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Freight transport modal shifts in a TIMES energy model: Impacts of endogenous and exogenous modeling choice

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HIGHLIGHTS

- Endogenous and exogenous approaches lead to different results on several indicators.
- The exogenous approach makes it possible to model disruptions.
- The exogenous approach is more flexible on the investment in complex technologies.
- Modal shifts reduce energy consumption, but it displaces it elsewhere (rebound effect)
- The endogenous approach shifts behaviors in a rather limited way.
- Only the maximum exogenous scenario results in significant cost avoidance.

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ABSTRACT

The freight transportation sector accounted for 10.1% of global emissions and 16.2% of Quebec's greenhouse gas emissions in 2018. In this sector, the most salient yet little explored behavioral change opportunity is the modal shift from heavy trucks to trains. Current model developments are being made so that E4 modelers represent modal choices as endogenous variables in the models. However, if we want to continue to improve the realism of the models, it is important to know if this modeling technique is suitable for a world where radical changes are required. In this study, two types of modal shifts are implemented and compared in a TIMES-type energy model: exogenous modal shifts, with demand-side scenarios, and endogenous modal shifts, with the introduction of substitution elasticities as an endogenous behavioral feature of the model. The results of this study show that only the exogenous approach allows the modeling of disruptions: in demand, in energy consumption, and in system costs. With respect to vehicle type, the exogenous approach avoids investments in complex infrastructure (i.e., catenary), at least in the medium term, while the endogenous approach leads to results where electric trucks and catenaries appear in 2030. Only the scenario with a significant modal shift from heavy trucks to trains (Exog_max) avoids substantial energy consumption (17 PJ in 2030 and 10 PJ in 2050). The concluding recommendation is to use the exogenous approach in a disruptive modeling context. In a world where a paradigm shift is needed, the exogenous approach allows for a better representation of concepts that have been seldom modeled until now.

1. Introduction

While many countries work on their energy transition, two major concerns arise. The first is the urgency of the situation: the timing will be decisive [1]. The second concern is the scale of the situation: if global warming is to be limited to 1.5C above pre-industrial levels, radical greenhouse gas reduction targets (i.e. 93 % reduction in GHG emissions in 2050 relative to 2010) must be put in place [2,3]. Energy/Economy/

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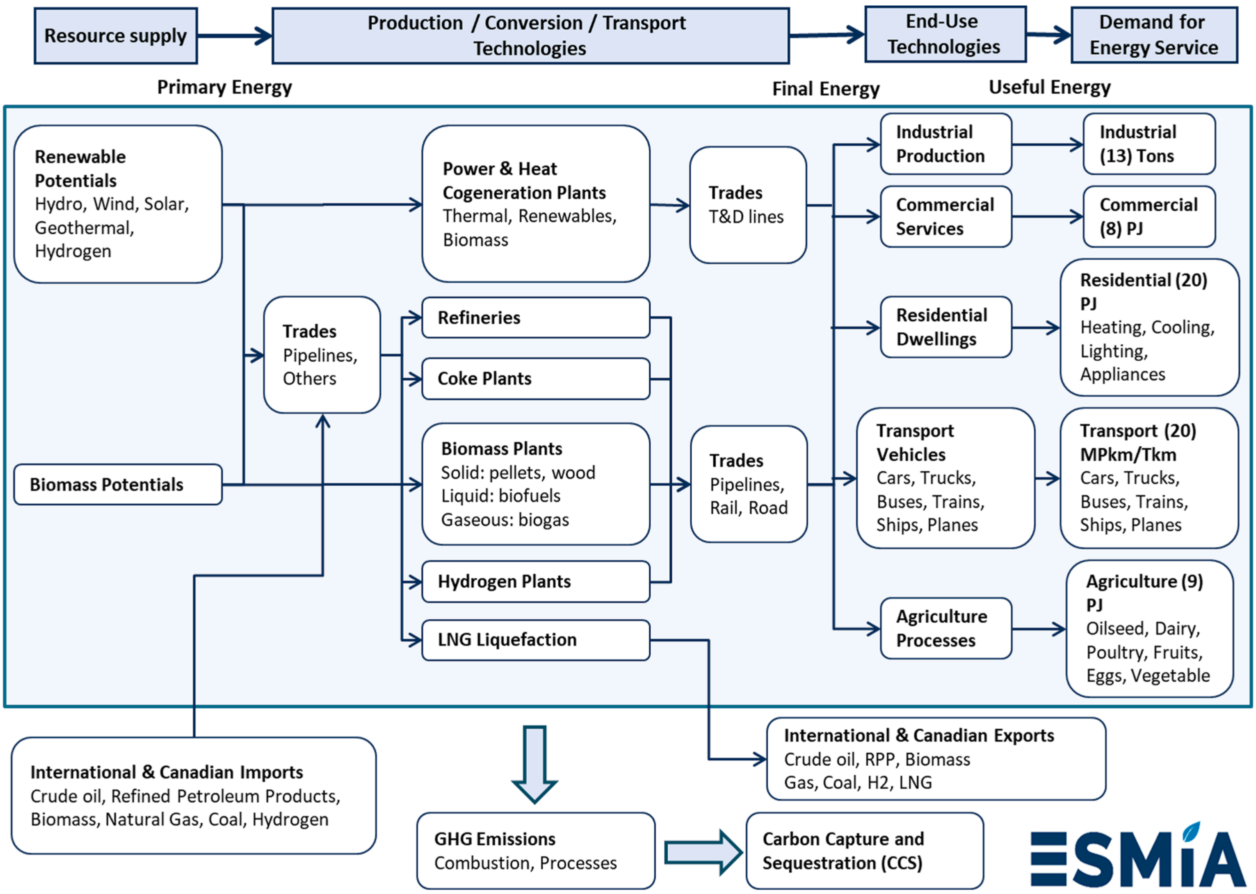

Fig. 1. NATEM general structure and interconnections between sectors (Simplified figure from [60]).

Environment/Engineering (E4) models and in particular TIMES models are currently pushed to their limits to achieve very high absolute greenhouse gas (GHG) emissions reduction targets. For instance, they must rely on still uncertain carbon capture and storage options to satisfy deep decarbonization levels, such as net-zero emissions by 2050 [4–6]. Technological options may fall short or be too expensive to reach these targets without significant behavioral changes [7–9].

The freight transportation sector represented 10.1 % of the world [10,11] and 16.2 % of Quebec's greenhouse gas emissions in 2018 [12]. This sector is a bigger challenge to decarbonize than the passenger transport sector because it's dominated by heavy trucks, for which electrification is less straightforward than for passenger vehicles. However, this sector is still little explored from a behavioral point of view [13]. In terms of behavior, the most salient yet little explored opportunity in the freight transport sector, given the reduction in energy consumption, is a modal shift from heavy trucks to trains [4,14–16]. The possibility of modal shift is still a challenge [17] and has been explored twice with the help of a TIMES optimization model, in the Nordic European countries and Denmark [4,18,19]. It has also been studied once in Quebec [20] but the iterative approach used did not permit to study of the impacts of such a decision on the whole energy system.

Several improvements in the behavioral representation in the transportation sector have been made in the E4 models [7]. In a partial equilibrium model, several features are determined and fixed by the modelers: the technical characteristics of the technologies (i.e. efficiency and costs), the constraints of the model (e.g., the fixed level of GHG emissions), as well as the demands for energy services. These features are called exogenous. Variables optimized within the model are called endogenous. In a model such as TIMES, the addition of behavioral variables in the transportation sector can be done exogenously or endogenously. The addition of exogenous behavioral variables can be done through transport-specific constraints that shape the model; by linking the TIMES model to an external transport-specific mode; or by simply setting the transport energy demand along a given trajectory. The endogenous behavioral variables have been classified into four types of variables, by Venturini et al. [7]: technology choice, modal choice, driving pattern, and new mobility trends. In this study, the modal shift between heavy trucks and rail is added to the model as an endogenous variable. The different approaches permit answering different questions (as highlighted by Tattini et al. [21]). For representing modal shifts, it is often suggested for modelers to endogenize change, by integrating as much as possible behavioral features and consumers' choices directly into the models [18,22]. The idea associated with endogenization is to improve the realism of behaviors, with internal model dynamics [19,23]. However, some authors argue that the use of exogenous scenarios is indispensable for representing radical changes and disruptions [3].

