The effect of truck loading factor on a major trucking route in Québec and on GHG emissions

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Paper prepared for presentation at the 'Climate Change Mitigation' of the 2023 TAC Conference & Exhibition, Ottawa, ON

Abstract

In this paper, we hypothesized that it is possible to reduce trucking greenhouse gas emissions in a relatively short time horizon by improving efficiency. As a matter of fact, improving truck efficiency by increasing their loading factor, in other words, maximizing the time when trucks are fully loaded and minimizing when they run without a cargo is a low hanging fruit that could be enforced by local incentives or regulations for long-haul cargo. This study analyzes the effect of truck loading factor on a major trucking route in Québec (highway 20) and it estimates potential GHG emission economy with a linear regression for different average load-factor scenarios. The regression analysis shows that removing 20% of the empty trucks travelling in the province of Quebec could lead to an annual reduction of 1.2 million tons of CO2 and social savings of nearly 300 million $. Results are based on a Monte Carlo analysis made with a tool called the MapEUR which uses different databases on trucks registrations, operation, road characteristics and weather conditions to estimate the fuel consumption of all the trucks travelling of a specific road segment and a given period. The scenario comparison provides better understanding of the potential benefits of increasing load factors and guide the amount of efforts that should be given from fleet operators and policy makers toward such solutions.

Introduction

In Canada, heavy trucks are the primary mode of goods transportation, responsible for moving 77.7% of the country's goods volume domestically, and 54.2% of exports and 71.5% of imports in trade with the United States (Fan. D & Heminthavong. K, 2022). This industry that has been growing since the early 2000s and is now worth 27.7 billion USD in Canada (IBISWorld, 2022). Unfortunately, the transportation sector, as a whole, accounts for one third of the Canadian total GHG (greenhouse gas) emissions (Fan. D & Heminthavong. K, 2022). These figures reflect the magnitude of trucking activities impact on GHG emissions and how, without interventions, it is expected to increase even further.

Electrification seems to be a feasible solution for decarbonizing the long-haul trucking industry and battery electric trucks will achieve a 26-34% cost advantage in 2030 over internal combustion engines (PricewaterhouseCoopers, 2022). Unfortunately, several factors make this transition slow and challenging, such as the high energy requirements of many trucks, which results in the need for heavy batteries that reduce freight capacity or shorter distances travelled between charges (Transport Écono Nord, 2021). Moreover, the development of recharging infrastructure is another challenge (Transport Écono Nord, 2021). The vastness of the Canadian road network, which totalizes 1.13 million km (McBride. J, 2021), and harsh climatic conditions that can deplete batteries faster add further complexity to the decarbonization process of this industry (Transport Econo Nord, 2021).

One solution in the short- and medium-term to reduce GHG emissions from trucking is to improve its efficiency. In Canada, long-distance trucks typically operate at only 60% to 80% of their load capacity (MaRS Discovery District, 2021b). Maximizing truckload capacity by minimizing empty returns is one approach to increase efficiency and reduce the number of trips required to transport the same amount of goods in a given area. It should be noted that in 2018, 40% trucks in Quebec were empty or almost empty (Ministry of Transport, 2018). Worldwide, on average, 43% of trucks present on the roads are empty (Worldbank, 2019). These statistics indicate room for improvement.

While reducing empty returns has the potential to increase efficiency, for some operation is it necessary such as for bulk or dangerous goods transportation. When it is physically/legally possible though, it still present significant logistical challenges. Reducing empty returns may require pooling transport activities among several companies, which could require a significant restructuring of activities and add various constraints. It is therefore essential to evaluate the potential environmental and economic benefits before embarking on such a large-scale effort.

This paper objective is to estimate the fuel and GHG savings as a function of the reduction in empty trips on a typical Canadian highway. To accomplish this, a linear regression model was developed using a database of simulated standard heavy vehicle traffic travelling between Montreal and Quebec City on Highway 20. This model is then used to estimate the potential fuel savings of reducing the number of empty trucks for equivalent highway links.

I-Literature review

The benefits of increasing truck load utilization, called the load factor, is well known in the literature. Teo *et al.* (2014) mentioned in their research that increasing the load factor of a truck will help reduce negative environmental effects, such as GHG emissions. This is due to the reduction in the number of trucks needed to transport the same number of goods (EEA, 2001; Taniguchi, Thompson, Yamada & Van Duin, 2001).

