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DECARBONIZATION OF LONG-HAUL TRUCKING IN EASTERN CANADA

SIMULATION OF THE e-HIGHWAY TECHNOLOGY ON THE A20-H401 HIGHWAY CORRIDOR

PROJECT COLLABORATOR

IET INSTITUT DE L'ÉNERGIE **TROTTIER**

PREPARED FOR

Energy Modelling Initiative
Bringing the Tools to Support Canada's Energy Transition

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NOTE

This study is financed by the Energy Modelling Initiative (EMI), a partnership between Natural Resources Canada and academic institutions to explore ideas that will form the basis of a Canadian energy systems modelling platform to share tools and results. The authors are grateful for their support as well as the contribution of reviewers. This simulation is the first step in a study proposal developed by the Chair in Energy Sector Management, HEC Montréal and CPCS, in collaboration with government, university and private partners, to compare the costs and potential of different decarbonization technologies along the A20-H401 highway axis in Eastern Canada.

IMPORTANT NOTICE. An earlier version of the report (dated March 21, 2021) titled, Simulation of the "e-highway" technology for the decarbonization of heavy transport on the A20-H401 highway corridor in Eastern Canada, contained errors and was replaces by this 2nd edition.

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CPCS (ref 20160)
May 2021

Graphic design: Brigitte Ayotte (Ayograph)

Cover image: DepositPhotos/sodesignby

Executive Summary

Connecting long haul trucks to overhead electrical wires (a catenary) on highways (e-highways) is being tested as an energy-efficient options for decarbonizing road freight, with Germany and Sweden taking the lead. The initial infrastructure investment is often seen as a limit to large-scale deployment. But when compared with other zero-emission options, the catenary technology offers some advantages. First, it is already used in transportation (e.g., trams, trains) and second, trucks can run on either a hybrid or battery system when travelling off the electrified corridors. This flexibility combined with efficient use of electricity and mature catenary technology makes for a solid contender in the mix of potential options for decarbonizing road freight.

The study simulates the potential of e-highway hybrid technology for the decarbonization of long-haul trucking on a 1,300 km highway corridor in Eastern Canada, connecting Quebec, Montreal, and Toronto up to the U.S. border (the A20-H401 corridor). The simulation is based on a GIS analysis of current flows of heavy vehicles (Class 8 and above), according to the present road capacity of the A20-H401, as this axis concentrates a significant part of long-haul trucking in Eastern Canada.

The construction of the e-highway infrastructure will require an initial investment of 4.1 billion CAD. When accounting for all other costs (hybridization of trucks, maintenance of the catenary system, and electricity) and comparing them with the benefits (savings on fuel and avoided GHG emissions), we find the investment's economic rate of return ranging from 7% to 13% , depending on adoption levels. The switch from diesel to electricity reduces yearly GHG emissions by 2.8 million tonnes of CO_2 equivalent.

Our simulation shows that the key factors influencing the economic viability of the e-highway are the cost of energy (diesel and electricity), the initial investment cost, and the rate of adoption by the industry. Relative to other decarbonization options, the uncertainty on investment costs is limited since catenaries have been in use for more than a century. The rate of adoption, on the other hand, remains a major unknown – but one that could be influenced by adapted support policies.

This simulation, sponsored by the Energy Modelling Initiative, is the first step in a study proposal developed by the Chair in Energy Sector Management, HEC Montréal and CPCS, in collaboration with government, university and private partners, to compare the costs and potential of different decarbonization technologies along the A20-H401 axis (Whitmore, Gignac, 2020).

Résumé

L’autoroute électrique à caténaire ou “ e-highway ”, qui consiste à alimenter en énergie des camions électriques à partir de caténaires (lignes électriques) aériennes, est en cours de test en Allemagne, en Suède et aux Etats-Unis. L’ampleur de l’investissement initial est souvent considérée comme un obstacle au déploiement de cette solution. Mais, comparée à d’autres options de décarbonisation du transport lourd, la technologie e-highway a plusieurs avantages. Elle s’appuie sur des décennies d’expérience dans le domaine ferroviaire, où les caténaires sont largement utilisées. Elle est flexible, puisque les camions peuvent utiliser une autre source d’énergie en dehors des tronçons électrifiés. Elle offre enfin un bon rendement énergétique, puisque les conversions d’énergie sont limitées.

L’étude simule le potentiel de la technologie des e-highways pour la décarbonisation du transport lourd de marchandises sur un corridor autoroutier de 1300 km dans l’est du Canada, reliant les villes de Québec, Montréal et Toronto jusqu’à la frontière américaine (le corridor A20-H401). La simulation est basée sur une analyse SIG des flux actuels de véhicules lourds (Classes 8 et supérieures), en fonction de la capacité routière actuelle de l’A20-H401, car cet axe concentre une part importante du transport routier longue-distance de marchandises dans l’Est du Canada.

La construction de l’infrastructure e-highway nécessitera un investissement de 4.1 milliards de CAD. Le taux de retour économique de cet investissement, tenant compte des autres coûts (hybridisation des camions, maintenance du système caténaire, et fourniture d’électricité), et des bénéfices générés (économies de combustible et émissions de GES évitées), s’établit entre 7% et 13% , selon le degré d’adoption de la technologie par l’industrie. Le passage du diesel à l’électricité permettrait de réduire les émissions annuelles de GES de 2,8 millions de tonnes équivalent CO_2.

La simulation montre que les principaux facteurs influençant la rentabilité économique de l’autoroute électrique sont le coût de l’énergie (diesel et électricité), l’investissement initial, et le taux d’adoption par l’industrie. Par rapport à d’autres options de décarbonisation, l’incertitude sur les coûts est relativement limitée puisque les caténaires sont utilisées depuis plus d’un siècle. Le taux d’adoption, par contre, reste une incertitude importante – qui pourrait être influencée par des politiques de soutien adaptées.

Cette simulation, menée avec le soutien de l’Initiative de Modélisation Énergétique, est la première étape d’une proposition d’étude développée par la Chaire de gestion du secteur de l’énergie, HEC Montréal et CPCS, en collaboration avec des partenaires gouvernementaux, universitaires et privés, dans l’optique de comparer les coûts et le potentiel de différentes technologies de décarbonisation le long de l’axe A20-H401.

Table of Content

List of Figures

List of Tables

Introduction

Reducing emissions from road freight transportation is arguably one of the most important challenges to reaching stated climate objectives given the complexity of this sector (e.g., logistics chains, regulations and cross-border traffic) and its importance in supporting daily economic activities, as well as the need for interoperability throughout North America. Freight transportation is essential for commercial exchanges of goods that support our quality of life. However, the heavy-duty truck sector also contributes to 8% of total national emissions (Sharpe, 2019), with its emissions having more than tripled between 1990 and 2018 (ECCC, 2021). Canada's goal to achieve net zero emissions by 2050 imposes decisive action in this sector, considering that globalization and increased trade flows, accelerated by e-commerce, will continue to push up demand for goods – and consequently emissions, unless decarbonization solutions are implemented along the value chain.