The rationale of this study is to challenge the need for endogenization in a context where countries aim to achieve some radical changes. The objective is to answer the following questions: Does integrating endogenous behavioral features allow E4 models to respond to the magnitude of the situation? What is the contribution of modeling a modal shift with an endogenous approach versus an exogenous one, when radical changes are explored? As the integration of behavioral variables in TIMES-type models is recent and still under development, the influence of these variables in a context of radical change has never been explored. The contribution of this research is therefore to fill this gap by studying the impact of the modeling choice made by the modeler, in a radical context. This gap is quite important as we are in a world where radical changes will be needed, and every modeling aspect can help better understand how to reach GHG emissions reduction targets. This study addresses a particular gap in modeling, faced by researchers who use models not designed for radical changes. The application of this study contributes to providing an insight into this modeling exercise in the Quebec region, which has not been done before. It should be noted that Quebec is only one case study to illustrate a global problem and a general methodological approach.

2. Method

2.1. The North American TIMES energy model

2.1.1. General specifications

The NATEM-Quebec model is being used in this study. NATEM (North American TIMES Energy Model) is a North American TIMES-type optimization model [24], and NATEM-Quebec is the portion of NATEM representing specifically the Quebec region [25]. TIMES (The Integrated MARKAL-EFOM System) was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program). TIMES is the successor of the models MARKAL and EFOM. 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 [24–27]. TIMES' main specifications are recalled in this section [19,28,29]. NATEM-Quebec can be defined as a bottom-up, technology-explicit, partial equilibrium, optimization model. These terms are defined in the following paragraphs.

It is defined as bottom-up because it goes from 2,415 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). 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, and winter), and four daily periods (day, night, and two peak periods). The discount rate is fixed at 5 %. The assumptions for GDP and population growth are based on the data in Vaillancourt et al. [25]. The structure of the model is presented in Fig. 1. The bottom-up models are the opposite of the top-down models, which represent an entire economy, using a relatively small number of variables, and focusing on macroeconomic features. In NATEM, each technology is explicitly identified and defined by several variables (costs, efficiency, capacity, etc.). NATEM is considered a technology-explicit model.

Partial equilibrium models are a subcategory of the so-called technologically explicit models (the other technologically explicit models being the simulation models). Partial equilibrium models use optimization techniques to find the equilibrium of a system (in the TIMES model, the energy system of a region), at the lowest cost. The equilibrium sought in NATEM is a balance between a production function and a demand function. The production function is implicitly calculated by the model, while the demand function for the energy services is exogenously specified by the modeler. The equilibrium between supply and demand is reached when the total surplus is maximized, i.e. when the sum of the consumer surplus and the producer surplus is maximized. 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 (over the full-time horizon considered).

Finally, it is cast as an optimization model because it determines the optimal energy system to meet the end-use energy demand, at the lowest cost, and over the chosen time horizon. The formulation of a linear optimization problem is composed of three main features:

- the objective function (Equation (1)):

$$OBJ(t) = \sum_{r=1}^{R} \sum_{y} \left(1 + d_{r,y}\right)^{REFY-y} * ANNCOST(r, y) \tag{1}$$

With $d_{r,y}$ the discount rate by region r and year y, REFY the base year, and $ANNCOST(r, y)$ the annual costs over region r in year y. In NATEM, the cost elements of the objective function are the following: the investment costs of each technology, the operation and maintenance costs, the activity costs, and the end-of-life costs. Minimizing the objective function is equivalent to maximizing the sum of the consumer and producer surpluses, thus seeking market equilibrium.

- the decision variables: the objective function is defined as a linear mathematical expression of the decision variables.
- the constraints: the optimization considers the physical resources and the constraints set by the user (i.e. GHG emissions targets) while minimizing the net total cost of the energy system through the objective function.

2.1.2. The demand function with constant elasticities of substitution (CES)

The end-use energy demands of the different sectors are essential drivers of the model. To model the possibility of substitution between previously distinct demands, CES functions were added to the TIMES code in 2016 [29]. The calibration of the CES functions is based on demand projections provided by the modelers, as well as on the shadow prices calculated by the model during a TIMES run without CES functions. The range of possible substitutions between the demands of each category is given as input, as well as the own-price elasticity for the aggregated demand. In a first step, the demand functions with CES have been modeled in a general way, in the non-linear version of TIMES (Equation (2)).

$$U = \left(\sum_{i} \alpha_i^{1/\sigma} * x_i^{\sigma-1/\sigma}\right)^{\sigma/\sigma-1} \tag{2}$$

With U the aggregate demand, α the proportion of ×, the component demand, and σ the elasticity of substitution. Subsequently, since TIMES is a linear optimization program, the demand functions with CES were linearized (Equations (3) and (4)).

$$U_k(t) = U_k^0(t) + \sum_{j=1}^{m} zm_{j,k}(t) + \sum_{j=1}^{n} zn_{j,k}(t) \tag{3}$$

$$U_k^0(t) = \sum_{i \in I(k)}^{m} DM_i^0(t) \tag{4}$$

With $U_k(t)$ the aggregate demand k, i.e. the sum of all reference demands $DM_i^0(t)$ that compose $U_k^0(t)$ the reference demand, and $\sum_{j=1}^{m} zm_{j,k}(t)$ et $\sum_{j=1}^{n} zn_{j,k}(t)$ the variable steps defining the minimum and maximum range in which the demand can be included.

The component demands $DM_i(t)$ are themselves linearized as a proportion $\alpha_{ki}(t)$ of the aggregate demand $U_k(t)$. The substitution range is included in the equation by adding the minimum and maximum elasticity of substitution variables $\sum_{j=1}^{m} sm_{j,k}(t)$ et $\sum_{j=1}^{n} sn_{j,k}(t)$ (Equation (5)).

$$DM_i(t) = \alpha_{ki}(t) * U_k(t) + \sum_{j=1}^{m} sm_{j,k}(t) + \sum_{j=1}^{n} sn_{j,k}(t) \tag{5}$$

A balance is then imposed so that the conditions linking aggregate demand and component demands are satisfied at each stage of the model calculation. This balance considers the variation of prices of the component demands, which readjusts the substitution between the different component demands.

