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Decarbonization through modal shift using a synchromodal platform: A case study in the great lakes

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Abstract – This paper offers an empirical study to explore the relationship between transportation modalities and environmental concerns, promoting the adoption of synchromodality as a strategic pathway to achieving sustainable freight transport. The study uses a synchromodal freight transportation platform to analyze the impact of carbon tax policy on modal shift and environmental sustainability. The synchromodal platform is based on an optimization model using Mixed Integer Linear Programming (MILP), incorporating carbon tax as a surrogate measure for environmental costs. A sensitivity analysis is conducted across four distinct scenarios in a case study in the Great Lakes region, focusing on the Canada-US transborder trade. The results of this study illustrate the considerable potential for increasing the utilization of more environmentally sustainable transportation modes in this region. While the addition of carbon tax entails increased total transportation costs for each unit of cargo, the synchromodal-enabled modal shift promises to mitigate transportation's negative externalities, including congestion, environmental impacts, and noise pollution. The results also highlight the role of synchromodality as a catalyst for sustainable freight transport decisions in the context of a carbon-conscious world.

Keywords: Synchromodal transportation; freight transportation; decarbonization; strategic decision-making; carbon tax policy; great lakes; physical Internet; sustainability

1. Introduction

Transportation, as the backbone of the global economy, has confronted a dramatic demand increase due to several driving factors, such as population growth, rapid globalization and urbanization, and the rise of e-commerce. Inherently, transportation causes a wide array of adverse externalities, including emissions, accidents, noise pollution, traffic congestion, and soil contamination (Macharis et al., 2012). Accordingly, the transportation sector has experienced a concerning escalation in environmental and societal externalities.

In the path of sustainable solutions development in the transportation sector, a paradigm shift is underway, with modal shift as a key strategy in the quest for sustainable transport. Several studies have identified unimodal road transportation as the primary source of negative externalities. These studies argue that the transition from road to more environmentally friendly modes, such as rail and marine transport, has the potential to substantially reduce the impacts (Arnold et al., 2004; Janic, 2007; Janic & Vleugel, 2012; Merchan et al., 2019; Mostert et al., 2017; Rotaris et al., 2022). Accordingly, to support the constant demand growth and alleviate externalities, freight transportation has witnessed several paradigm shifts since the introduction of containers in the 1960s (Macharis & Bontekoning, 2004). Different strategies have been described to decarbonize the freight transportation sector: 1) reducing demand; 2) optimizing vehicle use and loading; 3) increasing the efficiency of freight vehicles; 4) reducing the carbon content of fuel; 5) shifting freight to low carbon-intensity modes (McKinnon, 2016). This paper is focused on the latter solution, where shifting freight from road to rail and water, with much lower carbon intensity, is proven to be effective decarbonization schemes in short- and mid-time. Accordingly, the EU's primary

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strategy to reduce the freight sector's emissions is shifting freight to lower carbon-intensity modes (EUR-Lex - 52017PC0648, 2017).

Despite the massive efforts from industry, governments, and academia, the modal split remained virtually constant in the past few decades (Acero et al., 2022; Tavasszy et al., 2020). Recently, there has been an emerging concept in freight transportation known as synchromodal transportation. This concept involves the flexible deployment of various modes of transportation and the ability to switch between them, resulting in more integrated and efficient transport (Tavasszy et al., 2017). In a broader context, as outlined in the 'Roadmap Towards the Physical Internet' (ALICE, 2020), Synchromodality represents the second generation of logistics networks within the framework of the Physical Internet. The Physical Internet has the potential to revolutionize freight transportation, paving the way for a more sustainable and resilient global logistics network (Guo et al., 2017). While synchromodality is a key strategy that can contribute to achieving the goals of the physical internet, the physical internet encompasses a broader set of principles and concepts beyond just the optimization of transportation modes (Lemmens et al., 2019).

Imposing a Carbon tax on freight transportation is a powerful tool for governments to internalize the externalities through which they can influence the movement flows and affect the modal share (Halakoo et al., 2023; Karbasi & O'Hern, 2022). Therefore, the research question that this research aims to answer is: "What is the impact of Carbon tax policy on modal split?"

In order to answer the research question, this research offers an empirical approach by using a synchromodal freight transportation optimization model considering Carbon tax as a measure to internalize environmental costs and studying the impact of different scenarios on modal shift in the network. The utilized framework for synchromodal freight transportation incorporates a centralized Mixed Integer Linear Programming (MILP) model to allocate the demand from cargo owners to service suppliers considering the synchromodal concept. Then, a sensitivity analysis is performed to provide policymakers with a concrete reference to prioritize their future decisions and assess the decisions' impact before applying them.

The contributions of this paper are listed below.

- This study is the first to evaluate the impact of Synchromodality, coupled with decarbonization policy on environmentally sustainable freight transport in the Great Lakes context.
- The empirical approach is used to perform policy-driven analysis to assess the impact of Carbon tax on modal shift by considering the environmental costs according to the synchromodal optimization platform; providing a support tool for policy decisions.

The remainder of this paper is structured as follows. Section 2 provides a background and literature review of previous efforts and identifies the research gaps. Section 3 presents the synchromodal framework for policy-driven analysis. Section 4 describes the synchromodal optimization platform used to assess the policy impact on modal shift. Section 5 delineates the computational experiment results and the sensitivity analysis. Section 6 provides results discussion and managerial implications for policymakers, the optimization model limitations, and potential future research directions.

2. Background and literature review

According to one of the most recent systematic literature reviews in the field, modal shift is the most considered strategy in the freight transport decarbonization literature (Ghisolfi et al., 2022). The modal shift depends on infrastructure and geography. Road and rail transport are mainly constrained by the network capacity while for sea transport, the main constraint is the port capacity and hinterland infrastructure (Björk et al., 2023). The transportation systems in the US and Canada are closely connected, and both are ideal for rail freight and inland water transportation (Filom et al., 2022; Kaack et al., 2018).

