences are double-edged. On the one hand, if this behavior is not controlled, then it allows consumers to postpone their switchover date by ten years since they will still have time to change cars later when the technology will be better developed. In the GHG emissions reduction scenario, for example, people will keep their fossil fuel vehicles in the medium term before switching to EVs in the long term. The same thing happens in the carpooling scenario, in which consumers wait longer to switch to EVs, especially considering that they have more flexibility with the reduced energy demand. The long-term vision of consumers is diminished. On the other hand, if mass consumption is combined with a policy of electrification or reduction of GHG emissions, consumers can afford to invest faster in EVs.
4. Conclusions

In the context of an urgent energy transition, the objective of this study was to assess the contribution of a behavioral disruption in the transportation sector and to compare it with GHG emission reduction scenarios. Four scenarios were modeled in a Quebec context: a reference scenario, a GHG emissions reduction scenario by 2050, a massive electrification scenario for the individual transportation sector, and a behavioral disruption scenario. In addition to the fact that this study made it possible to propose, document and model an alternative point of view to current energy policies based on technological innovations, it also highlighted the following outcomes:

- The potential limits of technological solutions (reduction of GHG emissions and massive electrification scenarios): If we want the scenarios to achieve 80% GHG emissions reduction in 2050, carbon capture and storage technologies must be available on the market. Moreover, even if the technological scenarios allow us to achieve the environmental objective of reducing GHG emissions by 80% in 2050, they require a high investment if we do not want to face physical limitations in electrical capacity. According to our model, scenarios that achieve our objectives through innovation alone will also increase costs to invest in the vehicle fleet and in new electricity infrastructure (about CAD 2 billion/year).

- The need to integrate behavioral policies into our current energy policies by quantifying the benefits that will result from "environmentally friendly" behavior: Whether for road users or the government, the savings associated with a simple carpooling scenario would be significant (reducing household transportation costs by about 50% and limiting the need of new power generation infrastructure). In addition, technological efforts would be reduced to achieve the same environmental results. Such a scenario would, therefore, offer more flexibility and allow a faster energy transition if properly associated with technological innovation. Finally, the behavioral disruption postpones the required increase in carbon price, which could be a significant factor given the sensitivity to high carbon prices of many voters.

- The responsibility of the regions in the transition: By starting with small-scale solutions, it will be easier for each territory to make its own transition and to transpose this solution to the national or even international level. In this respect, the NATEM model can be used at several levels and describe the constraint of each region individually.

- The energy transition is a multi-stakeholder transition: The behavioral disruption scenario shows us that scenarios that combine the strengths of different actors lead to more efficient results and assure more flexibility. The energy transition must be driven as much by politicians as by consumers or by the various economic actors.

- Behavioral shifts' technicalities: It has been pointed out that the technological solutions considered today such as massive electrification can face some barriers that are not necessarily considered in the optimization. The same remarks apply to the behavioral disruption scenario as the difficulties of changing habits with carpooling are not considered other than in the sensitivity analysis. The psychological cost of changing to carpooling is not considered, and the psychological cost/social resistance to large electric investments is not integrated into the model either.

It should be noted that the purpose here was not to study the social acceptability of the proposed changes but to highlight their importance. The idea of this study was to quantify behaviors and lifestyle changes that, until now, had only been qualitative or calculated in a simplified manner, to measure their global contribution in the energy transition. The use of a TIMES-type energy optimization model has enabled us to quantify the savings and GHG benefits of our scenarios by 2050. Finally, this study can be considered as the first step in a broader work. Our behavioral scenario is simple, focusing only on the transportation sector. In this scenario, the increase in electricity consumption can still be ensured by renewable sources. A more global scenario could link measures in the different sectors (residential, industrial, commercial, transportation) and measure the global effects of a transition on society.
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**Appendix A**

Table A1 shows the breakdown of the transport sector by vehicle type, occupation, and associated passenger demand used for this study [35,57,58].

| Segmentation | Vehicle Class | Interior Volume (L) | Weight (kg) | Loading (pass/veh) | Distance Travelled (km/yr) | 2015 Demand (Mpass km) |
|--------------|---------------|---------------------|-------------|-------------------|----------------------------|------------------------|
| Small cars   | Two-seater, mini-compact, subcompact, compact | 0–3115 | - | 1.57 | 15,524 | 52,091 |
| Large cars   | Compact, midsize, full-size, station wagon | 3115–4530 | 1.57 | 15,838 | 45,747 |
| Light trucks | Pickup truck, SUV, minivan, van | - | 2722–3856 | 1.69 | 20,401 | 45,524 |

The rest of the section presents the essential updates that have been made to the NATEM model technologies. Tables A2–A4 show the fixed and variable operation and maintenance costs according to the vehicle class. Tables A5–A7 detail the different technology costs and their updated efficiencies by vehicle class. Efficiency data are from [32], cost data from [35,58], and forecasts for 2050 are based on the National Renewable Energy Laboratory [37].