Mckinnon criticized the non-utilization of truck capacity by describing the transportation industry as environmentally and financially irresponsible. Indeed, every unnecessary kilometer driven has a cost reducing competitiveness and profitability (Mckinnon, 2018). Thus, 90% of vehicle movements could be reduced without any loss of utility by improving truck utilization on each trip while reducing costs (Mckinnon & Edwards, 2010). There are seven factors that explain this inefficiency according to Mckinnon: (1) logistical trade-offs, (2) lack of information, (3) scheduling, (4) dimensional incompatibility, (5) trade silos and lack of collaboration, (6) traffic imbalances, and (7) regulations (Mckinnon, 2018). So, collaboration is necessary between regulators and legislators with logistics professionals to improve efficiency.

An illustration of this collaboration is the use of load factor schemes in Amsterdam and Copenhagen (Taniguchi, Thompson, Yamada & Van Duin, 2001). For example, in Amsterdam, trucks weighing more than 7.5 tons can access some streets only if they have a load factor of more than 80% and meet Euro II emission standards (Castro and Kuse, 2005). In Copenhagen, trucks over 2.5 tons require a certificate to stop in the Medieval City. The City Goods Ordinance issues the certificate if the trucks have a load factor of more than 60% over a period of three one-month periods and an engine that is less than eight years old. The ordinance was found to be effective in maximizing truck capacity utilization with an average load factor of approximately 70% (Teo *et al*., 2014). The increase in truck load allowed for a reduction in the number of vehicles needed to make deliveries and consequently reducing the cost on the environment and the GHG emissions. All of this was achieved through the use of incentives to get the logistics sector to cooperate.

Load factor maximization measures were initially discussed in an urban context, primarily to reduce the number of trucks in cities, which improves accessibility and mobility in urban areas, and reduce traffic and pollution (*Teo et al.*, 2014; Boudouin and Morel, 2002). Thus, optimizing the overall load capacity by reducing the number of empty and moderately empty vehicles would reduce truck trips and the impact of the issues mentioned. In this same perspective, Delaitre (2009) presented an optimization model that proposes a solution combining statistics and dynamics to optimize routes and loads. Other studies such as Castro & Kuse (2005); Allen & Browne (2010), and Huschebeck (2001) have shown that truck flow management policies such as time restrictions, or access restriction, in cities such as Prague, Budapest, Maribor, Paris, and Stockholm, have successfully maximized truck load factors.

Up to this point, measures to increase the load factor have primarily been applied to urban transport. Nevertheless, the impact of load factor on long-distance transport is equally or even more significant, as maximizing it would reduce transport costs and lead to a considerable reduction in freight traffic volume and GHG emissions. Therefore, this approach could be seen as a short-term alternative to electrification which is more difficult. Since distances between destinations are longer and loads are high, the energy needs require large batteries, reducing truck capacity (*Smith et al.*, 2020; *Cunanan et al.*, 2021). The study by Omar, Hoda, and Merida further demonstrates that it would be necessary to be able to generate enough electrical energy to meet the additional generation requirement related to battery consumption (*Talebian et al*., 2018).

These constraints to decarbonizing long-haul truck freight transport thereby highlight the importance of finding solutions that do not rely solely on the energy transition, such as increasing vehicle and operational efficiency. But before implementing incentives for such interventions, it is important to quantify their potential benefits and put the appropriate level of effort into them.

II- Methodology

The approach used in this study employs a linear regression method that is based on data representing the fuel consumption of trucks travelling on a typical highway segment in Quebec (highway 20 between Montreal and Quebec City). The regression was used to simulate the effect of reducing empty trips on the total consumption of all trucks. Once the regression model was validated, the next step was to quantify the impact of reducing the number of empty vehicles. A random withdraw method was performed for each trial. To accomplish this. The regression model was then applied to the fuel consumption MapEUR data to calculate the new fuel consumption. This method enabled the establishment of a relationship between truck loads and the energy consumption required for a certain amount of work. Furthermore, it enables the analysis of the impact of reducing empty vehicles on GHG emissions for trucks travelling on Highway 20 and other similar roads.

To analyze the impact of the independent variable "load factor" on the dependent variable "consumption," we developed two hypotheses:

1. The linear regression model result will adequately answer the research question.
2. Reducing the number of vehicles traveling empty would lead to a reduction in GHG emissions.

The data utilized for the regression was generated using MapEUR, a tool that estimates the energy consumption of each vehicle on a given segment by incorporating numerous parameters in a Monte Carlo simulation (Samson *et al.*, 2021). This simulation integrates different databases from MTQ (Ministère des Transports du Québec), SAAQ (Société d'Assurance Automobile du Québec), and Canadian Weather Energy and Engineering to simulate the typical fuel consumption of trucks between Montreal and Quebec City. The simulation factors in various weather conditions, driving conditions and behavior, truck types, and typical loads in Quebec.