However, several challenges complicated the development of decision-making models for intermodal and multimodal freight transportation paradigms. Limited data availability, network scale, and integration and inclusion of all network actors are among the most important factors (Caris et al., 2013). The modal shift models are studied and developed from eclectic viewpoints. The first category of modal shift models is mainly focused on modeling freight transport from an economic perspective in which the core effort is made to model the external costs of transportation and then simulate the impact of the external cost internalization, known as generalized cost, on the modal choice and competition (Beuthe et al., 2002; Merchan et al., 2019; Mostert & Limbourg, 2016; Santos et al., 2015). The second category of the literature analyzes the modal shift transition from a network perspective, mainly driven by the investment in the infrastructure that leads to changes in the network structure and its capacity (Loder et al. 2022; Ortegon-Sanchez & Oviedo Hernandez, 2016; Salvucci et al., 2019). The third category is focused on studying the role of policy and government in the path toward sustainable transport through modal shift including economic incentives, taxation, and legal requirements. The main intent is to encourage the modal shift to more sustainable modes such as rail and marine and assess the policy impact on the defined objectives such as reducing emissions and modal split changes (Hammadou & Papaix, 2015; Ovaere & Proost, 2022; Yan et al., 2021; Zhu et al., 2023).

There are four clear gaps in the literature. First, a vast majority of quantitative studies used multimodal and intermodal transportation as the main paradigm of modal shift, and adequate research on the use of synchromodal paradigm in this context is lacking. Second, the studies are mainly focused on Europe and China, and case studies on North America are limited. Third, the majority of the quantitative literature used simulation, structured questionnaires, and statistical models, we are not aware of the use of optimization models for assessing the effect of carbon tax in synchromodal systems. Moreover, the fourth noticeable gap in the synchromodality literature is the lack of policy-driven analysis in the North American context. On the other hand, more than 70% of the synchromodal transportation models considered the economic objectives exclusively (Rentschler et al., 2022) while for the policy trade-off models, it is essential to expand the attention scope and consider environmental objectives in the model to produce reliable policy insights (Winebrake et al., 2008).

To shed light on the Synchromodality concept, collaboration strategies in freight transportation paradigms are depicted in Figure 1. Synchromodal transportation combines vertical integration from intermodal and horizontal transportation from a multimodal concept (Dong et al., 2018). Accordingly, the differences between intermodal, multimodal, and synchromodal freight transportation paradigms are more distinguishable. According to core concepts of synchromodality, one of the most important elements is harmonizing these actors to increase the efficiency of the overall network and also maintain the balance between policymakers and operators (Agbo & Zhang, 2017; Yee et al., 2021). To this end, well-established collaboration is an inevitable part of synchromodality success (Ambra et al., 2019). Two principal elements of freight transportation systems are infrastructure and vehicles. The concept of collaboration and vertical and horizontal integration has been heavily studied in the literature (i.e., (Aloui et al., 2021)).

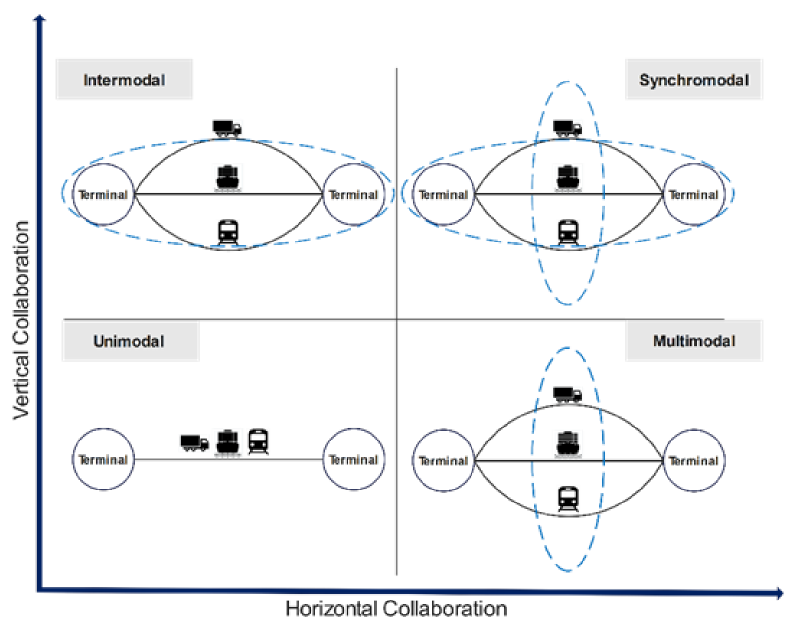


Figure 1. Collaboration in freight transportation paradigms (source: Behdani et al., 2014).

The concept of synchromodality is studied in various settings and problems. The majority of the synchromodality studies fall into "Shipment planning" rather than "Service planning" due to the operational level of the concept. In synchromodal transportation, modal choice and routing are not previously determined long in advance, while these decisions should be taken based on real-time information. In essence, synchromodality models mainly focus on the operational decision level due to the nature of the concept (Zhang et al., 2022). In line with this focus, scholarly research has extensively examined the challenges of shipment planning from various perspectives, principally organized according to the resultant decision type: shipment acceptance decision (based on the service configurations), shipment matching, and shipment routing optimization. Notably, a thorough and comprehensive review of the pertinent literature has been carried out by (Guo et al., 2021). Accordingly, the synchromodality model could provide a quantitative basis for further policy-driven analysis by analyzing the impact of policy on freight movements.

In view of the North American trade and transportation perspective, the current modal share is more heavily dependent on the unimodal road sector (Figure 2) in comparison to a more balanced modal share in Europe. Accordingly, there is more room for improvement and more environmentally friendly freight transportation networks by deploying less polluting transportation modes. There are distinct synchromodality features in North American synchromodality, such as a lack of a unified regulatory framework (border and customs), flag and crew issues for the marine sector, winter ice closure, and relatively lower integration of rail and truck sectors. Although synchromodality is not a one-size-fits-all solution for the aforementioned problems, it is considered a viable and promising solution paradigm at short and mid-term horizons. In this paper, we evaluate the effectiveness of a carbon tax policy, as a decarbonization scheme, on modal shift in Great Lake freight movements, by using an empirical approach through a synchromodal optimization platform. The model attempts to identify the environmental costs associated with freight transportation, to include the external costs, which is dominant in the literature. The model setting is modified based on North American transportation infrastructure and tested using real-world demand data. Accordingly, the model is tested based on the Canadian federal carbon taxation program to assess its impact on modal share.