**Table A2.** Breakdown of the O&M costs for the small cars in NATEM.

| Small Cars | Insurance, Registration ¹ (CAD) | Oil (CAD/km) | Brakes (CAD/km) | Tires (CAD/km) | Variables O&M ¹ (CAD/km) |
|------------|---------------------------------|--------------|-----------------|----------------|--------------------------|
| BEV        | 750                             | 0.000        | 0.004           | 0.019          | 0.023                    |
| PHEV       | 750                             | 0.003        | 0.006           | 0.019          | 0.028                    |
| FFV        | 750                             | 0.006        | 0.010           | 0.019          | 0.035                    |

¹ Fixed O&M costs = insurance and registration costs, Variables O&M costs = oil change, brakes change, and tires change.

**Table A3.** Breakdown of the O&M costs for the large cars in NATEM.

| Large Cars | Insurance, Registration ¹ (CAD) | Oil (CAD/km) | Brakes (CAD/km) | Tires (CAD/km) | Variables O&M (CAD/km) |
|------------|---------------------------------|--------------|-----------------|----------------|------------------------|
| BEV        | 1000                            | 0.000        | 0.004           | 0.020          | 0.024                  |
| PHEV       | 1000                            | 0.003        | 0.006           | 0.020          | 0.029                  |
| FFV        | 1000                            | 0.006        | 0.010           | 0.020          | 0.036                  |

¹ Fixed O&M costs = insurance and registration costs, Variables O&M costs = oil change, brakes change, and tires change.
### Table A4. Breakdown of the O&M costs for the light trucks in NATEM.

| Light Trucks | Insurance, Registration (CAD) | Oil (CAD/km) | Brakes (CAD/km) | Tires (CAD/km) | Variables O&M (CAD/km) |
|--------------|--------------------------------|--------------|----------------|---------------|------------------------|
| BEV 1500     | 0.000                          | 0.004        | 0.026          | 0.030         |
| PHEV 1500    | 0.003                          | 0.006        | 0.026          | 0.035         |
| FFV 1500     | 0.006                          | 0.010        | 0.026          | 0.042         |

1 Fixed O&M costs = insurance and registration costs, Variables O&M costs = oil change, brakes change, and tires change.

### Table A5. Efficiencies and costs of the small cars updated for NATEM.

| Technology | Year | Efficiency (Mkm/PJ) | Investment Costs (kCAD) | Fixed O&M (kCAD) | Variable O&M (CAD/km) |
|------------|------|---------------------|-------------------------|-----------------|-----------------------|
| Gasoline   | 2015 | 426                 | 24                      | 0.75            | 0.035                 |
|            | 2050 | 480                 | 24                      |                 |                       |
| Diesel     | 2015 | 544                 | 31                      | 0.75            | 0.035                 |
|            | 2050 | 760                 | 28                      |                 |                       |
| Natural gas| 2015 | 433                 | 36                      | 0.75            | 0.045                 |
|            | 2030 | 433                 | 36                      |                 |                       |
|            | 2050 | 433                 | 36                      |                 |                       |
| E85        | 2015 | 485                 | 27                      | 0.75            | 0.035                 |
|            | 2030 | 504                 | 26                      |                 |                       |
|            | 2050 | 533                 | 24                      |                 |                       |
| Hybrid-Gasoline | 2015 | 564             | 32                      | 0.75            | 0.035                 |
|            | 2030 | 596                 | 27                      |                 |                       |
|            | 2050 | 635                 | 25                      |                 |                       |
| Hybrid-Diesel | 2015 | 707            | 34                      | 0.75            | 0.035                 |
|            | 2030 | 768                 | 32                      |                 |                       |
|            | 2050 | 888                 | 30                      |                 |                       |
| Plug-In Hybrid | 2015 | 743             | 34                      | 0.75            | 0.028                 |
|            | 2020 | 743                 | 30                      |                 |                       |
|            | 2030 | 809                 | 27                      |                 |                       |
| Electric   | 2015 | 1244                | 38                      | 0.75            | 0.023                 |
|            | 2020 | 1526                | 35                      |                 |                       |
|            | 2030 | 1808                | 31                      |                 |                       |
|            | 2050 | 2154                | 27                      |                 |                       |