2.2. Environmental impacts

TIMES-type models generally account for emissions associated with

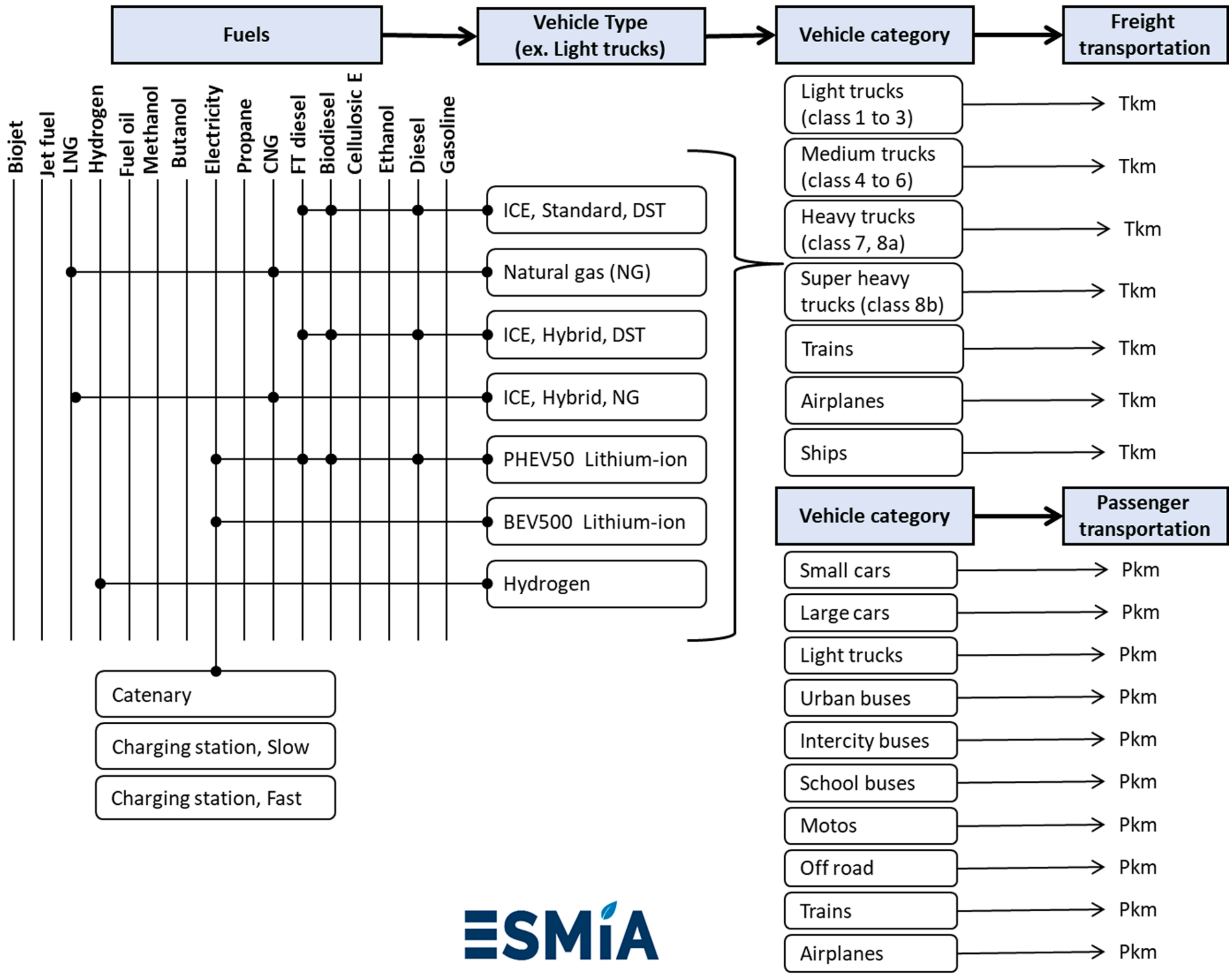

Fig. 2. The structure of the transportation sector in NATEM, with a focus on the heavy trucks segment.

fuel combustion and fugitive sources (emissions related to the extraction, processing, and delivery of fuels) [28]. 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 (CO_2), methane (CH_4), and nitrous oxide (N_2O)) as well as all GHGs, from fuel combustion, fugitive sources, industrial processes, agriculture, and waste. These greenhouse gases are then aggregated into a single equivalent amount of carbon dioxide (CO_2eq), 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 take place. Sometimes, there are no direct emissions associated with energy use 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.).

2.3. The freight transportation sector in NATEM

2.3.1. Structure of the freight transportation sector

In NATEM, the freight transportation sector is broken down into three distinct subsectors: road, maritime, and rail. The road sector is further decomposed into several subsectors corresponding to different classes of trucks: light trucks (class 1 to 3 vehicles), medium trucks (class 4 to 6 vehicles), and heavy trucks (class 7, 8a, and 8b vehicles). The desegregation of the freight transportation sector is summarized in Fig. 2.

2.3.2. Technologies

In this section, the detailed technologies for heavy-duty trucking are presented. Each technology is defined in terms of its cost (investment, operation and maintenance, and end-of-life), efficiency, distance traveled per year, tons transported, and lifetime. Class 8 trucks are broken down into two categories, 8a, and 8b, which correspond to trucks with engines of 12 L or less and trucks with engines of more than 12 L (Table 2). Demand for engine trucks over 12 L (Class 8b) accounts for 65 % of the total demand for heavy-duty trucking, according to 2016 SAAQ data [30]. Both slow charging stations (overnight charging stations) and fast charging stations (daytime charging stations) are modeled for the freight trucking sector. The use of the different charging stations varies by truck type: it is assumed that medium trucks charge up to 70 % at slow charging stations and up to 50 % at fast-charging stations and that heavy trucks follow the same charging profile as medium trucks. This

Table 1
Hypotheses considered for the catenary technology.

Technology	Start year	Efficiency		Inv. Costs		OM costs	Length	Lifetime
	yr.	kWh/km	MW/km	M$/km	$/kW	$/kW	km	yr.
Catenary	2030	1.6	0.7	2	1,500	30	215	50

Sources: [32,34–36].

Table 2
Hypotheses considered for the heavy trucks segment market.

Technologies	Year	Efficiency		Inv. Costs	OM costs	Annual distance	Lifetime
		Mkm/PJ	MJ/km	$/veh	$/km	km	
Heavy trucks - class 7 and 8a							
Diesel	2020	77.2	12.9	182,000	0.22	81,891	20
	2030	99.5	10.0				
	2050	118.1	8.5				
Natural gas	2020	68.9	14.5	252,000	0.23	81,891	20
	2030	97.6	10.2				
	2050	118.1	8.5				
Battery Li25 500 km	2020	276.2	3.6	450,000	0.19	81,891	20
	2030	356.9	2.8				
	2050	422.9	2.4				
Battery + catenary	2030	355.8	2.8	540,000*	0.19	81,891	20
	2050	421.9	2.4				
PHEV diesel + catenary**	2030	247.5	4.0	274,000*	0.20	81,891	20
	2050	303.2	3.3				
Heavy trucks - class 8b							
Diesel	2020	50.2	19.9	235,000	0.22	175,000	20
	2030	64.7	15.5				
	2050	76.7	13.0				
Natural gas	2020	44.8	22.3	354,000	0.23	175,000	20
	2030	63.4	15.8				
	2050	76.7	13.0				
Battery Li25 500 km	2020	180	5.6	550,000	0.19	175,000	20
	2030	232	4.3				
	2050	275	3.6				
Battery + catenary	2030	232	4.3	660,000*	0.19	175,000	20
	2050	275	3.6				
PHEV diesel + catenary**	2030	116	8.6	443,000*	0.20	175,000	20
	2050	138	7.3				

* Additional cost based on [32].
** Assumption of a maximum of 55% of the trip on the catenary.

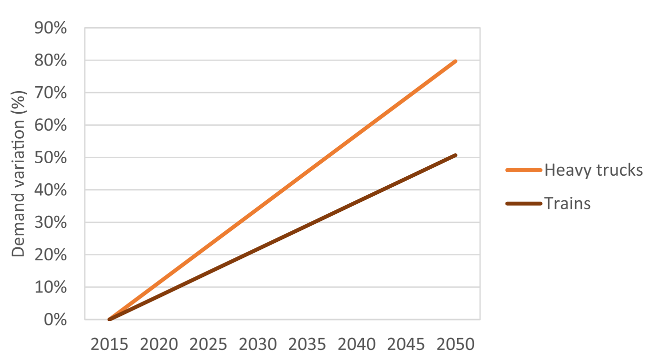

Fig. 3. Heavy trucks and trains demand variation for the Business-As-Usual (BAU) scenario compared to 2015.

constraint may not be logistically feasible and represents an optimistic assumption for the electrification scenario (heavy electric trucks may charge in greater proportion at fast-charging stations). These operational constraints are beyond the modeling level of this study. Too much heavy truck charging at slow charging stations could be a difficult constraint for a fleet of trucks to manage, with too much downtime. Electric heavy-duty trucks receiving their electricity via catenary are also modeled (Table 1). The hypotheses used for the conventional, battery, and hydrogen trucks were taken from existing technologies. The majority of the hypotheses considered were validated by a Quebec company (Énergir) with up-to-date knowledge on the feasibility of each technology in Quebec. A report with these hypotheses has been previously published [31]. The rest of the hypotheses were validated with data from the literature [12,31–33]. The catenary data were taken from a study of feasibility prepared in Quebec [34] and completed with data from Siemens, a company that has already installed some catenaries in European countries [32,34–36].