Canada's approach for decarbonising road freight

Reform of the sector, both technologically and logistically, will be key for achieving climate goals for 2030 and beyond. Despite the urgency, few policies by the federal government have started to reverse these trends. In addition to its carbon tax, set to increase to 170 CAD/tonne by 2030, the government has relied on three key initiatives to further curb emissions within the road freight sector. These include improving standards for heavy-duty trucks, subsidizing alternative truck technologies and fuels, and introducing a clean fuel standard with minimum levels of biofuels in diesel and gasoline.

Progress on developing standards for emissions and engines is complex for several reasons, notably the fact that Canada, with its relatively small market compared to the U.S., is forced to follow American standards. Progress is further slowed by the need to demonstrate new standards compatibility with Canada's winter conditions (Canada Senate, 2017). Finally, some provinces allow for heavy trucks to carry more weight compared to their American counterparts, which further complicates prospects of improving standards.

Support of alternative technologies to diesel has mainly focused on natural gas and hydrogen trucks given their extended range and shorter refueling times compared to battery-electric trucks. However, both financial and technical barriers currently prevent long-haul freight operators from investing in these technologies. For natural gas engines, fuel is cheap and abundant, but trucks remain costly, and fueling infrastructure and service support are not widely available. Converting to natural gas would only reduce greenhouse gas (GHG) emissions by 17% compared to diesel trucks (Ibid.), which is not compatible with a net-zero pathway. Hydrogen has added challenges on the supply-side. Currently, it is mainly obtained from steam reforming natural gas, which releases GHG. The process can be made cleaner by capturing those emissions and storing them (blue hydrogen), or by applying zero-emission electrical current to water to release the hydrogen (green hydrogen). However, both of these processes further increase the cost of production compared to producing hydrogen from natural gas.

Finally, the federal government announced in 2020 a Clean Fuel Standard (CFS) regulation to require liquid fuel suppliers to gradually reduce the carbon intensity of the fuels they produce and sell. This measure is expected to achieve 13% emission reductions below 2016 levels in the carbon intensity of liquid fuels used in Canada by 2030 (Government of Canada, 2021). To drive innovation at the lowest cost, the CFS establishes a credit market. The government also announced it will invest CAD $1.5 billion towards a Low-carbon and Zero-Emissions Fuels Fund, to increase support for domestic production of low-carbon fuels and their adoption, such as hydrogen and biofuels.

These key initiatives are important, but not sufficient to place Canada on a clear path towards zero-emission road freight. Many countries face the same challenges in tackling emissions from their freight sectors. Recognizing the limits of the current approach has led some decision makers, businesses and researchers to consider a new option using a familiar technology used in trains and trams: building an overhead catenary system to directly power heavy trucks equipped with pantographs, on dedicated highway corridors, also known as e-highways.

Introducing the e-highway concept

Catenary technology, which consists of overhead wires to supply electricity to vehicles equipped with a pantograph, has been used for over a century in transportation, for example in heavy rail, trolleys and light rail. In Canada, the technology was used for urban public transportation in major cities as early as the late 1800s (Sullivan, 2015). When combined with a decarbonized electricity supply, this option offers potential for major GHG reductions and efficient energy use.

The electrified highway technology (referred to as e-highway; see Figure 1) aims to transfer this technology to road freight transportation. A supporting structure built outside the road boundary holds two overhead catenaries, supplying the positive and negative electrical circuit. Electricity is transferred to the trucks through a pantograph installed on the roof. The pantograph can be rapidly connected and disconnected automatically as needed. This key innovation makes catenary trucking distinct from those used in trolleys buses and represents an essential feature if the technology is to be used by long-haul trucks. A secondary source of energy is used outside of electrified roads. This secondary source can be diesel or electricity (with a long-range battery), as well as hydrogen, bio-gas, etc. The technology is extremely flexible, as trucks equipped with the technology remain able to circulate on any road. Furthermore, the catenary system does not prevent other vehicles from using the electrified highway.

FIGURE 1. e-HIGHWAY PILOT PROJECT

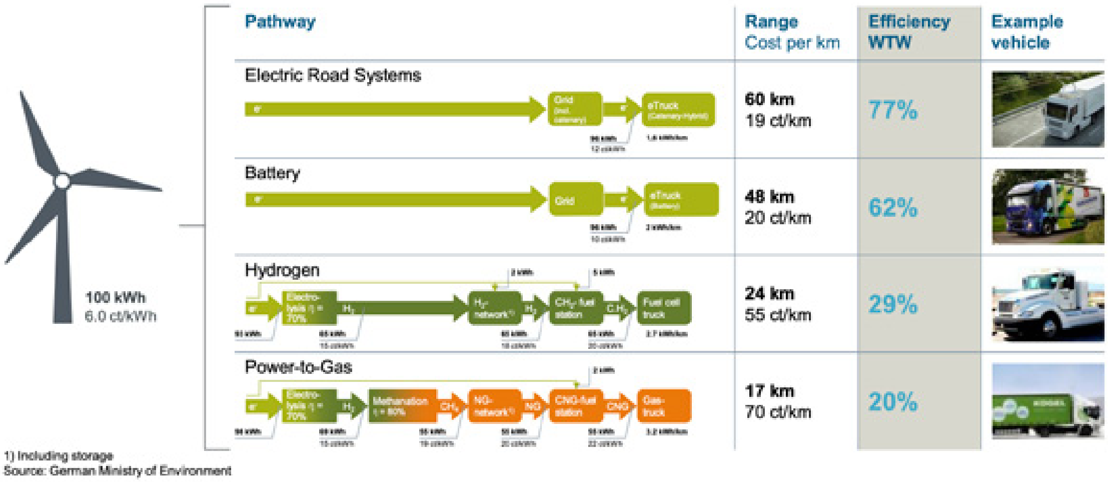
Source: Siemens/Scania

Several pilot projects have been put in place, co-sponsored by Siemens: a 2-km segment in Sweden (Connaissance des énergies, 2016), 1.6 km in California (Blanco, 2017). In Germany, three pilot projects are currently ongoing: a 10-km electric road test track with catenary overhead lines near Frankfurt that has been fully operational since July 2020 and that will be extended by 2022 (Scania, 2020); a 5-km portion of a motorway near Lübeck opened in 2019 (Fachhochschule Kiel GmbH); and a selected public test route on the B 462 between Kuppenheim and Gernsbach-Obertsrot (Baden-Württemberg Ministry of Transport). Sweden's transport administration gives the technology a Technology Readiness Level (TRL) of 8 on a 9-point scale.

Germany has announced the large-scale deployment of e-highway, with the objective of reaching 4,000 km of overhead catenaries by 2030 (National Platform Future of Mobility, 2020). In October 2020, Sweden set the goal of creating 2,000 km of electric roads by 2030 (Ministry of Infrastructure of Sweden, 2020). Other countries, including the UK, France and Italy, are paying close attention to the technology.