3. A Synchromodality Approach for Sustainable Transport Policy Analysis in Great Lakes

The arrangement of these main groups of goods in the Great Lakes presents an advantageous opportunity for synchromodal transportation involving the deployment of roads, railways, and maritime shipping (short-sea shipping). The concept of synchromodality could incorporate other modes of transportation, such as air, pipeline, and drones (Archetti et al., 2021; Delbart et al., 2021). However, due to the distinctive characteristics of air cargo (i.e., high monetary value and perishable pharmaceuticals), this study's scope is limited to road, rail, and maritime transportation.

Roughly 65% of Canada's populace resides in the provinces of Ontario and Quebec, presenting a potential beneficiary group for synchromodal transportation facilitated by movements across the Great Lakes. On the other side, approximately 25% of the US population resides in Michigan, Wisconsin, Minnesota, New York, Pennsylvania, Illinois, Indiana, and Ohio. To harness insights from data, the STATSCAN trade database (Canadian International Merchandise Trade Database, 2016) has been used to investigate trade transportation patterns. For a more precise delineation of the prospects associated with synchromodal freight transportation, it becomes imperative to outline the present trade landscape. Figure 2 portrays the overarching pattern of trade value flows within the Great Lakes region. Based on Figure 2 it's evident that Ontario is the principal gateway for cross-border trade on the Canadian side, while Michigan plays a similar role on the US side. Additionally, road transportation stands as the overwhelmingly dominant mode, aggravating externalities such as congestion, air pollution, and accidents. The existing modal distribution underscores the imbalanced reliance on unimodal road transportation for transborder trade, concluding that the status quo is economically and environmentally suboptimal.

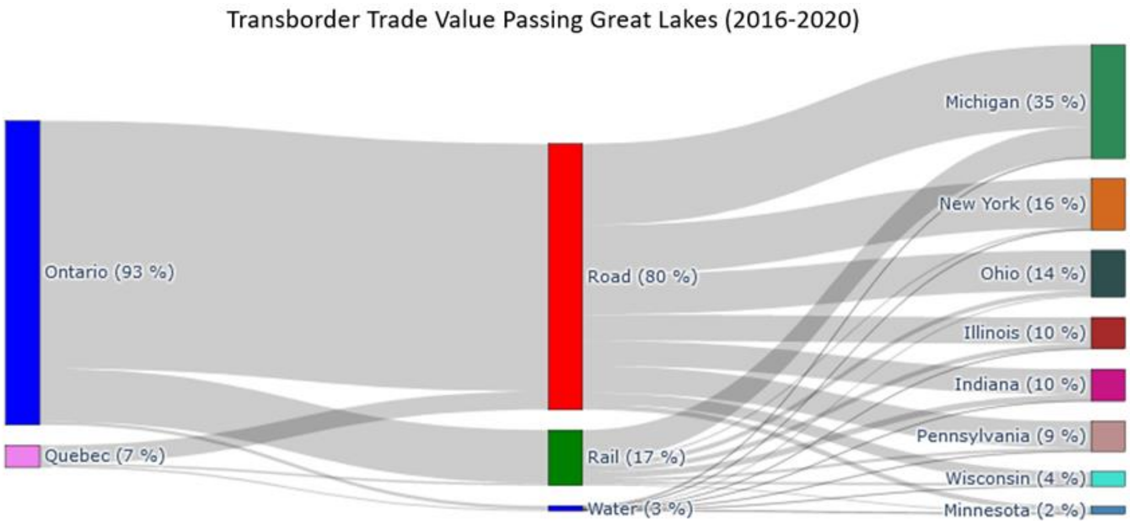


Figure 2. Transborder Trade flows' value from 2016 and 2020 (Total Value = 769 billion CAD) (Source: Filom & Razavi, 2023)

3.1 Problem definition

In order to assess the effect of Carbon tax on modal split and environmental sustainability, we consider a platform running by a global operator (5PL) that receives shipment requests from cargo owners (or their representatives) and transportation services from service providers. Moreover, the global operator receives (or contains) other necessary information such as spatial data, storage cost, cargo handling cost, and carbon tax. The model aims to solve the synchromodal shipment matching problem under synchromodal transportation constraints. Inspired by (Guo et al., 2021), the global freight operator has been considered to decide to match the shipment to the service. The platform ought to make the decision under synchromodality considerations. The platform's objective is to minimize transportation costs (economic and environmental) over an assumed planning horizon by considering container transit costs, cargo handling costs, and environmental emissions. An illustration of the global synchromodal freight operator is depicted in Figure 3.

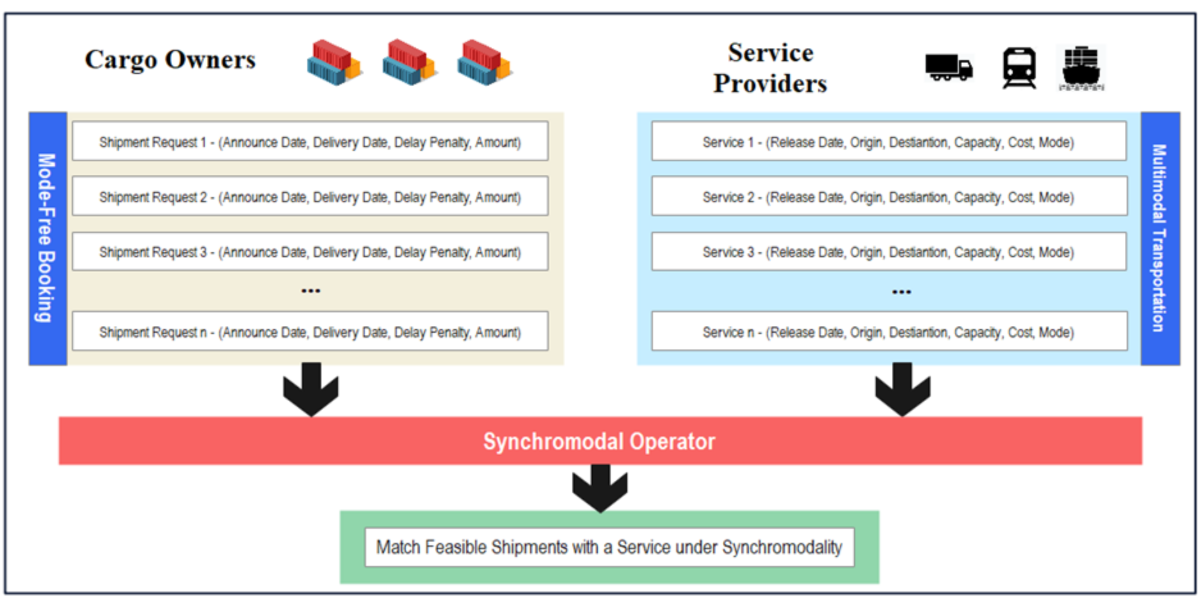


Figure 3. Global Synchromodal Operator (Source: Authors).