2.3.3. *Demand projection*

Demand is an essential input of the model and introducing a modal shift means shifting the demands of the freight transportation sector. Fig. 3 shows the projected increase in demand to 2050 compared to 2015 for heavy trucking and rail. These freight demand forecasts are aligned with many other ones, such are ITF [37] which sees global freight growing four times by 2050. This hypothesis highlights the importance of implementing a modal shift since the baseline assumption (BAU scenario) is that heavy truck demand could increase by 80 % in 2050 compared to 2015 and rail demand could increase by 48 % in 2050 compared to 2015. In Quebec, the province's roads are already operating at near capacity today and it seems difficult to envisage an increase in heavy trucking demand of 80 %. Moreover, the price per km of road versus the price per km of a railroad is similar (1.02 US M$/km for adding a lane to a road and 3.34 US M$/km for building a new road [38] versus 1.13 US M$/km for building a new railroad [39]). The current situation, therefore, suggests that it could be easier to develop railroads

Table 3
Short-term and long-term own-price elasticities for the heavy trucks and trains.

Segment	Own-price elasticities [44,45]		
	2020	2030	2050
Trucks	−0.25	−0.25	−0.35
Rail	−0.30	−0.30	−0.40

Table 4
Minimum and maximum substitution elasticities between heavy trucks and trains.

Segment	Substitution elasticities [46]	
	σ_{min}	σ_{max}
Heavy trucks - Rail	0.3	2.0

Table 5
The possible shift in demand depending on the merchandise type ().

Type of goods	Modal shift potential			Share of transported goods
	Weight	Value	Speed	%
Wood, wood products, paper, and printing	High	High	Medium	25.9
Ores and mineral products	High	Medium	High	13.5
Chemical and petrochemical products	High	Medium	Medium	13
Metal products	High	Medium	Medium	7.5
Other (waste, fertilizers, fuels, etc.)	Medium	Medium	Medium	12.6
Food products	Medium	Medium	Low	18.1
Unknown	Medium	Low	Medium	0
Mails and parcels	Low	High	Low	2.8
Furniture	Low	Low	Medium	1.1
Textiles, leather, and clothing	Low	Low	Medium	0.8
Machinery, electronics, and electrical appliances	Low	Low	Low	2.5
Vehicles and transportation equipment	Low	Low	Low	1.9

Source: [14,20,47].
Source: [21]

rather than additional roads.

2.4. Modeling modal shifts in freight transportation

Following the objective of this study, two types of modal shifts are implemented in NATEM: exogenous modal shifts, with demand-side scenarios, and endogenous modal shifts, with the introduction of substitution elasticities as a behavioral feature that can be optimized by the model. The modeling of these two methods is detailed in this section. The scenarios' contribution to the decarbonization of the freight transportation sector is then analyzed in the result section based on different indicators: the energy consumption, technologies used, and costs of the system.

2.4.1. Endogenous modal shifts through elasticities of substitution

It is important to note here that two types of elasticity are represented in the model: price elasticities and elasticities of substitution between sectors where a modal shift may occur. Price elasticities measure the response of demand to a change in a price signal (for example, an increase in the price of a train ticket). A vast literature exists on price elasticities and it is common to incorporate them into an optimization model [40–43]. Here, short-run (2020), medium-run (2030), and long-run (2050) price elasticities have been established, based on values from the literature [44,45]. It is important to mention the value of these price elasticities because cross effects with substitution elasticities were observed in this study. The values of the price elasticities chosen are presented in Table 3. The substitution elasticities represent the transfer of demand between two or more sectors following the variation of a price signal in one of these sectors. They are the variable that represents the modal shift. Here, the substitution elasticities were defined to model the shift between heavy trucks and trains. These elasticities were modeled as in [19,29], see also these studies for more technical modeling details. To estimate the impact of the value of the substitution elasticities chosen by modelers, a minimum and maximum range of cross elasticities [45,46] were considered for the main scenarios (Table 4). Other elasticity values (steps of 0.1 from $\sigma = 0.3$ to $\sigma = 2.0$) have been tested and are presented as a sensitivity analysis in the appendix.

Table 6
Storylines for the exogenous modal shift scenarios, from heavy trucks to trains.

Scenario	% intermodality	Description
Exog_max	59.4	90 % of goods with high potential, 50 % of goods with medium potential, and 20 % of goods with low potential.
Exog_min	17.0	50 % of goods with high potential, 0 % of goods with medium potential, and 0 % of goods with low potential.

Table 7
Description of the scenarios.

Scenarios	Description
BAU	Business as usual scenario including environmental policy measures currently in place.
Ref-GHG	Scenario aiming at achieving 2030 and 77.9 % of 2050 targets (due to feasibility constraints).
Exog_min	Modal shift through the demand-side scenario from heavy trucks to rail at 17.0 %.
Exog_max	Modal shift through the demand-side scenario from heavy trucks to rail at 59.4 %.
Endog_min	Endogenous modal shift through elasticities of substitution from heavy trucks to rail with a minimum crossed price elasticity of 0.3.
Endog_max	Endogenous modal shift through elasticities of substitution from heavy trucks to rail with a maximum crossed price elasticity of 2.0.

Note: In all the modal shift scenarios, Quebec achieves 100 % of its 2030 GHG emission reduction targets and 77.9 % of its 2050 targets on the territory. Own price elasticities are included.

2.4.2. Exogenous modal shifts through demand management scenarios

To quantify the exogenous modal shifts, a previous study conducted in Quebec in 2013 (Table 5) [20] was used as a starting point. The modal shift potential was defined according to the type of commodity and three criteria: the weight of the commodity transported, its value, and the required delivery speed. Based on these criteria and the type of commodity, two exogenous scenarios were defined (Table 6). The amount of demand transferred between heavy trucks and trains is calculated as a weighted average by each criterion (weight, value, speed). The weights were set differently depending on the scenario (minimum or maximum). These types of scenarios can be seen as scenarios that require an external intervention to be put in place (for example, an intervention from the government).

2.5. The scenarios considered

2.5.1. The scenarios

All the scenarios described are summarized in Table 7. Six main scenarios are defined in this study:

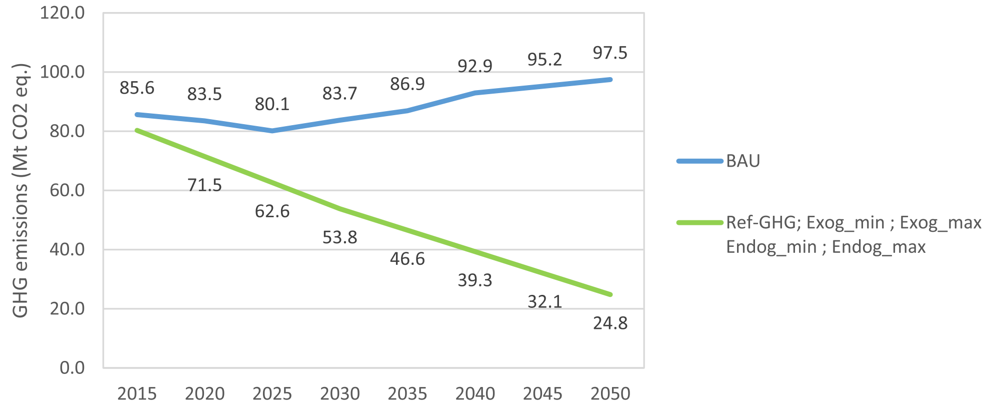

Fig. 4. GHG emissions attained for each endogenous and exogenous scenario considered.