The initial infrastructure investment is often seen as a limit to large-scale deployment. But when compared with other zero-emission options, the catenary technology offers some advantages. Electric trucks are by far the most efficient option in terms of energy use, because they require less energy per km than alternative propulsion systems (Amelang, 2021). Direct electricity use on an e-highway is even more efficient than battery-powered trucks, since with the latter some energy is lost in the charge/discharge of the battery. Less reliance on batteries could also alleviate the need and environmental impacts associated with the mining of critical metals. According to the German environment ministry, electric road systems have an overall efficiency of 77% , compared to 62% for battery-powered trucks and only 29% for hydrogen fuel cell trucks (see Figure 2).

FIGURE 2. WELL-TO-WHEEL EFFICIENCY OF SEVERAL PROPULSION TECHNOLOGIES



Source: Original figure from the German Ministry of Environment. In P. Akerman (2016). eHighway Electrified heavy duty road transport Presentation by Siemens at IAE Workshop - The future role of trucks for energy and environment, Brussels, 8 November 2016, p.5.

Another advantage of e-highways over battery-powered trucks is the weight. The weight of long-range batteries decreases the useful payload while this constraint is lifted with e-highway. Also, as catenaries are already used in transportation (e.g., trams, trains), the technology is well known and can become commercially mature quickly. Lastly, as trucks can run on either a hybrid or battery system when travelling off the electrical corridors, the technology is extremely flexible. These advantages make e-highway an interesting contender to add to the mix of potential options for decarbonizing road freight.

Potential relevance for Canada

To date, few studies have explored the potential of this technology to decarbonize freight in the Canadian context. Although the application of the concept in road freight is still in its infancy, it has the potential to mature rapidly since it is based on technological applications that have been mastered for more than 100 years. It therefore seems it could position itself as a tangible solution to reduce emissions. Key factors render the concept promising for Canada:

Linear transportation network. Canada's road network is made up of relatively few key highway corridors across the country. This continuity is particularly well-suited to e-highway technology and will facilitate its application given targeted investments would make it possible to electrify a significant portion of the movement of goods;

Clean and affordable electricity. Renewable sources of electricity are abundant and relatively inexpensive, compared to many countries.

Use of existing road and access to electrical infrastructure. E-highway overhead catenary systems allow trucks equipped with pantographs to travel on the same road network as other truck technologies. Furthermore, electrical infrastructure tends to follow the same corridors as main roads, as shown in the case of the A20-H401 on Figure 3. This will facilitate the deployment of the catenary system on the road axes and its adaptation over time, as advances are being made in the field.

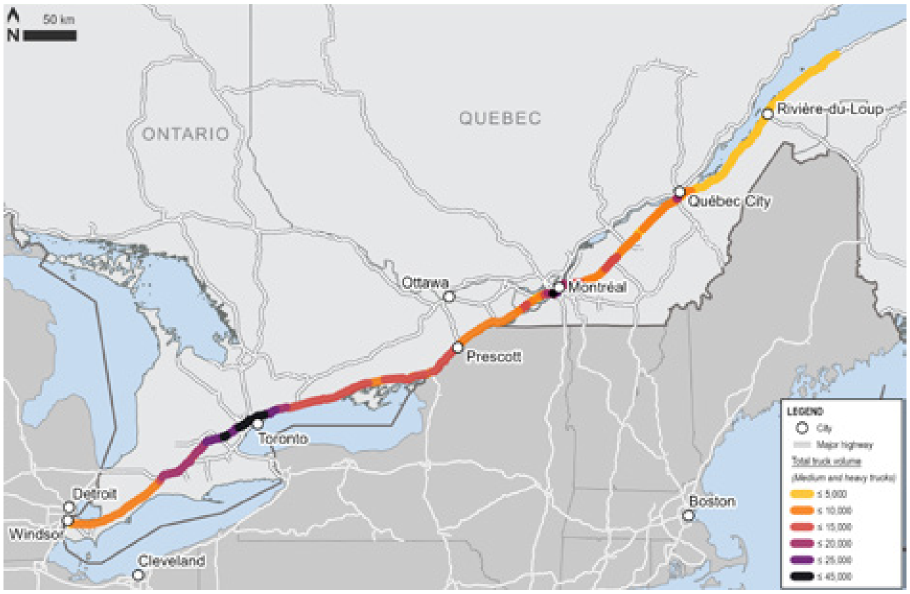
Flexibility. The concept is flexible in its application since it uses a hybrid system which can be upgraded to other fuels or on-board battery systems. In the early stages of a rollout, distances can be covered with a combustion engine, while future trucks could be equipped with a relatively small battery to cover the distance to and from electrified routes.

Furthermore, because the flow of heavy road freight is concentrated on main routes, only a small percentage of all roads would have to be electrified to make the system work. In Germany, it was estimated that 60% of heavy truck emissions occur on only 2% the road network, while almost 90% of truck trips after leaving the highway only cover 50 km or less (Amelang, 2021).

Objectives of the study

In this perspective, the objective of the study is to explore the potential of the e-highway technology for the decarbonization of long-distance freight on the A20-H401 highway corridor. This 1,300-km corridor, linking Quebec City, Montreal, and Toronto, to the U.S. border, has some of the busiest truck traffic of Eastern Canada, as illustrated in Figure 3 below.

FIGURE 3. AVERAGE ANNUAL DAILY TRUCK VOLUME ALONG THE A20-H401 CORRIDOR IN EASTERN CANADA



Source: CPCS analysis based on data from the Ontario Ministry of Transportation (MTO) and the Quebec Ministry of Transportation (MTQ) through their open data portals.

Our model allows the simulation of the e-highway technology on the A20-H401 corridor, in its widest possible extent (i.e., from Rivière du Loup in Québec up to Windsor at the Ontario/U.S. border). It is based on a cost-benefit model in Excel and relies on real truck flow data extracted from a Geographical Information System (GIS). It focuses on heavy trucks active on long-distance trips, as this segment is the most relevant for direct electrification with e-highway. “Heavy trucks” here refers to Class 8 and above / vehicles weighing 15,000 kilograms or more.

For the purpose of the simulation, we have considered hybrid diesel-electric trucks running on electricity whenever the catenary system is available, and switching to diesel on non-electrified roads. The simulator calculates, for each year over a 30-year horizon, the costs and benefits of the technology as compared with a business-as-usual baseline where the traffic would remain entirely diesel-based. The benefits include fuel cost savings and avoided GHG emissions. Of note, the simulator does not account for financing costs, nor for taxes.

This simulation is the first step in a study proposal developed by the Chair in Energy Sector Management, HEC Montréal and CPCS, in collaboration with government, university and private partners, to compare the costs and potential of different decarbonization technologies along the A20-H401 corridor.

Literature review

In this brief literature review, we focus on the parameters that are required for our simulation of the technology: infrastructure costs, potential for GHG emissions reductions, potential for cost savings, constraints related to Canadian climate, and the overall relevance of the technology for long haul freight.

While studies show that the e-highway technology offers high potential for decarbonizing road freight transportation, its application remains limited in the trucking industry and has primarily been tested in Europe.In North America, the first demonstration project took place in 2017 on a 1.6-km-long stretch near the ports of Los Angeles and Long Beach, California (Roether, 2017). No demonstration projects have been conducted in Canada.