The simulation of load factor variations between different trucks (i.e. variable of interest) is based on the distribution of truck types registered in Quebec (SAAQ, 2022), and the most recent origin-destination survey conducted in the region (Trucking in Quebec: Statistical and Economic Portrait, 2018).

MapEUR estimated the fuel consumption of 40,312 typical trucks in a year by combining thirteen random variables. This is an estimation of a physical model that represents the driving force needed for heavy truck travelling at a given speed on each 100 m segment of a predetermined road (highway 20 between Montreal and Quebec City). To estimate fuel consumption, the driving force values are integrated over the segments, considering engine efficiency and fuel calorific value (Samson *et al.*, 2021). The total truck traffic consumption can be calculated for a given road segment by multiplying the average consumption of the segment by the average annual daily traffic (AADT) for trucks in the segment (Figure 1).

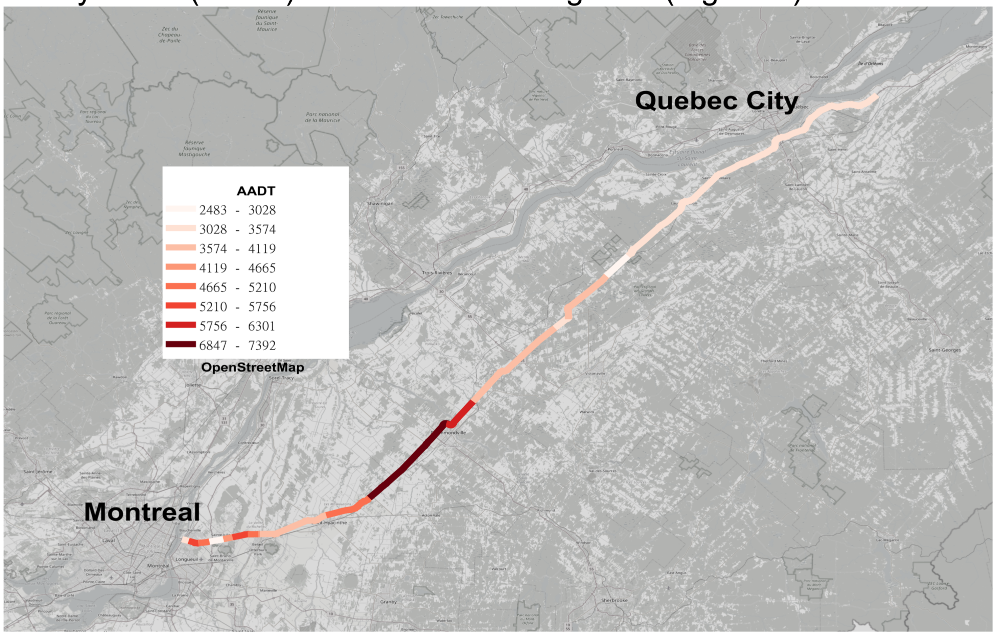

Figure 1 Average annual daily traffic (AADT) of heavy vehicles along the journey from Montreal to Quebec City; data provided by the ministère des Transports du Québec.

2.1- Data processing and analysis

The results of the Monte-Carlo Simulation from MapEUR, which considered fuel consumption as a dependent variable based on 37 different factors (such as driver behavior, load capacity, weather conditions, etc.), were imported into the Rstudio platform. Various processing and modeling operations were then conducted.

Initially, the dataset was reduced to examine only the load and consumption variables. Since regression models tend to perform poorly in the presence of asymmetry and non-normality, the "Skewness" function was used to assess that the target variable is symmetric. To avoid the influence of extreme values, data standardization was carried out, and values that were more than three standard deviations were eliminated as these were considered outliers. A total of 212 values (0.53%) were hence rejected. Furthermore, a QQ-plot and a Henry line were used to verify the normality of the consumption variable.

To avoid over-optimistic evaluations and over-learning, the data was split into a training set and a test set in a 75/25 ratio. This was done randomly to enable the model to be evaluated more accurately on data it has not been trained on.

The regression model was then tested on the test data for validation. Once the model was validated, it was applied to a new dataset that was representative of different percentages of empty trucks and the proportions of each type of truck, based on information obtained from the Ministry of Transport. Subsequently, different proportions of empty vehicles were eliminated progressively, in a random manner. It was necessary to remove trips of vehicles containing goods as well because the truck making an empty return trip contained goods on the outbound trip. Hence, to maintain the quantity of goods transported, the load from the deleted trucks was transferred to other trucks. This had a direct impact on the use of the load capacity of each truck, and thus the tonnage per kilometer. Lastly, the regression model was used to simulate fuel consumption for each proportion of empty vehicles eliminated.