In the realm of transportation and logistics, the synchromodal optimization models frequently handle the underlying uncertainties in factors such as demand fluctuations and travel times (Delbart et al., 2021). However, this model applies at the strategic echelon of decision-making — where its capacity for policy impact assessment takes center stage. Specifically, the focus shifts toward evaluating the influence of carbon tax implementation within the model's objective function. In this context, the conventional inclusion of uncertainties gives way to a deterministic approach. By deliberately sidestepping the vagaries of uncertain variables, this modified model offers a clearer lens through which policy outcomes can be anticipated. This approach enables stakeholders to grasp the direct repercussions of policy decisions on carbon taxation, enhancing the precision and strategic value of the assessment. Through this adaptation, the synchromodal optimization model finds renewed purpose in facilitating insightful policy evaluations that navigate the intricate landscape of sustainability and logistics with heightened accuracy.

3.2 Scope

The geographical scope of the study is concentrated on intermodal terminals in the Great Lakes region. Three main transportation modes (road, rail, and water) are viable for this scope. There are also two other transportation modes, air, and pipeline, which are out of the scope of this study due to the synchromodality concept. Four nodes are established on the Canadian side and five nodes are located on the US side. The geographical scope is depicted in Figure 4. We assume that pre-planned service data is available to the system at their announcement time, containing each service's mode, origin, destination, price, and capacity. Changing pre-planned services, pricing schemas, and considering demand and service uncertainty lie beyond the scope of this study. In addition, the study is only focused on containerized cargo, which is an inherent part of synchromodality.

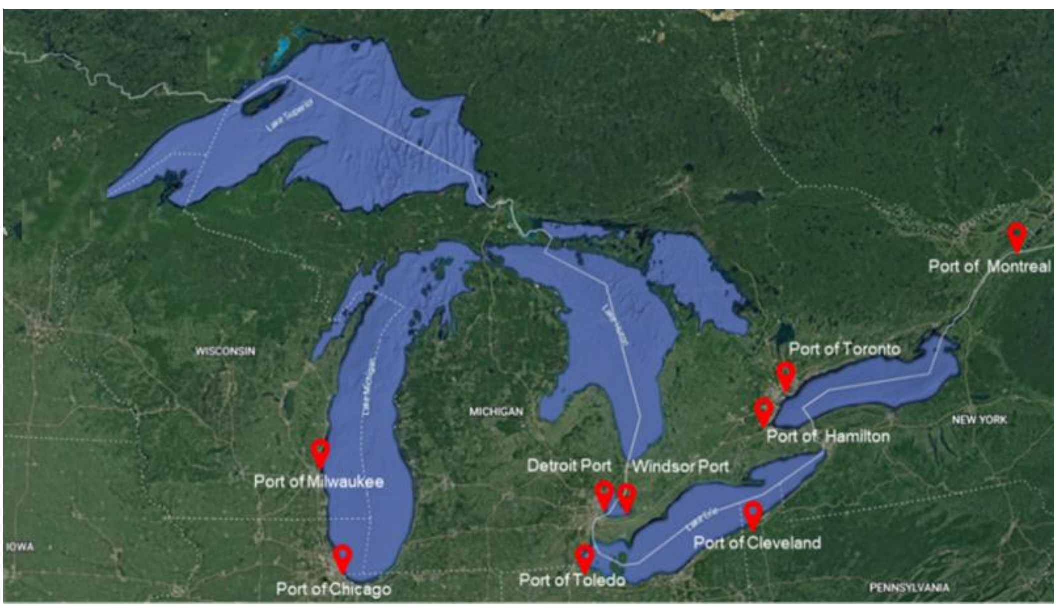


Figure 4. Geographical scope of the study.

Although there is no significant container operation in the regional ports selected for this study, we assumed that 20% of the port throughput is containerized cargo and then generated the demand dataset proportionately. Moreover, tendencies are gaining momentum to invest in the port container handling infrastructure by the governments and provincial decision-makers. To this end, the model aims to help the decision-makers and is focused on the strategic level.

4. Synchromodal Optimization Platform

The conducted literature review and the problem definition allow us to highlight the scope, identify best practices, and select the key variables related to costs, service schedule, lead time, flexibility, and sustainability. **Error! Reference source not found.**
Figure 5 illustrates the proposed methodological framework in this study. Since flow synchronization is the foundation of the study, a MILP model has been developed to optimize the freight flows, and sensitivity analysis is performed to assess the policy impacts. In this section, the MILP model is meticulously described. In what follows, the notation used for the formulation is described, then, the MILP formulation objective function and constraints are presented.

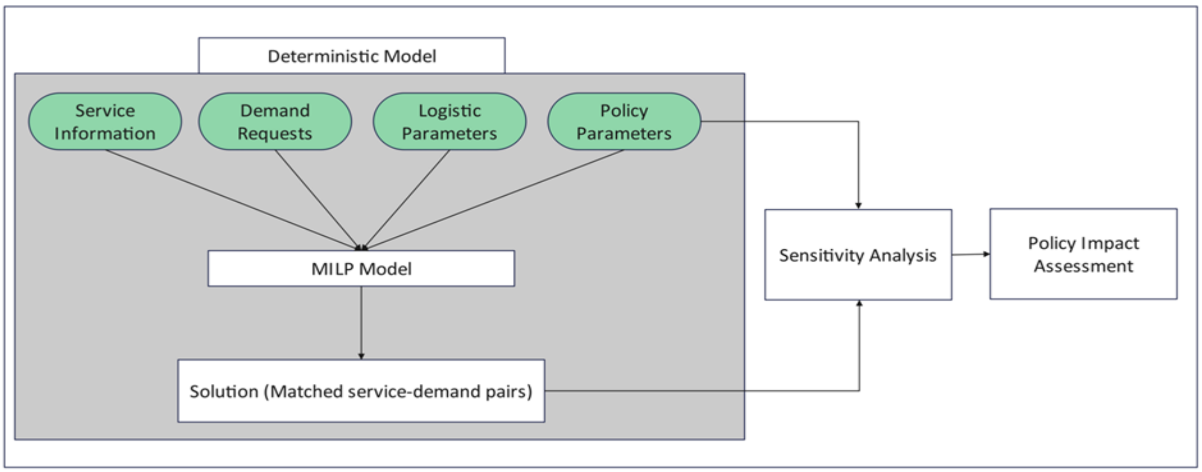


Figure 5. Proposed methodological framework.