Recent research in the Canadian context has generally focused on the broader question of how to decarbonize heavy transport and compared different technologies that could be used to attain governmental GHG emission reductions targets, notably in Quebec. To date, we have identified only one study on the "e-highway" technology and its potential application to a specific highway corridor in Canada (Sharpe, 2019). Published in 2019, it studies several zero-emissions technology options for trucks, estimates the related Canada-specific operations costs and CO_2 emissions and compares it to diesel and natural gas options.

Costs of the technology

The investment costs required for the installation of the overhead catenary system infrastructure are estimated to range between CAD 2.4 to 4.8 million per kilometer of highway, for one electrified lane in each direction (see Table 1). Variations mostly stem from design choices as regards the configuration of the system. In particular, denser traffic requires higher power per km, and so does the added functionality of on-the-go recharge of large batteries. The more power is provided, the higher the cost of the infrastructure.

TABLE 1. COST OF OVERHEAD CATENARY SYSTEM BASED ON LITERATURE

Source	Infrastructure cost, sum of both directions (CAD/km)
Evaluation and deployment strategies for overhead heavy-duty vehicles (2020) *Hacker, F., Blanck, R., Görz, W., Bernecker, T., Speiser, J., Röckle, F., Schubert, M., Nebauer, G.*	4,830,000 CAD/km* (This study assumes an installed power of 4MW/km, which is twice as high as most other studies.) **1.53 CAD/EUR exchange rate*
Energy Consumption and Life Cycle Costs of Overhead Catenary Heavy-Duty Trucks for Long-Haul Transportation (2018) *I. Marev and D. U. Sauer*	3,060,000 CAD/km* **1.53 CAD/EUR exchange rate*
Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost (2019) *D.T. Ainalis, C. Thorne, and D. Cebon* *The Centre for Sustainable Road Freight*	2,460,000 CAD/km* **1.77 CAD/GBP exchange rate*
Feasibility study for determination of the potentials of the hybrid overhead line truck for the Federal Ministry of Transport and Digital Infrastructure of Germany (BMVI) (2017) *Fraunhofer ISI, Fraunhofer IML, PTV Transport Consult GmbH, TU Hamburg-Harburg – IUE, M-Five*	3,060,000-3,825,000 CAD/km* The differences here come from assumptions around ease of grid connection and the need for protection barriers **1.53 CAD/EUR exchange rate*
An Examination of Heavy-duty Trucks Drivetrain Options to Reduce GHG Emissions in British Columbia (2019) *M. Lajevardi*	4,235,000 CAD/km (based on a 2012 study, which might be outdated) **1.21 CAD/USD exchange rate*

These findings support the notion that despite the "e-highway" technology having only been tested for the first time in 2016 (Siemens, 2016), the costs linked to catenary systems in transportation infrastructure, such as tramways and subways, provide for well-documented background data.

Beside the direct costs pertaining to the overhead catenary infrastructure, the implementation of the e-highway concept also requires additional investments for each individual truck. These costs are harder to capture from the review of the literature, partly due to the fact that the costs of the additional components (pantographand battery) are not always distinguished from the cost of ownership of the vehicle. Furthermore, different studies have considered different configurations for the trucks: drivetrains are either fully electric, or hybrid (diesel / electric); the size of the electric battery varies significantly.

Based on the studies that do break down this overall number, and focusing on the most relevant components, namely the pantograph and the battery, we see that the most expensive component is generally the battery which can cost up to CAD 90,000[1] (Mareev and Sauer, 2018); while the pantograph is estimated to cost between CAD 42,732[2] (Kühnel, 2018) and CAD 55,000 (Mareev and Sauer, 2018). However, it is expected that as the e-highway technology is more widely adopted by the industry and technological advancements are made; that the price of a pantograph will considerably decrease as manufacturing volumes grow. Some estimate that between 2025 and 2030, the cost of a pantograph will go from CAD 42,000[3] to CAD 26,000[4] (Kühnel, 2018) while others estimate its long-run cost will be CAD 13,000[5] (Wietschel, 2017).

Potential for GHG emissions reductions

All studies indicate that e-highway has a significant potential for GHG emissions reductions. The expected reduction varies however from study to study, depending on the exact configuration of the technology (type of truck, capacity of batteries, road corridors chosen, infrastructure available) and the electricity generation mix of the country.

In Germany, studies found GHG reduction ranging between 11% and 44% over a 10-year period in comparison to conventional diesel trucks, and on a well-to-wheel basis. Greater reductions are attained when considering fully electric trucks (up to 44%) in comparison to hybrid trucks (11-14% reductions) (Kühnel, 2018, Johrens, 2020). These numbers are specific to the German electric mix for which the GHG emission factors was 542g/CO_2 in 2015 and is estimated to decrease to 413g/CO_2 by 2030 (Kühnel, 2018).

In Canada, (Sharpe, 2019) estimates that the total life-cycle well-to-wheels GHG emissions for an electric (catenary) long-haul heavy duty freight truck will be 84% to 88% lower than that of a conventional diesel vehicle. Lajevardi (2019) finds that in British Columbia, battery electric catenary drivetrains using hydroelectricity would emit 95–99% less GHGs than a diesel comparator. In Quebec, it is estimated that a scenario forcing the complete electrification of heavy goods transport with battery-powered, fully electric trucks would allow the province to reach its target of a 37.5% reduction in GHG emissions in comparison to 1990 GHG emissions (Pedinotti-Castelle, 2020). Of note, the study considered battery-powered vehicles and not catenary systems.

Overall, we can say that though the exact numbers may vary from one paper to another, it is clear from the literature that overhead catenary trucks and the "e-highway" technology emit much less GHG than regular diesel vehicles, even in countries with power grid that are not net-zero-emissions.

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[1] It is important to note that battery costs will vary depending on specific parameters such as size and range.

[2] €28,000, 1.53CAD/EUR exchange rate

[3] €28,000, 1.53CAD/EUR exchange rate

[4] €17,500, 1.53CAD/EUR exchange rate

[5] 10,000 USD, 1.3CAD/US exchange rate

Potential for costs savings

The literature is less conclusive as regards to the potential cost savings, and overall economic viability. Differences in assumptions, notably with regard to investment costs, capacity constraints, utilization rates and financing options, make it more difficult to draw conclusions from existing studies.

Several studies focus solely on the costs of ownership of individual trucks which appear to be lower for catenary trucks, in comparison to diesel vehicles. (Sharpe, 2019) finds that the use of an overhead catenary truck results in 30 to 35% lower costs than the use of a diesel vehicle – but infrastructure costs are excluded, which is an important limitation.

Based on data from the Oeko Institute (Stephan, 2020) concludes that the investment costs required for overhead line trucks will be offset by lower operating costs in the future. (Ainalis, 2020) considers the implementation of an electrified road system in the UK to be financially attractive, with estimated payback periods of 1.5 years for truck operators, and 15-20 years for the infrastructure providers. The study also states that the British government would be able to introduce electricity excise taxes without hindering the financial viability of the technology for all parties involved.

For reasons of efficiency and economies of scale, greater savings should be attained if a significant fraction of major highways are electrified, rather than only a few portions.