### Table A6. Efficiencies and costs of the large cars updated for NATEM.

| Technology      | Year | Efficiency (Mkm/PJ) | Investment Costs (kCAD) | Fixed O&M (kCAD) | Variable O&M (CAD/km) |
|-----------------|------|---------------------|-------------------------|-----------------|-----------------------|
| Gasoline        | 2015 | 422                 | 30                      | 1.00            | 0.036                 |
|                 | 2050 | 518                 | 30                      |                 |                       |
| Diesel          | 2015 | 547                 | 34                      | 1.00            | 0.036                 |
|                 | 2050 | 732                 | 34                      |                 |                       |
| Natural gas     | 2015 | 410                 | 38                      | 1.00            | 0.046                 |
|                 | 2050 | 594                 | 38                      |                 |                       |
| E85             | 2015 | 509                 | 36                      | 1.00            | 0.036                 |
|                 | 2030 | 515                 | 34                      |                 |                       |
|                 | 2050 | 616                 | 31                      |                 |                       |
| Hybrid-Gasoline | 2015 | 442                 | 38                      | 1.00            | 0.036                 |
|                 | 2030 | 553                 | 33                      |                 |                       |
|                 | 2050 | 670                 | 31                      |                 |                       |
### Table A6. Cont.

| Technology      | Year | Efficiency (Mkm/PJ) | Investment Costs (kCAD) | Fixed O&M (kCAD) | Variable O&M (CAD/km) |
|-----------------|------|---------------------|-------------------------|------------------|------------------------|
|                 |      | Long Distance       | Short Distance          |                  |                        |
| Hybrid-Diesel   | 2015 | 545                 | 488                     | 53               | 1.00                   | 0.036                  |
|                 | 2030 | 650                 | 582                     | 36               |                        |                        |
|                 | 2050 | 674                 | 605                     | 34               |                        |                        |
| Plug-In Hybrid 100 km | 2020 | 645                 | 736                     | 40               | 1.00                   | 0.029                  |
|                 | 2030 | 797                 | 774                     | 33               |                        |                        |
|                 | 2050 | 1061                | 886                     | 30               |                        |                        |
| Plug-In Hybrid 50 km | 2015 | 597                 | 632                     | 40               | 1.00                   | 0.029                  |
|                 | 2020 | 696                 | 736                     | 33               |                        |                        |
|                 | 2030 | 774                 | 818                     | 31               |                        |                        |
|                 | 2050 | 777                 | 822                     | 30               |                        |                        |
| Electric 150 km | 2015 | 860                 | 1138                    | 44               | 1.00                   | 0.024                  |
|                 | 2020 | 929                 | 1247                    | 37               |                        |                        |
|                 | 2030 | 929                 | 1247                    | 34               |                        |                        |
|                 | 2050 | 929                 | 1261                    | 30               |                        |                        |
| Electric 300 km | 2015 | 1189                | 1289                    | 46               | 1.00                   | 0.024                  |
|                 | 2020 | 1297                | 1387                    | 41               |                        |                        |
|                 | 2030 | 1400                | 1592                    | 34               |                        |                        |
|                 | 2050 | 1505                | 1592                    | 30               |                        |                        |

### Table A7. Efficiencies and costs of the light trucks updated for NATEM.

| Technology           | Year | Efficiency (Mkm/PJ) | Investment Costs (kCAD) | Fixed O&M (kCAD) | Variable O&M (CAD/km) |
|----------------------|------|---------------------|-------------------------|------------------|------------------------|
| Gasoline             | 2015 | 252                 | 38                      | 1.30             | 0.042                  |
|                      | 2050 | 384                 | 38                      |                  |                        |
| Diesel               | 2015 | 314                 | 46                      | 1.30             | 0.042                  |
|                      | 2050 | 404                 | 46                      |                  |                        |
| Compressed natural gas | 2015 | 284                 | 56                      | 1.30             | 0.052                  |
|                      | 2030 | 401                 | 56                      |                  |                        |
|                      | 2050 | 402                 | 60                      |                  |                        |
| E85                  | 2015 | 265                 | 39                      | 1.30             | 0.042                  |
|                      | 2030 | 296                 | 39                      |                  |                        |
|                      | 2050 | 388                 | 38                      |                  |                        |
| Hybrid-Gasoline      | 2015 | 307                 | 57                      | 1.30             | 0.042                  |
|                      | 2030 | 411                 | 56                      |                  |                        |
|                      | 2050 | 548                 | 56                      |                  |                        |
| Hybrid-Diesel        | 2015 | 389                 | 48                      | 1.30             | 0.042                  |
|                      | 2030 | 548                 | 48                      |                  |                        |
|                      | 2050 | 548                 | 47                      |                  |                        |
| Plug-In Hybrid 50 km | 2015 | 513                 | 46                      | 1.30             | 0.035                  |
|                      | 2020 | 584                 | 43                      |                  |                        |
|                      | 2030 | 584                 | 40                      |                  |                        |
| Electric 150 km      | 2015 | 633                 | 39                      | 1.30             | 0.030                  |
|                      | 2020 | 773                 | 46                      |                  |                        |
|                      | 2030 | 1165                | 44                      |                  |                        |
| Electric 400 km      | 2015 | 1268                | 39                      | 1.30             | 0.030                  |
|                      | 2020 | 1389                | 57                      |                  |                        |
|                      | 2030 | 1429                | 46                      |                  |                        |
Appendix B