1) **The BAU** 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 and the Transport Electrification Plan [48–50] and the renewable fuels strategy [51] and can be detailed as follows:
   a. 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 \$10 per ton of CO2 in 2012 up to \$66 per ton in 2050) [52–54].
   b. 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) [50]. This objective was adjusted in November 2020, increasing it to 1,500,000 electric vehicles [55].
   c. All gasoline vehicles run on a minimum of 5 % of ethanol and 2 % of biodiesel for diesel vehicles, a policy implemented in 2010 [51].
   d. The Regulation respects the quantity of renewable natural gas to be delivered by a distributor [56], with 5 % RNG required in Quebec's energy mix in 2030 and 10 % RNG required after 2030.
   e. Vehicle manufacturers must comply with the corporate fuel average economy (CAFE). Vehicles, therefore, have minimum energy efficiency [25].
2) **The Ref-GHG** reduction scenario. This scenario includes the Clean Fuels Standard and the Renewable Natural Gas Regulation and is further aligned with Quebec's GHG reduction targets (37.5 % reduction in GHG emissions in 2030 and 80 % in 2050 from 1990 levels) [57,58]. It should be noted that in the Ref-GHG scenario, Quebec's reduction targets are not met in 2050. Indeed, without options such as carbon capture and sequestration (excluded because of its uncertainties), or the reduction of energy demands, the model does not find a solution that would allow it to reach all of Quebec's reduction targets in 2050. Only 77.9 % of Quebec's GHG emission reduction is achieved in 2050.
3) Two demand-side modal shift scenarios: **exog_min** and **exog_max** are described in section 2.3.2. For the Exog_min scenario, the possible substitution between heavy trucks and trains is set to a minimum value of 17 %, while for the Exog_max scenario, the possible substitution between heavy trucks and trains is set to a maximum value of 59.4 %.
4) Two endogenously modeled modal shift scenarios, as described in section 2.3.1. For the **Endog_min** scenario, the possible substitution between heavy trucks and trains is set to a minimum value (σ_{min} = 0.3) while for the **Endog_max** scenario, the possible substitution

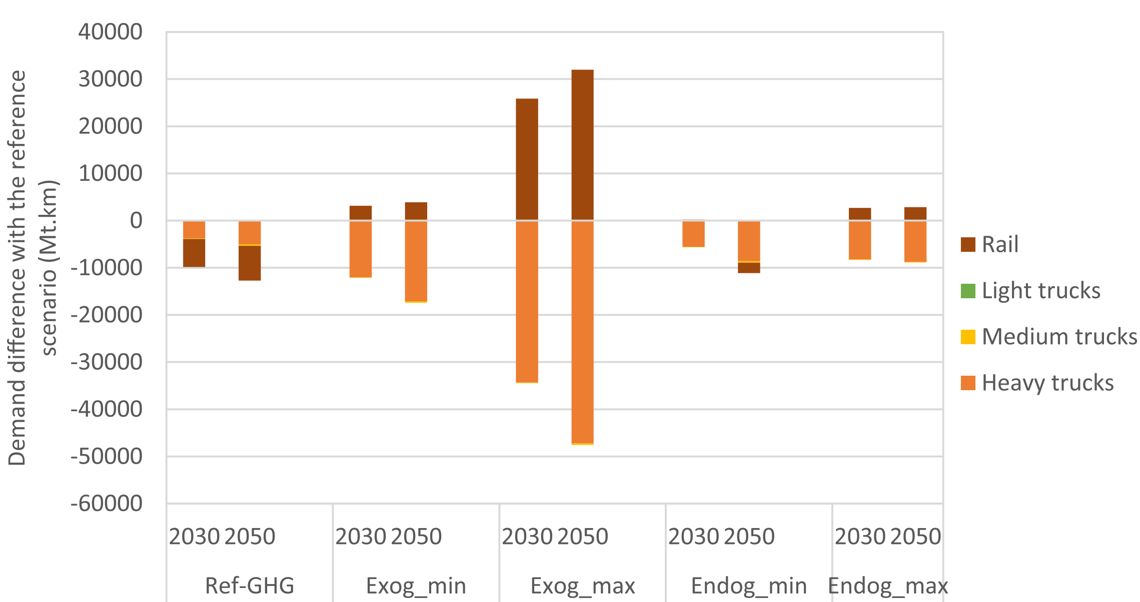

Fig. 5. Demand shift compared with the BAU scenario in the exogenous and endogenous modal shifts scenarios considered.

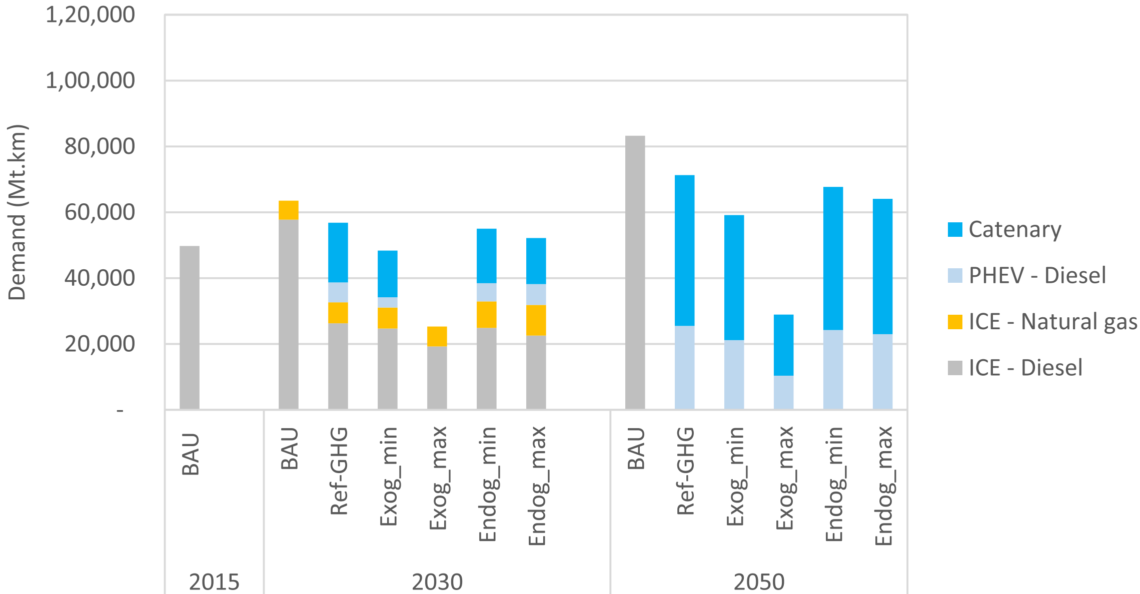

Fig. 6. Final heavy trucks demand (Mt.km) per vehicle type in the exogenous and endogenous modal shifts scenarios considered.

between heavy trucks and trains is set to a maximum value ($\sigma_{max} = 2.0$).

2.5.2. *Scenario equivalence*

For the different approaches to be comparable, the scenarios need to be functionally equivalent. Fig. 4 presents the GHG emissions bounds for each scenario, between 2015 and 2050. This figure shows that regardless of the approach adopted to model the modal shifts, the scenarios are equivalent in terms of GHG emissions. It should be noted that Quebec's GHG targets are ambitious and the models are already extremely constrained to achieve these targets. As all scenarios achieve the same levels of GHG emissions, they are functionally equivalent.

3. Results

3.1. *Demand shift*

Fig. 5 shows how the modal shift spreads between heavy trucks and trains in each scenario in the medium term (2030) and the long term (2050), compared to the baseline scenario without any elasticities (BAU). This figure shows the modal shift according to the approach considered, but also the cross-effects between the modal shift approach and the price elasticities of the model.