4.1 Model's variables and parameters

A brief definition of variables and parameter and their associated notations used in this study are presented in Table 1.

Table 1. Notation.

Sets	Definition
N	Intermodal Terminals
M	Modes (ship, train, truck)
R	Shipment Request
S	Services ($S = S^{truck} \cup S^{rail} \cup S^{marine}$)
S^m	Services with mode m ϵ M
S_i^+	Services Departing from terminal i ϵ N
S_i^{+m}	Services Departing from terminal i ϵ N with m ϵ M
S_i^-	Services Arriving at terminal i ϵ N
S_i^{-m}	Services Arriving at terminal i ϵ N with m ϵ M
S^{+t}	Services Departing from Origin Terminals during time interval (t-1, t]
S^{-t}	Services Arriving at Destination Terminals during time interval (t-1, t]
Parameters	**Definition**
o_r	Origin terminal of request r ϵ R, o_r ϵ N
d_r	Destination terminal of request r ϵ R, d_r ϵ N
u_r	Container volume of interest r ϵ R
a_r	Announce time of request r ϵ R

e_r	Release time of request r ϵ R
l_r	Due time of request r ϵ R
L_r	Lead time of request r ϵ R, $L_r = l_r - e_r$
m_s	Mode of service $s \in S$, $m_s \in M$
o_s	Origin terminal of service $s \in S$, o_s ϵ N
d_s	Destination terminal of service $s \in S$, d_s ϵ N
U_s^t	Free capacity of service $s \in S$
c_s	Travel cost of service $s \in S$ per container
m_v	Mode of vehicle v ϵ V
D_s	Scheduled departure time of service $s \in S$
A_s	Scheduled arrival time of service $s \in S$
t_s	Estimated travel time of service $s \in S$
c_i^m	Loading/Unloading cost per container at terminal i ϵ N with mode m ϵ M
f_i^m	Loading/Unloading time at terminal at terminal i ϵ N with mode m ϵ M
c^E	Activity-based carbon tax charged by institutional authorities
B	A large number used for binary constraints

Variable	**Definition**
$\boldsymbol{x_{rs}}$	Binary variable which is 1 if service $s \in S$ is matched with request r ϵ R, 0 otherwise

4.2 MILP model

The MILP formulation is presented in this section. The objective is to minimize the freight transportation overall cost, as represented in Equation (1). It includes transit service cost, loading/unloading cost, storage cost, delay cost, and environmental cost. A more detailed explanation of the objective function terms is presented in Table 2.

$$\min_{x^t}\Big(\sum_{r \in R^t}\sum_{s \in S} c_s x_{rs} u_r + \sum_{r \in R^t}\sum_{i \in N} c_i^T x_{rs} u_r + \sum_{r \in R^t}\sum_{s \in S} c^E x_{rs} u_r\Big) \tag{1}$$

Table 2. Overall transportation cost elements.

$\sum_{r \in R^t}\sum_{s \in S} \boldsymbol{c_s x_{rs} u_r}$	Transit Service Cost
$\sum_{r \in R^t}\sum_{i \in N} \boldsymbol{c_i^T x_{rs} u_r}$	Loading/Unloading Cost
$\sum_{r \in R^t}\sum_{s \in S} \boldsymbol{c^E x_{rs} u_r}$	Environmental Cost

The model's constraints equations and definitions are reported in Table 3.

Table 3. MILP model constraints.

#	Equation	Definition
2	$\sum_{s \in S_{o_r}^+} x_{rs} \leq 1, \forall\, r \in R$	Match at most one service with the same origin for each request
3	$\sum_{s \in S_{d_r}^-} x_{rs} \leq 1, \forall\, r \in R$	Match at most one service with the same destination for each request

4	$\sum_{s \in S_{d_r}^+} x_{rs} \leq 0, \forall\, r \in R$	Eliminate subtours of shipments itineraries in the destination
5	$\sum_{s \in S_{o_r}^-} x_{rs} \leq 0, \forall\, r \in R$	Eliminate subtours of shipments itineraries in the origin
6	$\sum_{s \in S_i^+} x_{rs} \leq 1, \forall\, r \in R, i \in N$	Eliminate subtours of shipments itineraries arriving to the origin, each itinerary must have one origin and one destination
7	$\sum_{s \in S_i^-} x_{rs} \leq 1, \forall\, r \in R\,, i \in N$	Eliminate subtours of shipments itineraries leaving the destination, each itinerary must have one origin and one destination
8	$\sum_{s \in S_i^-} x_{rs} = \sum_{s \in S_i^+} x_{rs}\,, \forall\, r \in R\ \ , i \in N$	Flow conservation at transshipment terminals
9	$\sum_{r \in R^t} x_{rs} \leq U_s^t\,, \quad \forall\, s \in S$	Total container volume of requests matched with service s do not exceed the service free capacity
10	$e_r + t_{o_r}^s \leq D_s + B(1 - x_{rs}),$ $\forall\, r \in R\,, s \in S$	The departure time of service s minus loading time must be earlier than the release time of request r. B is a large number to ensure time compatibility

For subtour elimination, constraints 4 to 8, the problem is formulated so that when a service that arrive at the request origin and depart from the request destination, the constraints guarantee that there is no duplicate terminal on the route by enforcing tight upper bounds. A simple example of an acceptable subtour and a violated subtour is depicted in Figure 6. The idea behind the subtour formulation is that a service route is from one node to another node, without any intermediary point. The pseudocode for the framework is presented in Algorithm 1. The main idea is to filter the feasible shipments to decrease the search space for the optimization model to yield more timely solutions and provide the ability of working at operational decision level.