Constraints related to Canadian climate

It is well known that low temperatures impact battery-powered vehicles. (Sharpe, 2019) for instance finds that Canada's extreme weather conditions in the winter would reduce the driving range of battery-powered trucks by 25% at –20 degrees Celsius (Sharpe, 2019). But the effect of Canadian winters on e-highway has not been studied, to our knowledge.

An interview with Patrik Akerman, Head of Business Development, Siemens eHighway, allowed us to explore the issue on a preliminary basis.[6] The feedback from pilot e-highway projects in Northern Europe (Sweden, Germany) seem to indicate that the system can withstand sudden heavy winds, cold temperatures, snow and ice accumulation under normal winter conditions. The electric current in the catenaries naturally heats the wires, thus melting ice and snow. The design of the cantilever arms has already been adjusted to prevent snow accumulation.

The ability of the e-highway to withstand ice storms remains untested as of now. The current design of poles would possibly need to be strengthened to support heavier loads caused by the sudden accumulation of ice. This would probably result in slightly higher construction costs.

Benefit of the technology for long haul freight

Existing literature views the e-highway technology as being a promising solution for the decarbonization of road freight transport. A conclusion regarding the relevance of the e-highway concept is that although theoretically feasible, technology development for some components of the technology is still in progress, warranting further research and testing (Stephan, 2020). However, given that the technology has been used in transit systems in the Canadian context, and is widespread in railways worldwide, there is also a precedent to draw data from.

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[6] Authors' interview with Patrik Akerman, Head of Business Development, Siemens eHighway, February 3rd, 2021.

E-highway offers some advantages over 100% battery-electric trucks. The technology is more efficient because it avoids energy losses when charging and discharging batteries. The reduced need for heavy batteries also means that catenary trucks are lighter, which allows increased payload, thereby increasing efficiency per load. With e-highway, there is no downtime for recharging the battery. And although making and building the infrastructure would be energy intensive, once installed, it could be used for decades - surviving many generations of battery-electric trucks (Amelang, 2021).

Such benefits, combined with GHG reduction potential and relatively low maintenance and repair costs, has made e-highway systems a potentially cost-effective option to decarbonize road freight. Cambridge University's Centre for Sustainable Road Freight concluded in a recent study that "overhead catenaries and compatible HGVs [heavy goods vehicles] are the most energy-efficient and cost-effective solution to fully decarbonize the UK's road freight network", and further added that "investments in pantograph electric vehicles would pay back the vehicle operators in 18 months (through lower energy costs) and the electrification infrastructure could pay back its investors in 15 years (through electricity sales)". Similarly, in a 2018 study, the Federation of German Industries recommend electrifying 4,000 - 8,000 km of Germany's 13,000-km autobahn network as "the most cost-efficient way to reduce greenhouse gas emissions", despite the necessary infrastructure investments (Gerbert, 2018).

Despite these promising opportunities, the large upfront investment in the overhead wire infrastructure does present a disadvantage. Like many other technologies, as long as the infrastructure is not in place, trucking operators won't invest in trucks equipped with the technology to use it. And if there are no trucks, no-one will invest in the infrastructure, creating a "chicken-and-egg problem" (Amelang, 2021).

Although the e-highway system is gaining traction with industry and governments, experts diverge when it comes to evaluating its future prospects. A key risk is that the window for large-scale deployment of electric highways could narrow as improvement in battery-electric trucks increases. This has led some experts to argue that "a rapid rollout of a large-scale test infrastructure will be decisive if catenary trucks are to remain in the technological race" (Amelang, 2021).

In conclusion, all studies looked at agree on the high potential of road electrification as a way to decarbonize freight transport. However, all are careful to raise concerns in regards to the challenges the implementation of this fairly new concept may face; from energy capacity constraints to investment requirements in infrastructure and need for further research, technology development and testing.

Model and methodology

Modeling approach

Our model allows the simulation of the e-highway technology on the A20-H401 corridor, in its widest possible extent i.e. from Rivière du Loup in Québec up to Windsor at the Ontario/U.S. border. It is based on cost-benefit model in Excel and relies on real truck flow data extracted from a Geographical Information System (GIS).

The entire extent of the route under study has been divided into segments, as illustrated in Table 2 below (see also Figure 4).

TABLE 2. HIGHWAY SEGMENTS OF THE A20-H401 CORRIDOR USED IN THE SIMULATION

	Highway segments	Distance (km)
1	Rivière du Loup - Quebec (without city areas)	167
2	Quebec City area	38
3	Quebec-Montreal (without city areas)	215
4	Montreal city area	72
5	Montreal - Prescott (without city area)	146
6	Prescott - Toronto (without city area)	288
7	Toronto city area	97
8	Toronto - Windsor (without city area)	321
Total A20-H401 corridor (including city areas)		*1,344*
Total A20-H401 corridor (excluding city areas)		**1,137**

Of the 8 segments, no. 2, 4, and 7, corresponding to city areas, have been excluded from the simulation for two reasons. First, the cost of constructing and maintaining the infrastructure is likely to be significantly higher, and more complicated to estimate, in densely built areas. Second, an important fraction of long-distance trips originate not from the cities themselves, but from logistics hubs on their peripheries. From a GHG emission perspective, the benefits of electrifying the highway in city areas is therefore probably smaller, and much more complex to estimate accurately.[7]

The simulator allows for specification of a scenario for the year of construction of each individual segment, as well as a scenario for the adoption of the technology by the trucking industry. The simulator calculates, for each year over a 30-year horizon, the costs and benefits of the technology as compared with a business-as-usual baseline where the traffic would remain entirely diesel-based. The simulator considers in particular:

- Capital and operating expenditure (CAPEX and OPEX)
- Fuel cost savings, as compared with diesel-only trucks
- Avoided GHG emissions, as compared with diesel-only trucks

These yearly figures are then used to determine key economic indicators and assess the relevance of the technology.

Again, the simulator does not account for financing costs, nor for taxes.

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[7] The electrification of truck traffic in urban areas would however bring significant advantages in terms of local air quality and public health.

Data sources and assumptions

Truck traffic

The simulation is based on the flows of heavy trucks (Class 8 and above / Vehicles weighing 15,000 kilograms or more) active on long-distance trips on the A20-H401 corridor. This specific information is not readily available from existing data sources and we therefore developed a specific methodology to arrive at an accurate estimate, as detailed in the next paragraphs.

The truck traffic information was obtained from the Ontario Ministry of Transportation (MTO), and the Quebec Ministry of Transportation (MTQ) through their open data portals. Both MTO and MTQ provide information on the average annual daily traffic (AADT), and the modal share of trucks on their respective highways.[8] Table 3 and Figure 4 below illustrate the heavy truck data we have gathered.

We have assumed that for each segment of our study, the truck AADT counts towards the middle of the segment, far from any major population center, would be representative of the long-haul trucks covering the entire length the particular segment. However, the truck AADT from both MTO and MTQ define heavy vehicles as vehicles transporting goods and people, and include vehicles above 4,500 kg in their truck AADT reporting. These are generally vehicles belonging to Class 3 and above, which includes light, medium and heavy trucks, and buses. To retain only Class 8 and above, we have turned to similar corridors in North America for which a more granular count of trucks is available.[9] We have found that, far from any major population center, the share of heavy trucks is relatively stable and varies between 66% and 80%. We have retained 75% for our study.