2.2- Linear regression

Since we are trying to estimate the potential gains from reducing empty trips. It was therefore necessary to study the relationship between the fuel consumption of long-distance trucks and vehicles with a load of 0, which means that they are empty, using a regression analysis. This allowed for the estimation of the dependent variable *Y,* which in this case is fuel consumption, from the independent variable *X,* which represents the load of a vehicle, a continuous variable. The regression model then describes the relationship between these two variables by attempting to fit them onto a hyperplane that best represents the data set. This enables us to study the effects of variations in the proportion of empty vehicles on our dependent variable.

The linear regression method is described by the following equation:

$$Y = a + bx + e \quad (1)$$

Here, *a* represents the intercept with the *Y*-axis when the load of a long-distance truck is 0, and *Y* is equal to *a*. The parameter *b* is the slope of the regression line and indicates how much the average fuel consumption changes when the load increases by one unit. The parameter *e* represents the residuals or the error, which is the difference between the predicted and actual value of consumption. The variables *a* and *b* are estimated using statistical methods that take the variables of fuel consumption and truck load as inputs in order to find the best fitting line.

A second regression model was created that took into account the different types of trucks present in the dataset, thereby increasing the accuracy of the first model. From a simple regression to a multiple regression, x_1 represents the truck load, x_2 represents the four different types of trucks, x_3 represents the type of driving of the driver, and x_4 represents the aerodynamic coefficient of the devices on the truck. Thus, the new regression equation is as follows:

$$Y = b_0 + b_1 x_1 + \cdots + b_r x_r + e \quad (2)$$

Where *b* from 0 to *r* represents the regression coefficient. The regression equation takes into account the predicted weight and the coefficient *b* in the case of multiple regression.

To measure the relationship(s), the coefficient of determination R^2 was used as a quality measure to describe the observed data. It measures the variations of *Y* that can be explained by the dependence on *X*. Therefore, the higher the value, the better the precision in explaining the variations by the model. We were interested in seeing what percentage of the variations in consumption can be explained by the number of empty vehicles and whether this relationship is significant.

$$R^2 = \sum (Y_P - \bar{Y})^2 / (Y - \bar{Y})^2 \quad (3)$$

III- Analysis of results

The data was structured to represent the current state of trucking on Highway 20, between Montreal and Quebec City. Figure 2 presents the distribution of the weight of goods transported by each vehicle in percentage for the MapEUR dataset. Based on our initial assumptions, the number of trips made by empty trucks represented 40.6% of the total number of trips for an average load factor of 36%. These values are representative of the most recent report from the Quebec Safety and Trucking Branch, which highlighted that 40.1% of trucks were empty or almost empty, 9.0% of trucks were full or almost full in terms of mass, and 27.1% in terms of volume (Ministry of Transportation, 2018). The peaks in the histogram presented in Figure 2 represents these scenarios for different vehicle types and typical freight categories as reported in the same study.

These statistics reflect a lack of efficiency in the use of truck load capacity. This results in enormous environmental and economic costs, since at this level of activity the simulation shows that an average of 284 million liters of fuel which is equivalent to 780,000 tons of CO_2 are required to maintain long-haul operations year-round on Highway 20 between Montreal and Quebec City.