The effects of price elasticities alone are visible in the first scenario of the figure, Ref-GHG. With price elasticities alone, as the GHG target must be met, the global demand is reduced. In the two exogenous scenarios (Exog_min and Exog_max), one can observe, on the one hand, the effect of the modal shift, which forces the model to shift from heavy trucks to trains (to different degrees depending on the minimum or maximum scenario); and on the other hand the cross-effect with the

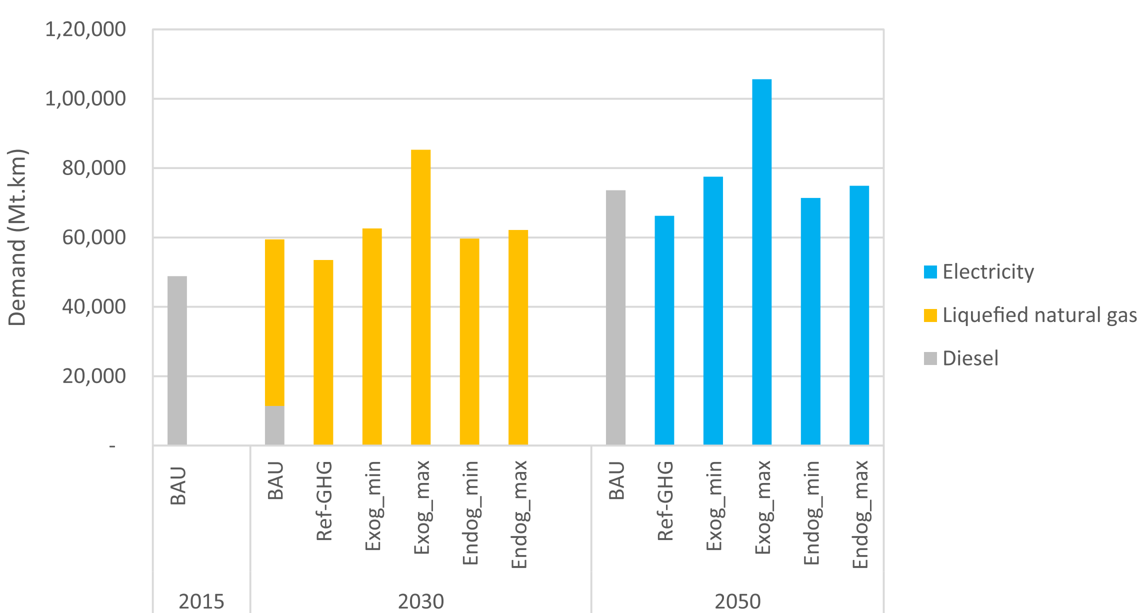

Fig. 7. Final trains demand (Mt.km) per vehicle type in the exogenous and endogenous modal shifts scenarios considered.

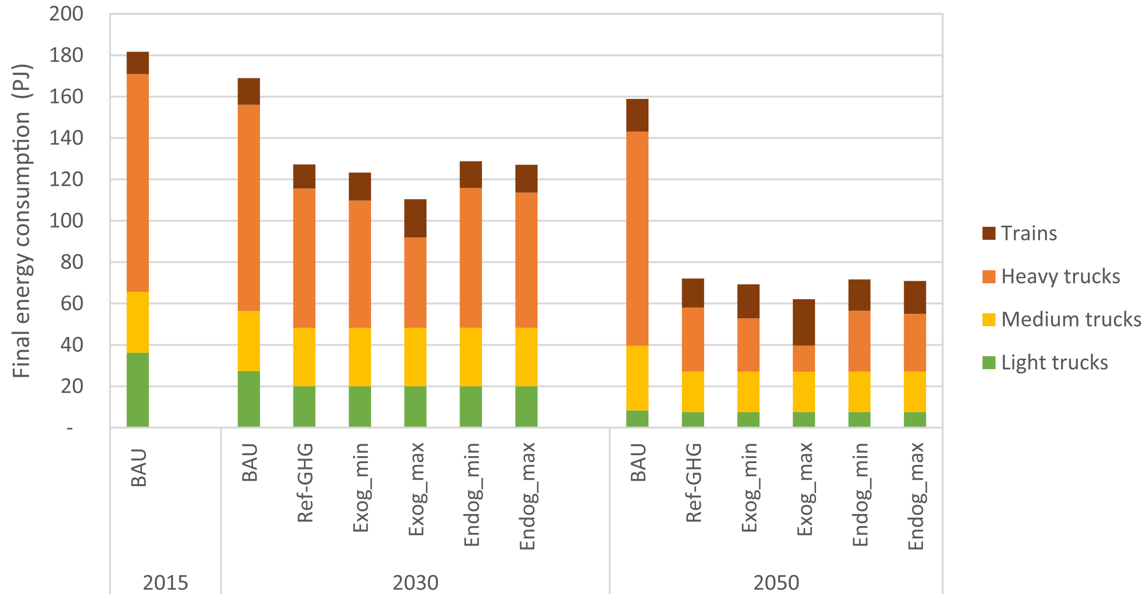

Fig. 8. Final energy consumption (PJ) in the road and rail freight transportation sector in the exogenous and endogenous modal shifts scenarios considered.

price elasticities that reduce the overall demand. These two effects combined explain why the increase in rail demand is less important than the decrease in road demand (for example, in 2050, in the Exog_max scenario, the demand for trains has increased by 31.995 Mt.km while the demand for heavy trucks has decreased by 47.276 compared to the BAU scenario). The same cross-effects are observed for both endogenous scenarios. The cross effect of price elasticities with the demand shift is, however, larger, because the modal shift is smaller when done endogenously. Thus, in the Endog_min scenario, there is no increase in demand for rail in 2030, and demand for rail even declines in 2050 despite the modal shift that occurs.

This figure shows that, depending on the approach considered, the effects on demand are not the same. With the exogenous approach, the transfer of demand may be more disruptive; while with the endogenous approach, the cross-effects with other types of elasticity are much more visible. This figure suggests that both approaches might not lead to the same conclusions and are worth exploring. This figure is the starting point for the reasoning of this paper. In the next sections, results for other key indicators of optimization models are explored.

Fig. 5 shows that the exogenous approach allows for a faster and larger scale decrease in heavy truck demand (between −31 % and + 40 % compared to 2015), offset by an increase in rail demand (between + 59 % and + 116 % compared to 2015). The endogenous approach varies little from the baseline scenario (increase in heavy truck demand from 58 % to 65 % compared to 2015 and increase in rail demand from 48 % to 54 % compared to 2015).

3.2. Vehicle types

The second indicator studied is the different types of vehicles used. Fig. 6 shows the type of heavy trucks on the market until 2050, while Fig. 7 shows the type of trains.

The Exog_min scenario avoids 12.1 % in 2030 and 12.6 % in 2050 of the total demand for heavy trucks, compared to the Ref-GHG reference scenario. The Exog_min scenario avoids 3.1 % in 2030 and 5.0 % in 2050 of the total demand for heavy trucks, compared to the Ref-GHG reference scenario. The Exog_max scenario avoids 8.1 % in 2030 and 10.1 % in 2050 of the total demand for heavy trucks, compared to the Ref-GHG reference scenario. The minimum exogenous scenario, which is also a feasible scenario, allows going further in terms of heavy truck demand reduction than the maximum endogenous scenario. The maximum exogenous scenario allows avoiding 55.4 % in 2030 and 50.2 % in 2050 of the total demand for heavy trucks, compared to the Ref-GHG reference scenario. In particular, the Exog_max scenario avoids investment in heavy diesel hybrid trucks in 2030, as well as in heavy electric trucks, which is not insignificant given the region's constraints.

On the other hand, the Exog_min scenario increases the total rail demand by 17 % in 2030 and 2050, compared to the Ref-GHG reference scenario. The Endog_min scenario increases rail demand by 11.5 % in 2030 and 7.8 % in 2050, compared to the Ref-GHG reference scenario. The Endog_max scenario increases rail demand by 16.1 % in 2030 and 13.1 % in 2050, compared to the Ref-GHG reference scenario. Finally, the Exog_max scenario increases rail demand by 59.4 % in 2030 and 2050, compared to the Ref-GHG reference scenario. However, since trains are less energy-intensive than heavy trucks, the increase in train demand in all transfer scenarios still results in a decrease in energy consumption, as seen in Section 3.3. In addition, the type of train entering the market remains the same (LNG trains in the medium term and electric trains in the long term) regardless of the scenario.