FIGURE 4. LONG DISTANCE HEAVY TRUCK VOLUME ON EACH SEGMENT OF THE STUDY CORRIDOR

Source: CPCS analysis based on data from the Ontario Ministry of Transportation (MTO) and the Quebec Ministry of Transportation (MTQ) through their open data portals. Numbers are rounded up for readability

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[8] MTQ provides AADT and truck modal share for different years. While the latest AADT information is from 2019, the truck percentage information was collected between 2016 and 2019. In such cases, we have assumed that the modal share of trucks remained constant over the period. In the case of Ontario, the most recent AADT are for 2016. To ensure consistency with the Quebec data,we have applied an annual growth rate of truck AADT of 1% , based on historical traffic data, to expand the truck AADT from 2016 to 2019.

[9] The Vancouver – Seattle – Portland corridor in the U.S. as well as the traffic flow between Alberta and British Columbia along Highway 1 in Canada.

TABLE 3. LONG DISTANCE HEAVY TRUCK VOLUME ON EACH SEGMENT OF THE STUDY CORRIDOR

Highway segments	Daily traffic of long distance heavy trucks (1-way)
1. Rivière du Loup - Quebec (without city areas)	1,392
2. Quebec city area	*excluded*
3. Quebec-Montreal (without city areas)	1,448
4. Montreal city area	*excluded*
5. Montreal - Prescott (without city area)	2,859
6. Prescott - Toronto (without city area)	3,207
7. Toronto city area	*excluded*
8. Toronto - Windsor (without city area)	3,477

Over the simulation horizon, truck traffic growth is assumed to be linear. Annual increments are equivalent to 1% of the traffic on year 1, reflecting the historic trend over the past five years.

Techno-economic parameters of the e-highway technology

The e-highway concept can be implemented under several configurations. For the purpose of the present study, we have considered hybrid diesel-electric trucks. The trucks have a dual diesel-electric drivetrain. They run on electricity whenever the catenary system is available, and switch to diesel on non-electrified roads. The trucks need to be fitted with a pantograph to connect to the overhead catenary, and are also equipped with a small-range buffer battery[10] to account for limited periods of disconnection on an otherwise electrified highway (e.g. when taking over) and for going short distances (5-20 km) away from the highway and back.

The catenary system that we have modeled is designed to accommodate the maximum traffic on the segment. It provides power to supply the trucks' engines and recharge their buffer batteries. In the configuration that we retained here, it does not allow on-the-go recharge of larger batteries. However, that option is also feasible from a technical perspective.[11] Table 4 below summarizes all the parameters used for the simulation.

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[10] Existing prototypes of diesel-electric catenary trucks, currently tested in Germany, have a 18 kWh battery (about 10 km of electric autonomy when not connected to the catenary). New prototypes, expected in 2021, will have a 74k Wh battery (about 40 km). (Sue, 2019)

[11] This requires more power and thus increases the infrastructure costs per km. But under this configuration, and provided that trucks have large enough batteries, only a fraction of the highway (possibly as lows as 30%) has to be electrified to provide the same electrical range.

TABLE 4. TECHNO-ECONOMIC PARAMETERS USED FOR THE SIMULATION OF E-HIGHWAY TECHNOLOGY ALONG THE STUDIED CORRIDOR IN EASTERN CANADA

Parameter	Value	Source / Justification
Overnight CAPEX of the infrastructure	3,600,000 CAD/km	Costs from the literature vary from 2.4 to 4.8 million CAD per km of highway, depending on the proposed configuration of the system (see table 1). We adopted a conservative estimate, corresponding to the e-highway configuration retained for the simulation, and considering that Canada's climatic condition may require strengthening the system, while economies of scale remain more limited than in Europe or the U.S.
OPEX of infrastructure	2% of CAPEX per annum	Our literature review did not provide much information on O&M costs. We have retained a number that is in line with typical O&M costs for electric infrastructure.
Extra capital cost per individual hybrid diesel catenary truck compared to conventional diesel truck	Decreasing from 70,000 CAD/truck in 2025 to 20,000 in 2040	This corresponds to the extra investment per truck, covering the pantograph, the electric drive train, and a buffer battery. The cost of the truck itself is excluded. Studies anticipate a downward trend for the cost of pantographs, and batteries as well.
Electricity consumption on e-highway	1.5 kWh/km	Value available in the literature range from 1.23 to 1.94. We have taken a median value, noting that the A20-H401 does not present any topographical challenge.
Carbon contents of electricity	QC: 1.2 g CO_2eq/kWh ON: 40 g CO_2eq/kWh	The carbon contents of Ontario's and Quebec's electricity is very low. Source: Natural Resources Canada's 2017 National Inventory Report
Cost of electricity	QC: 0.07 CAD/kWh ON: 0.14 CAD/kWh	See discussion below
Diesel consumption on highway	0.45 liters/km	Average of 5.25 mpg (Ontario) and 5.31 mpg (Quebec). Source: GEOTAB
Carbon contents of diesel	2.6 kgCO_2eq/l	Source: Natural Resources Canada's 2017 National Inventory Report
Cost of diesel	0.78 CAD/liter	Source: Natural Resources Canada, 17 Feb. 2021. Taxes are excluded (0.389 CAD/liter). The carbon tax is accounted for separately (see Carbon value).

Costs of electricity

The cost of supplying electricity to the catenary system is not known yet, and would depend on a variety of factors such as the load curve (whether the demand is flat, or comes with peaks), the exact distance from the existing grid, and the voltage level at which electricity would be delivered. This would require further study, in coordination with the grid operators in Quebec and Ontario. At this stage, we have retained the following numbers, based on electricity price statistics for large industrial customers: 0.07 CAD/kWh in Quebec, 0.14 CAD/kWh in Ontario (rounded up from NRCan statistics). We also note that the existing electric grid already runs close to the highway (see Figure 4), thus facilitating the supply of electricity to the e-highway infrastructure.

Carbon value

In the simulator, the value of avoided CO_2 emissions follows the federal government policy: starting from CAD 30 per tonne of CO_2 equivalent in 2021, it increases yearly to reach CAD 170 in 2030. It remains constant afterwards.

Simulation results and analysis

Economic viability of the technology under high adoption scenario

We first use the simulator to test the economic viability of the technology under unconstrained conditions of the deployment of the technology. In other word, if it were immediately and widely adopted by the trucking industry, would the benefits justify the heavy investment costs?

To answer this question, we simulate an "ideal" scenario under which the entire corridor is electrified at once, and 100% of the traffic of heavy trucks on long-distance trips switches to e-highway as soon as the infrastructure becomes available. We then measure the simple payback period, i.e. the number of years after which the savings (avoided diesel costs and avoided CO_2 emissions) entirely offset the initial investment costs of building the infrastructure and equipping trucks with a pantograph and an electric drivetrain. The simple payback period (see Table 5) is a basic, yet powerful indicator to determine whether the technology can be viable from an economic perspective.