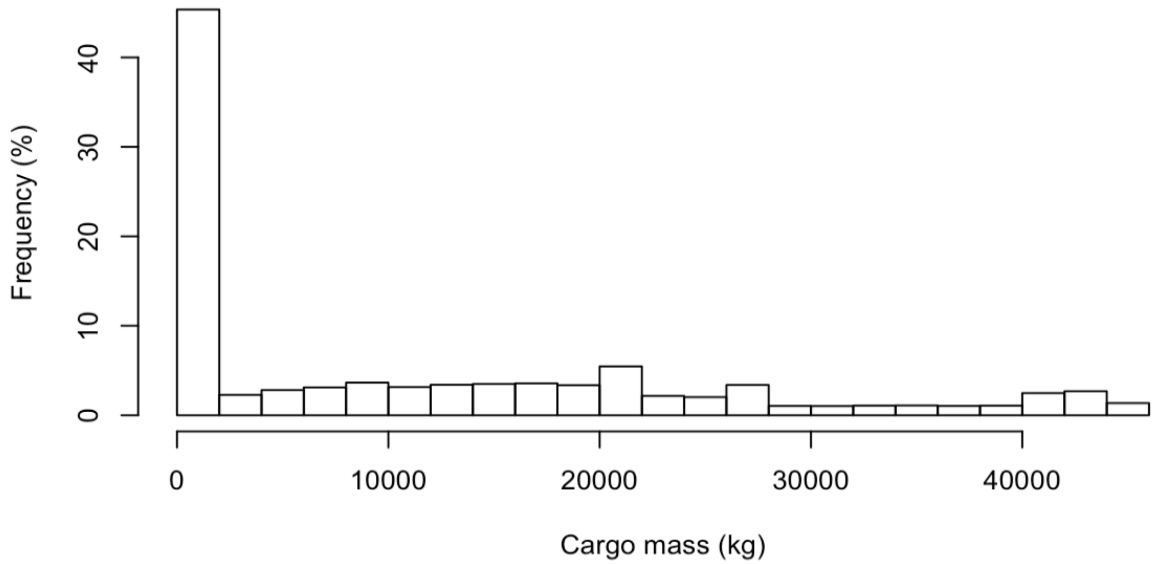

Figure 2 Distribution of the truck cargo mass of the MapEUR dataset.

The data described above were used to create a regression model. The model was designed to capture the relationship between the weight of the goods transported and the fuel consumption required. In addition, on Highway 20, four major truck types are observed (chassis cab, semi-trailer, chassis-cab-trailer, and road train), so the relationship between fuel consumption and load factor may differ from one type to another. Therefore, four different regressions were performed to study the relationship separately. The results showed (Table 1) that there is a positive and significant relationship between the weight of the transported goods and the fuel consumption with p-values < 0.0001. Implying a good fit between the data and the model. However, the adjusted R^2 varies for these four vehicle types from 16.5% to 33.7%. These variations in R^2 show that the impact of load factor on fuel consumption also depends on the type of vehicle. The relationship is strongest for chassis cab trucks, which have the highest adjusted R^2 of 33.7%. Therefore, there is a stronger relationship between the weight of the goods and the fuel consumption. However, it is important to note that out of all the different elements that can influence consumption, the load factor alone is able to explain an average of 23% of these fluctuations regardless of the type of truck.

Table 1 regression summary

Regression Model	*P*-value	R^2	*b*
Chassis cab	2.2e-16	33.75 %	0.0006517
Semi-trailer	2.2e-16	16.46 %	0.000294
Chassis cab trailer	2.2e-16	31.58 %	0.0002764
Road train	3.4^{e}-5	8.13%	0.0000867

Given that none of these models offer an R^2 greater than 50%, a large part of the variation cannot be captured. As a result, the regression model cannot provide reliable predictions to quantify the impact of a reduction in the load factor. This would distort the quantitative analysis of the impact of reducing the number of empty trucks on diesel consumption. For this reason, other elements such as the type of truck, the aerodynamic coefficient of the truck, and the driving style of the driver have been added. These elements were selected because they are more easily controlled by the different transport companies through training or the purchase of equipment. In contrast to external factors such as climate or pavement type, which are difficult to change. The new regression model provides a *p*-value < 1e-7 and an error-adjusted R^2 of 95%, which is significant and much more accurate than the first model. Here, for every 1% increase in fuel-efficient driving, there is a 0.9% reduction in fuel consumption per liter. Meanwhile, for every 1% increase in the weight of the transported goods, there is a 0.03% increase in fuel consumption per liter. Moreover, using a bigger truck increases fuel consumption by 11.5% for the same cargo mass. Figure 3 also shows that the model does not overestimate or underestimate with residuals more or less proportional to 0. These elements make the model sufficiently relevant and efficient. It is then possible to say that the model can be used to predict the new consumption caused by a redistribution of the weight of goods in the trucks following a reduction in the number of empty trucks on the road.