Algorithm 1. Shipment service matching framework.

Input:	Intermodal Terminals, Services, Capacity, length of planning horizon
Output:	Matching decision, planned itinerary, emissions, cost
Initialize:	Let $R \leftarrow \emptyset, U_s \leftarrow 0, A_s \leftarrow 0, D_s \leftarrow 0$
1:	**for** decision epoch $t \in \{0,1,2, \dots, T\}$
2:	Fetch requests R for time t, departure time of services for time t for all modes,
3:	**for** request $r \in R$ at t **do**:
4:	**for** intermodal terminal n $\in N$ **do**:
5:	**if** time constraints are not satisfied: go to r += 1, **else**:
6:	Update feasible request shipment matching for time t
7:	Get optimization model
8:	Determine matching decision x_{rs} for time t
9:	Update free capacity
10:	Update itinerary
11:	Calculate total emissions
12:	Calculate total cost over horizon T

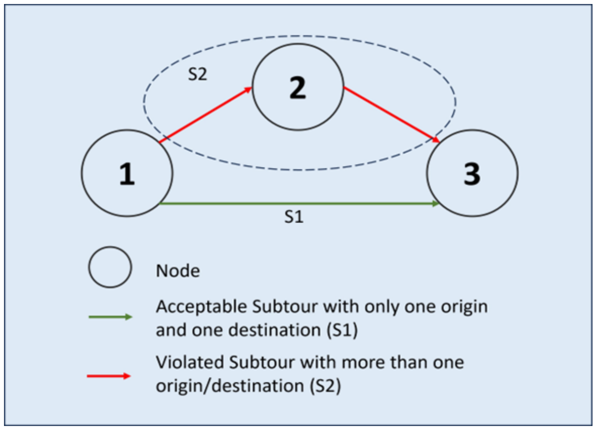


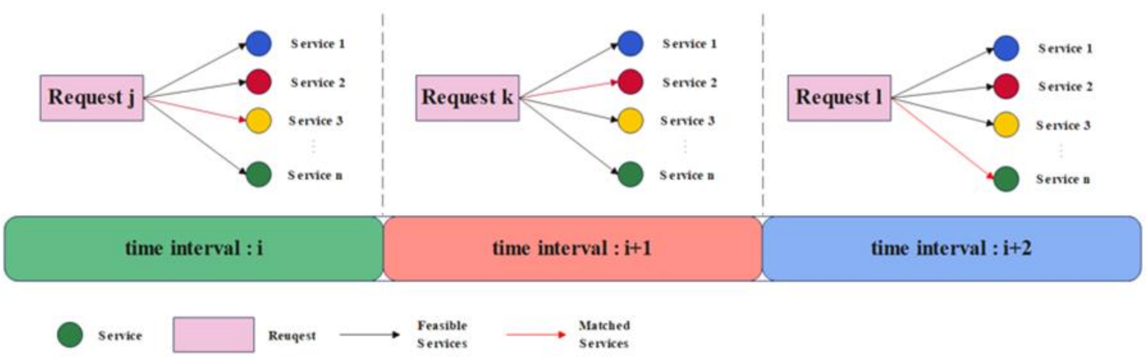
Figure 6. Subtour elimination constraints example.

5. Computational Experiments

In this section, we present the results of the MILP computational experiments. All experiments were conducted on a computer equipped with an 11th Gen Intel(R) Core (TM) i7-11850H @ 2.50GHz and 32GB of RAM. The commercial GUROBI solver is used to model and solve the MILP model. The model contains 81200 integer variables, and it has been solved in 1930 iterations. The zero-optimality gap criterion has been satisfied in all experiments.

5.1 Experimental setup

The mechanism of the shipment matching, and data overview is illustrated in Figure 7. Accordingly, the request j is announced at time interval i, and the MILP model detected "n" feasible services to match to that request. Then, based on the overall cost minimization schema, the MILP model decided to match this request to "Service 3" which yields minimized objective function. In each time interval (one hour) the model processes the announced requests and potential services periodically. In addition, two sample request data and three service data is illustrated.



Request	Origin	Destination	Volume(TEU)	Announce Time
R1	Windsor	Toronto	10	5
R2	Chicago	Montreal	35	20

Service	Mode	Origin	Destination	Capacity (TEU)	Departure Time	Arrival Time	Travel Cost (CAD/TEU)
S1	Road	Windsor	Cleveland	1	8	18	700
S2	Rail	Hamilton	Chicago	50	22	96	250
S3	Marine	Toledo	Toronto	150	15	132	80

Figure 7. Illustration of matching mechanism and data overview.

The model is tested on a small sample for numerical experiments. For the demand side, the data extracted from the STATSCAN transborder trade database (containing more than 30 million records at commodity level) for the Great Lake movements. The demand requests dataset contains 700 sample requests containing 8200 TEU for a month, according to the port throughput values between 2016 and 2020, proportionately. Accordingly, it is safe to say that the data is representative for the actual flows in the region. Based on "Transport Canada Annual Report 2022", around 17% percent of total port throughputs are containerized cargo (Transportation in Canada 2022). While this ratio may not be precisely 17% for the region of study, we assumed that 20% of the port throughput is containerized cargo and then generated the demand dataset proportionately. The 20% assumption is based on the above-noted Transport Canada report, considering the Canadian government's investment in regional ports' container infrastructure. The service dataset is based on synthetic data for the Great Lakes, and we assumed that the truck services are always available for the global operator. The service dataset contains 40 trains, 50 ships, and unlimited truck capacity.