TABLE 5. SIMPLE PAYBACK PERIOD, ASSUMING 100% OF THE HEAVY-TRUCK TRAFFIC USES E-HIGHWAY

Highway segments	Avoided GHG, in Mt CO_2eq per year	Simple payback period
1. Rivière du Loup - Quebec (without city areas)	0.3	12 yrs
3. Quebec-Montreal (without city areas)	0.3	11 yrs
5. Montreal - Prescott (without city area)	0.4	8 yrs
6. Prescott - Toronto (without city area)	1.0	8 yrs
8. Toronto - Windsor (without city area)	1.2	7 yrs
Total A20 - H401	**3.2**	**9 yrs**

When considering individual segments of the corridor, the payback period is shorter on segments 5, 6 and 8 i.e. from Montreal to the U.S. border. This is because heavy truck flows on these segments is significantly denser than on segments 1 and 3 i.e. from Rivière-du-Loup to Montreal.

The payback period for the entire corridor is 9 years. This means that if the technology were widely adopted, the initial investment costs would be fully compensated after 9 years, which is very reasonable for infrastructure of this scale. This initial simplified simulation relies on an unlikely scenario of 100% immediate adoption by the industry. It is however useful from a conceptual perspective as it shows that the high initial investment costs, under certain conditions, is totally justified.

Deployment scenario and adoption of the technology

We now simulate a more realistic scenario for the deployment of the catenary system and the progressive adoption of the technology by the trucking industry (see Figure 5 below). Our aim is to verify whether, under this scenario, the technology remains economically attractive.

FIGURE 5. DEPLOYMENT SCENARIO: PROGRESSIVE CONSTRUCTION OF E-HIGHWAY INFRASTRUCTURE ALONG THE A20-H401 CORRIDOR IN EASTERN CANADA

Source: CPCS, 2021

Under our scenario, the deployment starts on the South-West part of the route, where traffic is denser (see Figure 5). To avoid dealing with interjurisdictional issues at first, we start with segment 6 that is entirely located in Ontario, then proceed to segments 5 (Ontario – Quebec) and 8 (Ontario – U.S. border). We proceed in 5-year increments, to allow for reasonable construction time, resolution of interjurisdictional issues, and progressive adoption by the industry. The North-East part of the route, where traffic is lower, is the last to be electrified. Proceeding this way increases the economic rate of return for the less dense segments, as the rate of adoption of the technology on the rest of the corridor will already be reasonably high when the catenary system reaches them.

We assume that the number of hybrid trucks will be very limited at first, and increase at a slow pace, as illustrated by Figure 6 below. In the first year of operations, less than 450 trucks are assumed to have switched to the technology. This represents about 0.2% of Ontario's and Quebec's combined heavy truck fleet. We also assume that the adoption of the technology will eventually plateau at 80% of the heavy truck traffic on the corridor. These conservative assumptions are informed by actual data on the adoption of electric vehicles on various market segments.[12]

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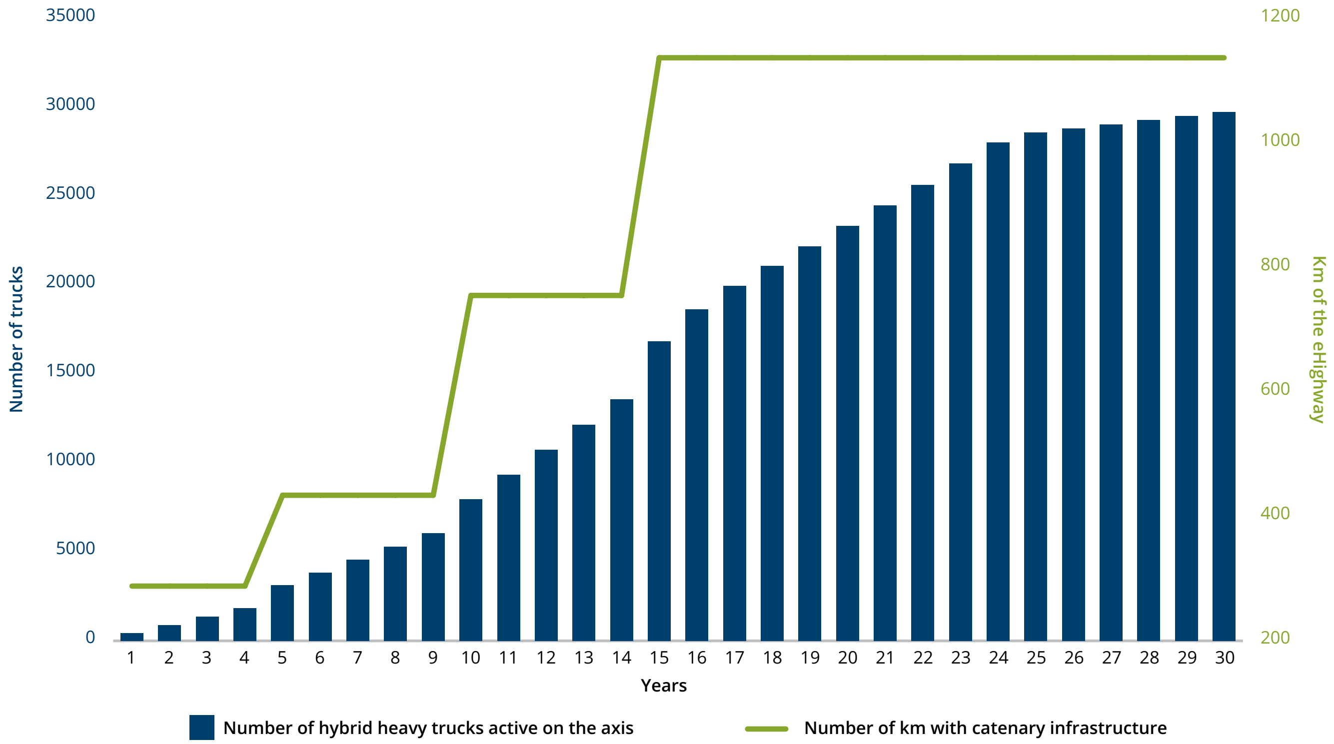
[12] For instance, "in the third quarter of 2020, 3.7% of total new vehicles registered in Canada were zero-emission vehicles" (StatCan, 2021). Electric vehicle adoption in Canada over all vehicle classes is expected to reach 14% by 2040 (Navius Research, 2020)

FIGURE 6. DEPLOYMENT SCENARIO: PROGRESSIVE ADOPTION OF THE TECHNOLOGY BY THE TRUCKING INDUSTRY



Source: CPCS, 2021.

The simple payback period would not be adequate here since the investment is done in stages. Instead, we use the economic internal rate of return (EIRR) as an indicator of economic viability. The EIRR is a measure of net benefits of a project, expressed as a percentage of the initial investment. It can be understood as the annual rate of return that will be generated by a project – in a way similar to an interest rate. Unlike a financial IRR which compares costs to project revenues, an economic rate of return compares costs to wider societal benefits (such as GHG emissions reduction), which are converted to dollar figures for the purpose of the analysis.