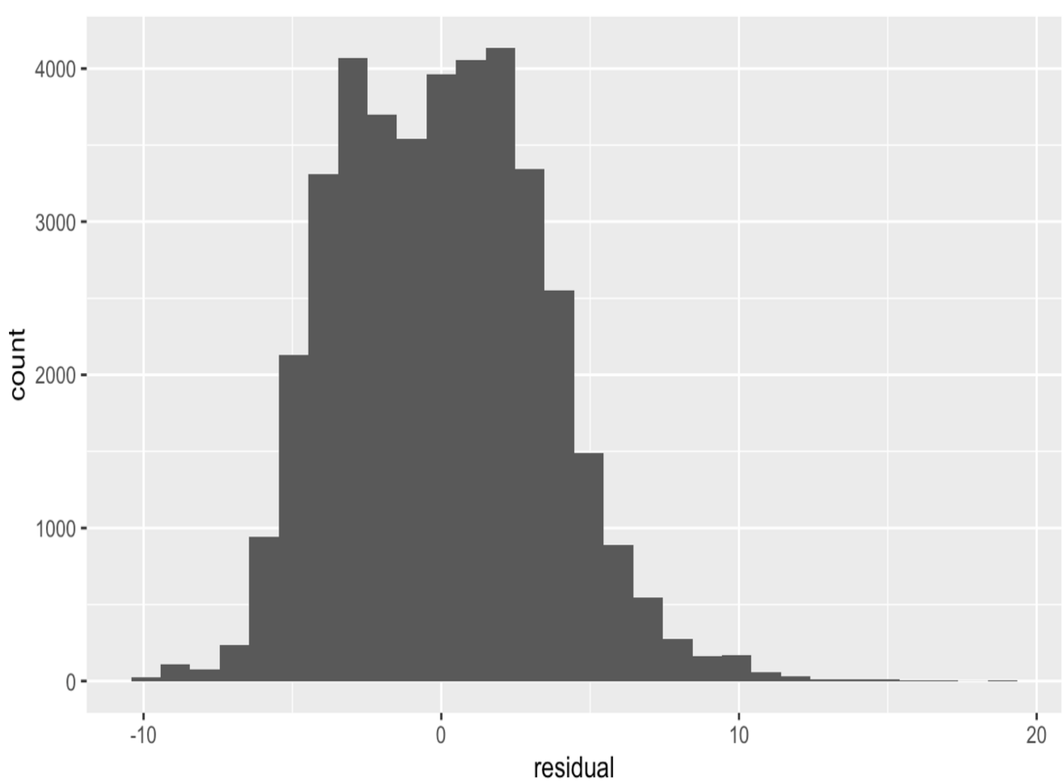

Figure 3 Distribution of the residuals of the fuel consumption prediction model (equation 3)

Table 2 illustrates the impact of reducing the number of long-distance trucks on the road, with the same amount of freight being transported and the load of removed vehicles being distributed to other trucks. This ensures the activity level and carrier capacity remain unchanged to meet the customers' needs. However, changes in vehicle loads affect fuel consumption, and the regression model is used to calculate the new consumption after the change in the load factor for different proportions of vehicles removed.

The first column of Table 2 represents the different proportions of empty vehicles removed, while the second column shows that the average consumption varies around plus or minus 1 standard deviation from one proportion of empty truck to another. Removing all empty vehicles increases the average load factor from 38% to 63%, resulting in a 40% fuel saving. According to column 4, an average of 0.02 liters of fuel is required to transport 1 ton over 1 km.

Table 2 summary table of the impact of reducing the proportion of empty vehicles.

Proportion of empty truck removed (%)	Average consumption in (l) per truck	savings compared to the initial position (%)	Average l per t.km	Average load factor (%)
0	93.11	0	0.034	37.76
10	92.42	2.57	0.033	38.53
20	91.34	11.61	0.031	41.93
30	91.46	19.35	0.029	45.39
40	92.01	27.10	0.026	50.54
50	93.85	29.69	0.025	52.00
100	92.35	39.85	0.020	62.93

Furthermore, Figure 4 shows the increasing relationship between the load factor and the percentage of empty vehicles removed, while Figure 5 highlights the benefits of reducing empty trucks. Fuel savings increase with a reduction in empty trucks on Highway 20, although the relationship is not entirely linear due to the distribution of freight weight from the removed trucks into other trucks. This method was chosen as removing only one outbound or return trip means that the transport cycle is incomplete. The corresponding outward and return trip must be removed to complete such an activity. Thus, the goods transported by the empty truck must be distributed to other trucks to maintain the loads, resulting in a better use of the load of each truck. This improves the load factor in the system by an average of 9.6% for each 10% reduction in the proportion of empty vehicles, as shown in column 5 of Table 2.