As a sensitivity analysis on this scenario, two other disruptions are presented in this section. As doubt could be raised on the feasibility of a 2020–2025 disruption, the first alternative is a disruption scenario with a different timeframe. This scenario is called carpooling_2030 in the following figures. In this scenario, the number of passengers per vehicle is the same as in the carpooling scenario, but the shift happens five years later. The disruption occurs between 2025 and 2030. A second sensitivity analysis is made on the scale of the disruption. As doubling the number of passengers per vehicle may appear too ambitious, another disruption scenario is established here. This scenario is called carpooling_number in the following figures. Table A8 shows the detailed shift in demand for the carpooling_number scenario.

Table A8. The detailed shift in demand that could occur in Quebec with an alternative carpooling scenario.

| Distance (km) | Number of Passengers per Vehicle (Alternative Carpooling Scenario) | 2017 Number of Passengers per Vehicle | Total Demand (%) | Shift in Demand (%) |
|---------------|-------------------------------------------------|---------------------------------|-----------------|-------------------|
| <1            | 1.5                                             | 1.2                             | 23.6            | −25               |
| 1–11          | 1.9                                             | 1.5                             | 53.1            | −25               |
| 12–50         | 2.0                                             | 1.6                             | 20.2            | −25               |
| 51–100        | 2.3                                             | 1.8                             | 2.2             | −25               |
| >100          | 2.6                                             | 2.1                             | 1.1             | −25               |

Figure A1 shows GHG emissions breakdown in the transportation sector due to the sensitivity analysis’ scenarios. Figure A2 shows the penetration of electric and hybrid vehicles from 2015 to 2050 under the investigated scenarios. Figure A3 shows the total expenditures per household for all vehicle types combined.

Figure A1. Annual GHG emissions of the transportation sector in Quebec, for the reference scenario, the carpooling scenario, and the sensitivity analysis scenarios considered.

The reduction in GHG emissions would be immediate in 2025 in the carpooling scenario (32.6% of reduction in just five years relative to the reference scenario, between 2020 and 2025), whereas the reduction in GHG emissions would be a 21.1% reduction between 2020 and 2025 relative to the reference scenario, in the carpooling_number scenario. For the carpooling_2030 scenario, in which the disruption happens in 2030, the reduction in GHG emissions would be of 13.8% of reduction between 2020 and 2025 relative to the
reference scenario but should then reach 40.3% of GHG reduction between 2025 and 2030. Delaying the disruption would, therefore, allow more time to plan the changes but should then be more radical five years later.

The carpooling scenario involves a slightly slower penetration of electric vehicles when the demand disruption occurs (between 2020 and 2030). After 2030 (after the demand shift), demand resumes, and the electrification of the transport fleet begins. In both the carpooling_2030 scenario and in the carpooling_number scenario, the penetration of electric vehicles would be more gradual. This gradual penetration would permit heterogeneous groups of consumers to change their fossil fuel vehicles and buy electric vehicles in a broader range of years.

The carpooling scenario reduces household costs by 53.6%. As expected, the carpooling_number scenario reduces costs by 25%. The carpooling_2030 scenario, in which the disruption occurs in 2030, reduces costs by 37.8% in 2030 and falls between the other two scenarios. In 2040, however, the carpooling_2030 scenario reduces costs by 57.8% compared to the baseline scenario and by 58.1% in 2050, which leads to lower costs than the carpooling scenario. This trend is explained by the fact that demand is delayed but is more radical, which is reflected in household expenditures.
Figure A3. Total annual household expenses in their vehicles, disaggregated into investment cost, activity cost (use cost), and operation and maintenance cost, for three years (2030, 2040, 2050) and the scenarios considered (reference, carpooling, carpooling_2030, carpooling_number).

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