These two figures confirm that the two approaches can lead to different results. Due to the difference in the energy efficiency between the trucks and the trains, the exogenous approach leads to significant savings on the heavy trucks vehicles demand (in Mt.km) without fundamentally changing the train vehicle penetration. In the exogenous scenario with a high modal shift potential (Exog_max), the catenaries appear only in 2050, whereas the endogenous approach leads to results, where electric trucks and catenaries appear in 2030. The catenaries are a technological innovation quite difficult to implement, as there is the need to construct it from scratch. The exogenous approach, although disruptive in terms of demand, gives, therefore, more time to implement a complex technology. This observation suggests that the exogenous approach may be more feasible to apply to the reality of a region, contrary to the assumption formulated in the introduction.

3.3. Energy consumption

The third indicator studied is energy consumption. Fig. 8 shows the energy consumption of road and rail freight transport. Of the four modal shift scenarios, only one scenario - Exog_max - shows a significant difference in energy consumption compared to the Ref-GHG scenario, in which Quebec meets its emission reduction targets without the help of any modal shift. The only scenario in which modal shift is implemented

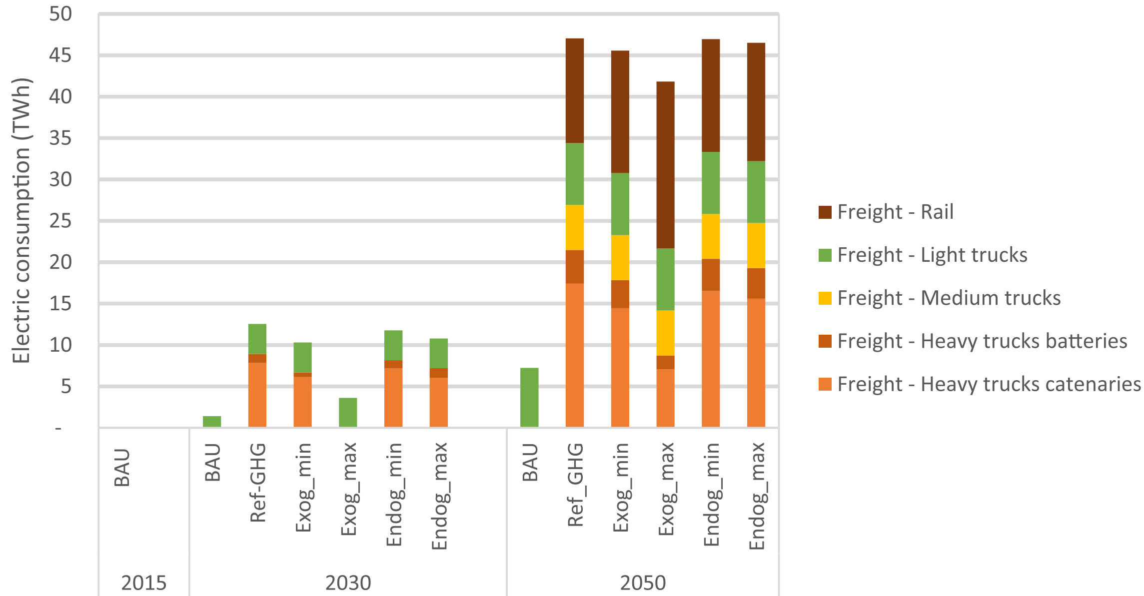

Fig. 9. Final electric consumption freight transportation (TWh) in the exogenous and endogenous modal shifts scenarios considered.

abruptly, Exog_max, avoids 17 PJ of consumption in 2030 and 10 PJ in 2050. This can be explained by the different cross-effects contributing to the energy consumption: the global decrease of demand generated by the price elasticities, the demand shift generated by the modal transfer, and the fact that the trains are lee energetic than heavy trucks. In the Exog_min scenario, 4 PJ are avoided in 2030 compared to the Ref-GHG scenario, and 3 PJ are avoided in 2050. In the Endog_max scenario, no PJ is avoided in 2030 and only 1 PJ is avoided in 2050 compared to the Ref-GHG scenario. Finally, in the Endog_min scenario, 2 PJ are even added in 2030 compared to the Ref-GHG scenario. In these three scenarios, the difference in energy consumed due to the modal shift is displaced in the other sectors. This is called a rebound effect. As this rebound effect is only captured in the different energy sectors, it could be the subject of a future analysis to analyze the rebound effect on the whole economy.

Since massive electrification is expected in the transportation sector, in all scenarios where the emission reduction targets are met, the energy avoided by a modal shift will largely be electric. Fig. 9, therefore, focuses on the electricity consumption of freight transport in the different scenarios. The avoided electricity ranges from 1 to 2 GWh in 2030 and from 1 to 3 GWh in 2050 for three modal shift scenarios (Exog_min, Endog_min, and Endog_max), compared to Ref-GHG, which corresponds to the production of a large hydropower system in Quebec, such as the La Romaine 3 complex [59]. The Exog_max scenario avoids 9 GWh in 2030 and 6 GWh in 2050, which corresponds to two, even three, large hydropower plants in Quebec. This scenario avoids electricity consumption per catenary in 2030, which is interesting since catenaries represent 61.5 % of the electricity consumption of freight transport in 2030 in the Ref-GHG reference scenario and are a technology that requires major work for its implementation. In terms of electricity consumption, the results show that the Exog_max scenario, in which the modal shift is implemented in the form of a behavior change, avoids a significant consumption of energy in the Quebec region. This scenario avoids the consumption of electricity from catenaries in the medium term. The other scenarios avoid between 1 and 3 GWh of electricity and lead to relatively similar energy consumption.

These two figures refine the previous message. In terms of energy consumption, only the maximum exogenous scenario leads to significantly different conclusions. The other scenarios lead to comparable results, where the differences in terms of electricity consumption are small (3 GWh maximum) compared to the total energy consumption of the sector. The energy avoided by the modal shift is displaced elsewhere, and the rebound effect of the modal shift on energy consumption would be an interesting effect to investigate further. As the results are similar in terms of energy consumption, the “energy consumption” indicator could be studied to test the robustness of the results.

Table 8
Total cost difference compared to the reference-GHG scenario (G$) in the exogenous and endogenous modal shifts scenarios considered.

Scenario	Exog_min	Exog_max	Endog_min	Endog_max
Cost difference (G$)	−7.8	−26.8	−1.1	−1.6

3.4. *Cost difference*

The fourth indicator is the system costs. Table 8 presents the total avoided costs compared to the Ref-GHG scenario. The endogenous scenarios have relatively similar costs to the Ref-GHG scenario; while the exogenous scenarios have much higher avoided costs. It is, therefore, less expensive to shift demand with external intervention (in the exogenous demand scenarios), as a government might do for example, than to let the model make the change incrementally, based on optimal system costs (in the endogenous scenarios, where the modal shift is modeled as substitution elasticities). This conclusion is the opposite of what one might think at first glance, that is that disruption or abrupt change would be costly to a system.

Fig. 10 shows the costs of trucks and trains in the freight sector, as well as the electric infrastructure costs in the region. These costs are compared to the Ref-GHG scenario. This table confirms the previous table in the freight sector. Compared to the Ref-GHG scenario, mainly heavy trucking costs are avoided, as well as electrical infrastructure costs, to a lesser extent. The additional train costs are not significant between the modal shift scenarios and the Ref-GHG scenario. Only the maximum exogenous scenario results in significant cost avoidance ($1,434 M in 2030 and $2,291 M in 2050), which also confirms the previous conclusions.