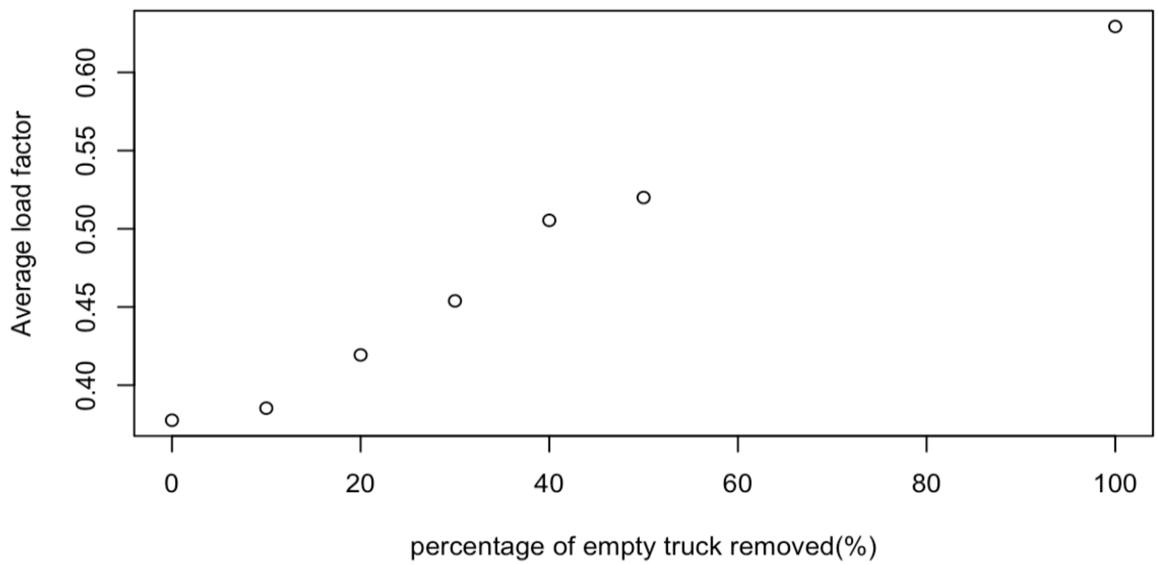

Figure 4 average load factor by percentage of empty truck removed from the road.

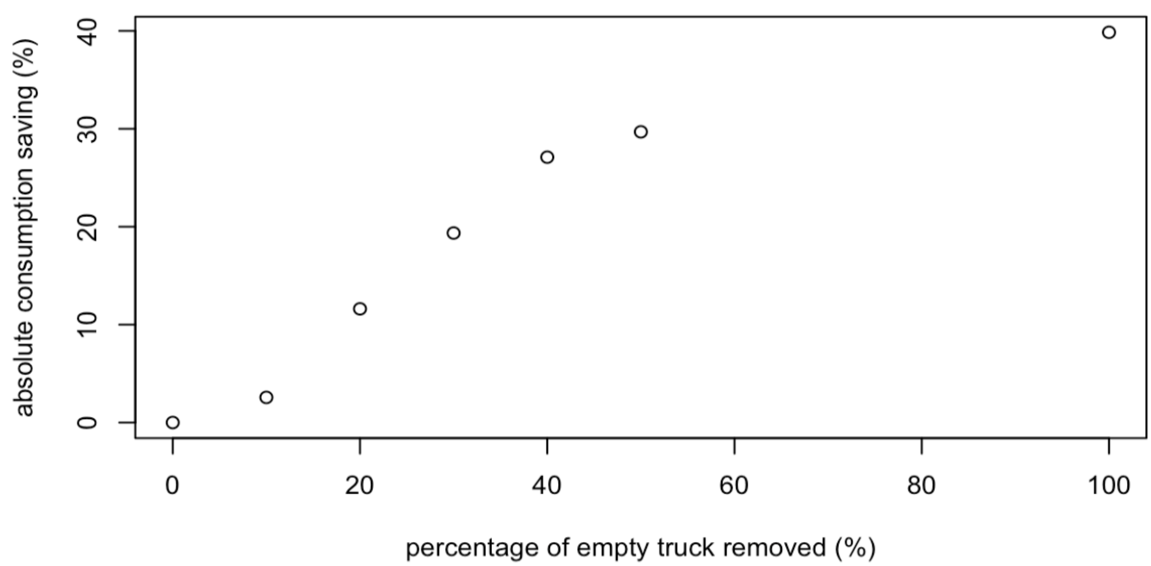

Figure 5 energy saving by proportion of empty vehicle removed from the road.