5.2 Parameter settings

The following values are set for the model coefficients based on the studies by (W. Guo, Atasoy, and Negenborn 2022; Y. Zhang et al., 2022) : Train loading cost = 20 CAD/TEU, Truck Loading Cost = 25 CAD/TEU, Ship Loading Cost = 20 CAD/TEU, Train Loading Time = 30 Minutes/TEU, Truck Loading Time = 2 Hours/TEU, Ship Loading Time = 20 Minutes/TEU. It should be noted that the emission amounts are known to the system based on the service information. For Carbon Tax, the base scenario is equal to 0.05 CAD/Kg according "Canada Federal carbon pollution pricing benchmark" ("The Federal Carbon Pollution Pricing Benchmark - Canada.Ca"). The rate is planned to increase by 0.015 per year per Kg. Accordingly, two futuristic scenarios for Carbon Tax have been analyzed, first one is 0.10 CAD/kg which is for 2026 and the second one is 0.15 CAD/kg for 2030. A very aggressive scenario has been added as the final one in which the Carbon tax is set to 0.20 CAD/kg to analyze the extreme cases of the policy impact. Moreover, to study the impact of tax, "No Carbon Tax" scenario is added to the results to shed light on the policy impact.

5.3 Modeling results and sensitivity analysis

According to scenarios description in the previous section, the model outputs are reported in Table 4. The total transportation cost for one month for the region, total amount of emission in Kg, emission and cost per TEU (for 8200 TEU), and share of environmental cost are listed below.

Table 4. Impact of Carbon Tax Policy on MILP model outputs.

	Scenario 1	**Base Scenario**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Carbon Tax (CAD/Kg)	No Carbon Tax	0.05 CAD/kg	0.10 CAD/kg	0.15 CAD/kg	0.20 CAD/kg
Total Transportation Cost (CAD)	627,602	760,051	907,755	1,069,275	1,193,180
Emission (Kg)	1,984,370	1,630,895	1,572,882	1,457,427	1,348,920
Emission per TEU (Kg)	242	199	192	178	165
Environmental Cost (CAD)	-	81,545	157,288	218,614	269,784
Total Transportation Cost per TEU (CAD)	77	115	121	130	146
Environmental Cost per TEU (CAD)	-	110	19	27	33
Share of Environmental Cost	-	11%	17%	20%	23%

Since the application of the model is mainly focused on the policy impact, it is more reliable to reduce the impact of sample size and monitor relative indicators, such as total transportation cost per TEU, emission per TEU, and environmental cost per TEU. According to Figure 8 it can be deduced that by increasing the Carbon tax, the emission per TEU begins to decrease while the cost per TEU depicts the opposite behaviour. In addition, the share of environmental cost begins to increase, and it is more than doubled between base scenario and scenario 4. By considering the total transportation cost from the "No Tax" scenario to Scenario 4, we can see an almost 100% increase in cost due to policy imposition, in exchange for a 30% emission reduction, which is known as "Internalizing" the externalities in the transportation economics context.

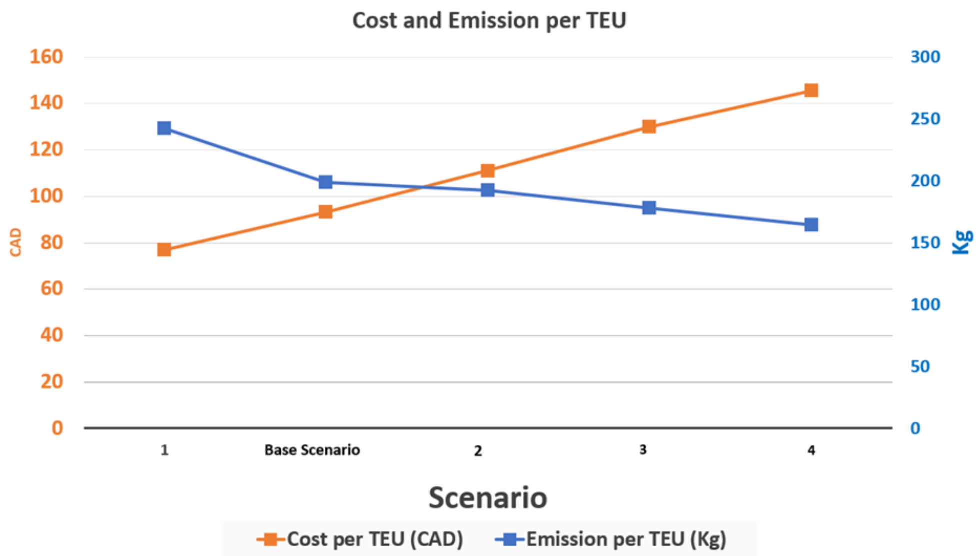


Figure 8. Comparison of cost and emission per TEU.

In order to assess the strategic-level impact of the Carbon tax on freight movements, modal shares are analyzed across the described scenarios and results are shown in Figure 9. In scenario 1, in which no tax has been imposed, the road sector share is 51% while the highest emission per TEU is yielded for this setting. In the base scenario, the carbon tax equals 0.05 CAD/kg and it is obvious that by applying the policy, the road sector share has been decreased drastically by more than 10 percent while share of marine and rail sectors are increased by 8 and 3 percent, respectively. In the next scenario, we assumed the carbon tax is increased to 0.10 CAD/kg. Accordingly, the share of marine transportation has increased by 2 percent, the rail share increased by 1 percent, and the truck share has decreased by 3 percent. It should be noted that in this scenario road and marine share became equal. Then, the Carbon Tax again increased to 0.15 CAD/kg which leads to a two percent increase in both rail and marine volume, while the road share declined by 4 percent. Finally, in the most aggressive scenario for Carbon Tax, it has been raised to 0.20 CAD/Kg showing that the marine percentage has increased by 2 percent while the rail share has increased by 1 percent. The road share is decreased to 30%. By considering the above results, it is safe to conclude that by increasing the Carbon tax, the road sector starts losing its share to marine and rail competitors while in that competition, the marine sector acquires more rapidly due to its lower environmental costs.