4. Conclusion

The rationale of this study is to challenge the need for endogenization in a context where the countries aim to achieve some radical

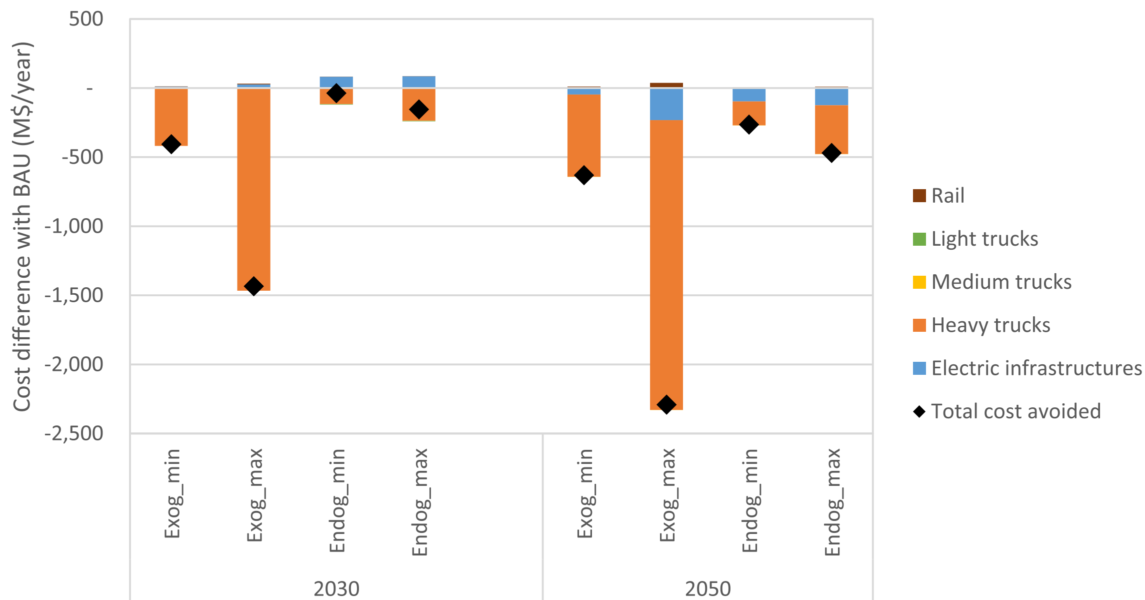

Fig. 10. Avoided costs in the freight transportation sector compared to the Ref-GHG scenario in 2030 and 2050 in the exogenous and endogenous modal shifts scenarios considered.

changes. The objective was to answer the following questions: Does integrating endogenous behavioral features allow E4 models to respond to the magnitude of the situation? The indicators studied led to several analyses. With the exogenous approach, the shift in demand between heavy trucks and trains is more disruptive. With the endogenous approach, the cross-effects between substitution elasticities and own-price elasticities are such that the resulting modal shift is linear. In terms of vehicle type, the exogenous approach avoids investments in complex infrastructures (i.e. catenaries), at least in the medium-term, whereas the endogenous approach leads to results where electric trucks and catenaries appear in 2030. The exogenous approach gives more time to implement complex technologies. This observation suggests that the exogenous approach may be technically more feasible in the context of decarbonization, where all the energy sectors will be pushed to their maximum. Only the scenario with a high modal shift from heavy trucks to trains (Exog_max) permits to avoid a significant energy consumption (17 PJ in 2030 and 10 PJ in 2050, compared to the “technology only” scenario, Ref-GHG), while the other scenarios lead to comparable energy consumption. The energy avoided by the modal shift in the other scenarios is displaced elsewhere, and the rebound effect of the modal shift on energy consumption can be captured by the model. The two approaches confirm that the costs of modal shift will be mainly concentrated in new transportation infrastructures and investment in new technologies. As mentioned previously, only the maximum exogenous scenario results in significant cost avoidance.

Based on the results of this study, several recommendations can be highlighted for modelers. The first recommendation is to consider different approaches in the modeler’s process to integrate behavioral features in their optimization models. Indeed, the two approaches used in this paper to model the same objective (reaching the GHG emissions targets of a region, with the help of modal shift) lead to different results on several indicators. The second approach is to use the endogenous approach when fewer data are available. The endogenous approach allows us to show that even when permitted, the model introduces behavior changes in a rather limited way, reaching a plateau. Modelers can use this approach to model the internal mechanics of the model, without adding an external intervention. An endogenous approach is also a compact approach that requires fewer hypotheses (only the definition of the elasticities of substitution, which remain exogenously determined). The concluding recommendation is to use the exogenous approach when there is a need for disruption, in a modeling context where endogenous variables no longer allow to go far enough in the solutions considered. The exogenous approach makes it possible to model disruptions: in demand, in energy consumption, and in the costs of the system. In a world where a paradigmatic change is necessary, the exogenous approach allows for a better representation of concepts that have been seldom modeled until now. The exogenous approach can also allow for more temporal flexibility on technology penetration. This approach can be used when one wants to give models more flexibility under strong constraints.

It should be noted that Quebec is only one case study to illustrate a global problem and a general methodological approach. The conclusions specific to Quebec can be useful to some regions with a northern climate. The conclusions specific to the methodology choices applied in this study can be useful to all modelers. There are of course other types of behavioral models (e.g., agent-based models) specifically developed to model behaviors. This study does not pretend to replace these types of models. It is also important to note that the endogenous representation of modal shifts is simplified and is only applied to one sector. Finally, the overall economic dynamics are not modeled in this study, even though scenarios such as the ones modeled would have implications for the transportation industries. Future research could investigate the further implementation of the modal shifts in the model (e.g., by including other sectors), and indicators other than GHGs could also be investigated to improve the robustness of the model.

CRediT authorship contribution statement

Marianne Pedinotti-Castelle: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Pierre-Olivier Pineau:** Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Kathleen Vaillancourt:** Data curation, Methodology, Resources, Software, Supervision, Validation. **Ben Amor:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

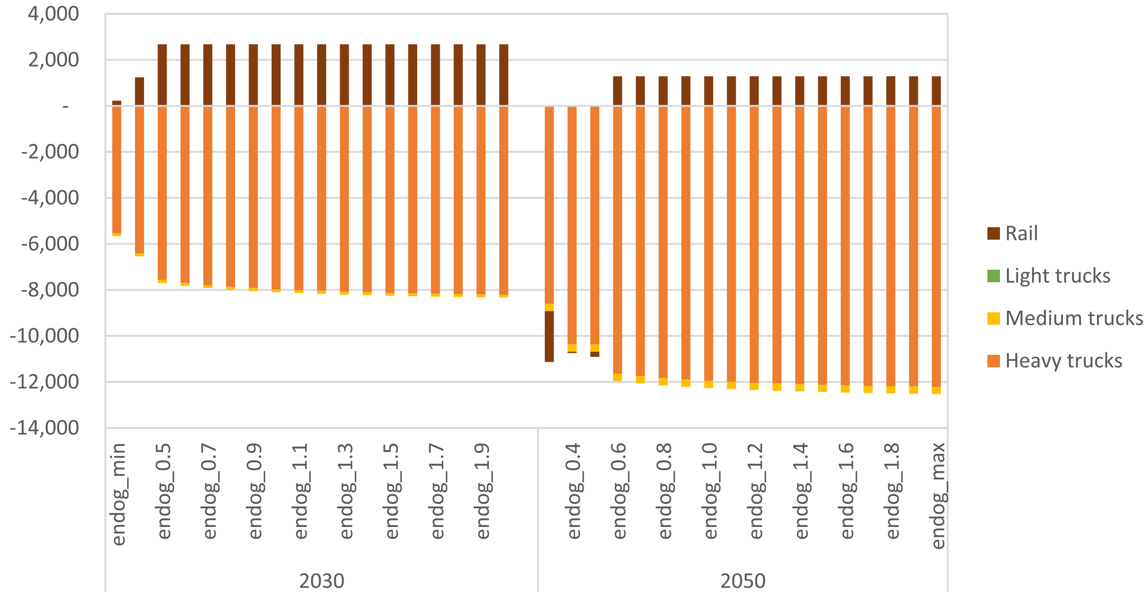

Fig. A1. Demand shift compared with the BAU scenario, in the endogenous scenarios considered, with different values of substitution elasticities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

As mentioned in Section 2.3.1, other elasticity values (steps of 0.1 from σ = 0.3 to σ = 2.0) have been tested and are presented in Fig. A.1. This Figure shows that even when permitted, the model introduces behavior shifts in a rather limited way, reaching a plateau.

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