The MapEUR tool estimated that trucks consume 284 million liters of diesel per year on the 245 km stretch between Montreal and Quebec City. The data was used to train a regression model to make consumption projections. These projections of trucking in Quebec allowed us to realize that a 100% reduction of empty trips on Highway 20 (Montreal - Quebec) would correspond to a savings of about 40% of fuel used, or 113.6 million liters of fuel. This could result in a significant economic cost savings for carriers. Considering the current average cost of diesel fuel, which is 2.6 $/L, carriers could save an average of 282.4 million $ per year (Régie de l'énergie Québec, 2023). This reduction in fuel usage would also represent a saving of more than 300,000 tons of CO_2. However, achieving a 100% reduction of empty trucks in impossible, at least in the short term. A more achievable goal would be a 20% reduction, which would result in a savings of 12% less fuel or 34 million liters of fuel. This would correspond to an annual saving of about 90,000 tons of CO_2, just for this segment of road.

It is also possible to calculate the economic cost of these savings by referring to the social cost of carbon, which evaluates the impact of each ton of emissions in all areas. With a social cost of 247 $/t, this reduction in emissions would result in social savings of approximately 22 million $ (Federal Minister of the Environment, 2020). The carrier side would also benefit from these savings, with $88.4 million in fuel cost savings, not including maintenance, insurance, and driver salaries. These savings are substantial, considering that we are only talking about Highway 20, which is 245 km of road, representing only 6% of the 4064 km of highway managed by the Quebec government (Transports Québec, 2021). If such a policy was applied to all trucks in Quebec, it would result in a saving of 1.2 million tons of CO_2, or 12% of the 10 million tons of CO_2 related to the trucking sector in Quebec (Transport Quebec, 2021). Taking into account the social cost GHG emission, such a reduction would bring social savings of nearly 300 million $.

To achieve this result, there needs to be support and incentives for individuals to act. The state should review policies associated with long-distance trucking, such as weight policies or time policies, like those found in urban areas. This would push transport companies to maximize their load factor. The state could also provide financial aid for the installation of computer systems when several companies decide to share their vehicle fleets.

By eliminating empty runs and redistributing loads, it is not just a matter of providing several customers with the truck of one transport company. It is about creating a network between carriers to deliver a group of customers. This is a concept of mutualization, which involves all participants in a distribution network. It implies cost-sharing by different carriers and customers, and is quite different from the classic mutualization of transport, which involves making a vehicle available to a pool of companies for the delivery of their goods, allowing savings of up to 15% according to several studies (FM logistic France, 2018). Implementing such a strategy would result in savings beyond 15%. However, there is a great need for an IT system and training to enable effective data sharing in real time. This would allow for a global vision of transportation at each stage to adapt the logistics chain. In addition, this represents a saving for public authorities because a reduction in the number of journeys made would lead other indirect benefit like decreasing in road maintenance needs and mitigating drive shortage issues.

Conclusion

In this study, data from long-distance trucking on Highway 20 (Montreal-Quebec City) were used to develop a regression model that aims to quantify the impact of reducing the number of empty trucks on GHG emissions. The goal is to identify a solution that is applicable globally. The analysis assumed that the transport companies could only control the type of trucks used, the driver's driving style, and the truck's load.

The results of the analysis revealed that among the various types of trucks examined, chassis cabs had the strongest positive correlation with fuel consumption in liters. The adjusted-error R^2 for the relationship was 34%, showing that this type of vehicle consumed the most fuel per t.km transported. The load factor was also shown to impact fuel fluctuations by an average of 23%. Therefore, it is a critical factor in transport management. Incorporating different types of trucks and driver behavior, the combination of load factor and these factors produced a regression model with an R^2 of 95% and a p-value < 0.0001.

Moreover, the study found that a 20% reduction in the number of long-haul trucks traveling empty on Highway 20 between Montreal and Quebec City would result in a 12% reduction in fuel consumption, equivalent to 34 million liters of diesel. The reduction in fuel consumption would translate to a saving of 90,000 tons of CO_2 and $88.4 million in fuel costs, not including maintenance, insurance, and driver salaries. Given the current climate issues and government initiatives, it is essential to reduce GHG emissions from the transportation sector as soon as possible, without waiting for the arrival of electric trucks.

As such, the mutualization of long-distance trucks appears to be a feasible solution in the short term, offering potential savings of 1.2 million tons of CO_2 emissions in Quebec. Implementing this policy provincewide would result in an annual reduction of 1.4% of total province emissions. This would translate into a social cost reduction of about 300 million $, an equivalent of the whole Quebec government's eco-trucking budget (Office of the Minister of the Environment and Climate Change, 2022). Additionally, stakeholders could realize savings in operating, maintenance, and environmental costs. However, achieving these goals requires joint action between governments and the transportation industry. Many of the companies in these sectors are SMEs, faced with limited funding to make operational transitions. Expertise, subsidies, and policies that promote the optimal use of the load factor, similar to those in urban areas, are necessary to support them.

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