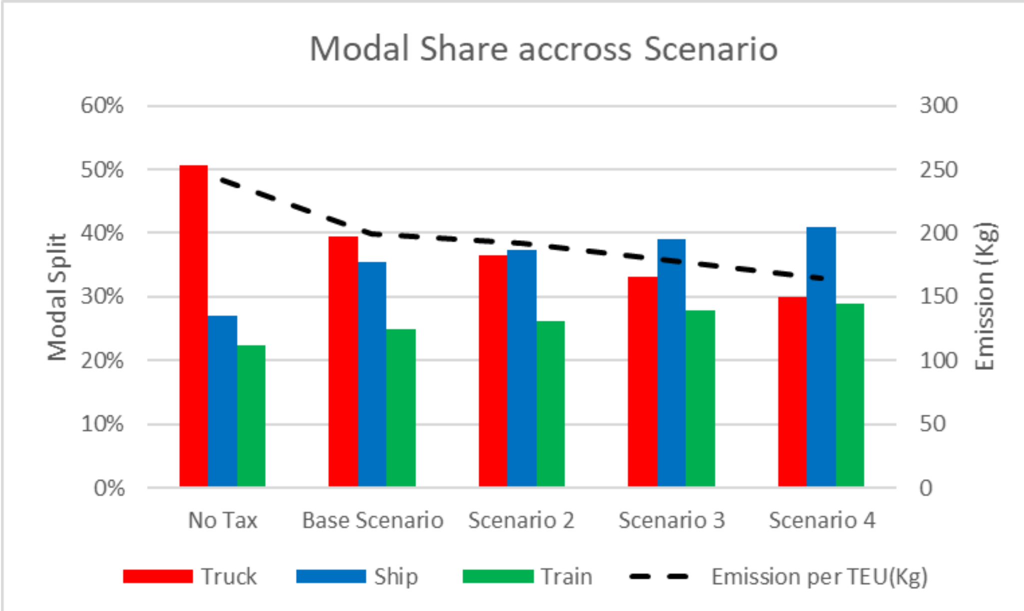


Figure 9. Carbon Tax sensitivity analysis impact on modal shares.

5.4 Discussion

In the modelling and scenario analysis, we considered a set of sample requests based on the available data and used synthetic data for the services. The model output could have been more precise by adding online real-world to the model. Moreover, the assumption of having unlimited truck capacity on the service side may alter the final results to even stronger modal shift. Therefore, data availability is the main limitation of this study. However, adding more data might bring another limitation to the model, which is computational tractability. Optimization problems are usually categorized as N-P hard problems meaning that by increasing the input size, the solution time will increase exponentially. Therefore, the size of the problem instances might affect the tractability of the model. Solving the model for large instances of data demands specific heuristic algorithms and more advanced numerical methods. Nevertheless, the aim of this research is to depict the policy impact on the movements in a case study and the results successfully demonstrated the more balanced modal share and decreased amount of emission.

Considering the intricate relationship between transportation modes and their environmental implications, synchromodality entails a heightened awareness of the environmental consequences. This increased awareness, coupled with implementing mechanisms such as a carbon tax, empowers stakeholders to make conscientious decisions that prioritize environmentally sound choices within the synchromodal framework. This is also supported by the model outputs showing that the synchromodal paradigm on one hand, and imposing rational Carbon tax, is an effective decarbonisation scheme for both governments and practitioners.

6. Conclusions

In this study, we explored an application of a deterministic synchromodal optimization model to investigate the role of Carbon tax policy on freight movements. A global operator platform has been considered through which a set of shipment requests are matched with a set of services under the synchromodal concept. To solve the problem, we developed a MILP model and performed a sensitivity analysis for the carbon tax parameter. Some key managerial and strategic insights drawn from this study are presented below, followed by discussions on the limitations of the current study and the future research areas. In what follows, key managerial insights elicited from the aforementioned experimental results are listed:

- According to the results, imposing more aggressive taxation schemes on transportation, the internalization of the externalities is becoming more vivid. The amount of emission per TEU has decreased by more than

30 percent while the cost per TEU is almost doubled. The trade-off forces the transportation customers and providers to pay more for the sake of society's welfare and environmental sustainability.

- Thanks to the synchromodal concept, the results show that it is possible to expand the modal share of marine and rail operations to reduce the negative externalities of the road sector. Accordingly, the idea of the global operator (5PL) depicted that it could bring more flexibility to assign the shipments to different routes that could be useful in case of extreme events such as service disruptions, labour strikes, canal blockage, and extreme weather.
- The carbon tax policy sensitivity analysis has proven that it is a powerful tool for governments to influence the modal share. The share of the road sector decreased by almost 10% in the analysis, which could bring numerous benefits, such as reduced congestion and alleviated environmental impacts. However, the results show that the cost for a single TEU increased from 115 to 146, which is more than 20 percent. It is the role of decision-makers to carefully consider the impact of the added cost on supply chains and the end customers, and other strategies such as subsidization. This is a different realm of research that could benefit from the developed application.
- The idea of transportation service consolidation, which is the global operator idea in this paper, could be viewed as Logistic as a Service (LaaS). The LaaS concept can offer cargo owners and transportation customers to manage their requests through a centralized, customizable, and environmentally friendly platform that offers diverse sorts of services. Through this centralized platform, it is much easier to handle the contractual information and expedite the payments. Therefore, due to the scalability of LaaS solutions, the freight movement cost is decreased by 5-10% (Wang, 2017; Zhang et al., 2015). However, it should be noted that governments are required to take well-informed strategies to maintain the market dynamic, prevent monopolistic competitors, and leverage the social sustainability of the transportation industry.

This research study can be advanced in different areas. First, the idea of using Carbon Tax as a proxy for environmental costs is attractive but not overarching since there are other negative externalities associated with transportation, such as noise, other types of pollution, time, and so on. To this end, it is fruitful to monetize the rest of the externalities and consider them as cost elements in the objective function. Second, to harness the ultimate potential of synchromodality, it is essential to consider the operational decision-level application. Since the model is built to test at strategic decision level, it is an inherently deterministic model that might confront difficulties in real-world implementations in light of real-world uncertain factors such as demand volume and travel time. When it comes to operational decision level, uncertainty directly affects the model behaviour and outputs. The transportation industry inherently entails uncertainties in demand, travel time, service properties, etc. Therefore, incorporating this impactful factor in the operational optimization models must be considered. Although it is a challenging extension to the above model, it will bring more applicability and precision to the model. Third, since the model directly interacts with streams of data from the dynamic and data-rich world, the integration of AI models with diverse streams of real-world data might open up transformative possibilities. The model's ability to interact with various data streams, each representing a unique facet of our environment, empowers it to leverage its performance. Fourth, more explicit mathematical modelling can be developed to consider more complex real-world strategies such as elaboration of a model that is able to incorporate the vehicles using alternative fuels (e.g., Hydrogen-powered ships, electric trucks) and analyze the model behavior facing disruptions or driver shortages.

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