Annual savings on fuel costs, exclusive of taxes, reach CAD 360 million per year once the deployment is complete. The avoided GHG emissions reach 2.8 million tonnes of CO_2 equivalent: 0.6 million in Quebec and 2.2 million in Ontario. Valued at CAD 170 per ton after 2030, this represents CAD 470 million per year.

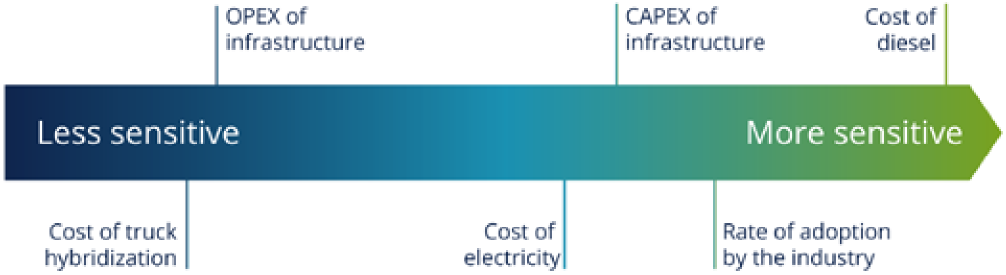
These annual benefits are to be compared to an initial investment of 4,100 million for the construction of the infrastructure, and 640 million for the hybridization of trucks.

Under this scenario, the economic rate of return of the infrastructure is 7%. It reaches 10% for the Segment 8 (Toronto to the U.S. border) that has the densest traffic. These figures can be compared with typical discount rates for public investment, to check whether the investment makes sense. Rates used by provincial and federal governments in Canada typically range between 3.5% and 8%. The e-highway can thus be considered economically viable.

Key factors influencing the viability

The simulator can also help us understand which factors have the biggest impact on the technology's viability, known as a sensitivity analysis. The following section provides a preliminary analysis on the most relevant techno-economic parameters used in the high-adoption scenario described in Section 4.1. Although further analysis would be required, preliminary results in Figure 7 show the range of influence of various parameters, from the cost of truck hybridization, which has the least influence of the viability of the technology to the price of diesel which has the most influence.

FIGURE 7. SENSITIVITY TO VARIATIONS OF TECHNO-ECONOMIC PARAMETERS OF THE E-HIGHWAY



Source CPCS, 2021.

Although the variations in the cost of hybridization have less impact on the overall viability, this parameter could be important for those considering truck purchase. This variable could weight into the decision to invest in a pantograph and start using the e-highway, in turn increasing the utilization rate of the infrastructure.

The preliminary analysis suggest that parameters that have a stronger influence on the economic viability of the e-highway technology are:

1. The initial investment cost required to build the catenary system;
2. The rate of adoption of the technology;
3. The cost of diesel and, to a lesser extent, of electricity.

As discussed in the literature review, there is some uncertainty on the investment costs, but this uncertainty is limited. Catenary systems have been in use for more than a century, in Canada and worldwide, so the technology can be seen as mature (with a TRL of 8 out of 9, see section 1.2). In addition, there are no major topographic or geographic challenges along the A20-H401 corridor that would cause significant cost increase. Questions remain, of course, around how local conditions will influence the cost as compared with international references. Strengthening may be required to withstand extreme climatic events in winter (see discussion in section 2) but the corresponding cost increase will probably not exceed five or ten percent.

The uncertainty around the adoption of the technology by the trucking industry is a bigger concern. In our simulation, the economic viability of the investment is directly related to assumptions on the rate at which trucks switch from diesel to e-highway. If the adoption rate is divided by two, the simple payback period more or less doubles.

The cost of diesel is the most influential parameter. Should the cost increase by + 50% , for example, the payback period (as calculated in section 4.1) would decrease substantially to 5 years instead of 9 years.

Discussion

Our simulation shows that, under a favorable yet achievable deployment scenario, the construction of an e-highway on the A20-H401 corridor could be a viable option for the decarbonization of heavy transport. For an initial investment of 4.7 billion CAD covering the construction of the infrastructure and the hybridization of trucks, annual economic benefits (savings on fuel and avoided GHG emissions) could reach 0.8 billion CAD per year once the deployment is complete. The switch from diesel to electricity reduces yearly GHG emissions by 2.8 million tonnes of CO_2 equivalent.

The simulator shows that the economic viability of this e-highway is mostly sensitive to energy prices, to the initial construction cost, and to the rate of adoption by the trucking industry. Uncertainty on construction costs remain rather limited since the catenary technology, in use for railways for decades, is mature. On the other hand, uncertainties on the adoption rate are high, because e-highways have not yet been deployed on a commercial basis. Beyond the attractiveness of the potential fuels savings and avoided GHG emissions and carbon cost, the question remains of whether this technology can fully accommodate the operational constraints and needs of the heavy truck industry. It will also be important to confirm our assumptions that the electrification of one main corridor (but not of secondary road axes) is indeed a workable option for the industry. Could the existence of an e-highway contribute to modifying the behavior of market players, with some trucking companies offering a shuttle service between the start and end of the catenary, and others taking goods further from those points? Future research on e-highway potential in Canada should seek to obtain a better understanding of the preferences of the industry, and how the e-highway can be deployed to accommodate these preferences. This research would also be useful to inform the design of possible support policies aimed at encouraging the adoption of the technology.

Our study focuses on overall economic benefits, but does not address the crucial question of how these benefits could be shared between trucking companies, infrastructure provider(s), and the community at large. Also, issues related to the financing structure and financing costs have not been taken into account. Future studies are needed to explore these questions, and examine how benefit sharing allocations will impact industry players' appetite for the technology. Other feasibility considerations, including potential overhead clearance issues, would also need to be explored.

Another avenue for future research would be to simulate other configurations of the e-highway. For the purpose of the present study, we have considered hybrid diesel-electric trucks running on electricity whenever the catenary system is available, and switching to diesel on non-electrified roads. Under this configuration, the entire length of the road (except for urban areas) has to be electrified. Other scenarios could look at alternative switching systems to biofuels instead of diesel, or integrating e-highways with improved intermodal freight logistics (e.g., rail). Another interesting configuration would be to design the catenary for the on-the-go recharge of battery-powered trucks. This requires a stronger, more expensive catenary system, but shorter stretches of the road need to be electrified as trucks run on battery in between. The investment per truck is higher (long range batteries remain significantly costlier than pantographs), but the initial cost to deploy the e-highway is reduced, thus reducing the risks associated with large infrastructure investment.

Finally, it would also be interesting to look at other highways feeding in on this backbone and evaluate both its potential impact of adoption of the technology, costs and GHG emission reduction.

This simulation is the first step in a study proposal developed by the Chair in Energy Sector Management, HEC Montréal and CPCS, in collaboration with government, university and private partners, to compare the costs and potential of different decarbonization technologies along the A20-H401 axis (Whitmore, Gignac, 2020). To that end, the methodology and results of the e-highway simulation will be used to improve the simulator with regards to the presentation of truck flows, which was held constant at 2019 value in the present simulation. We will also seek to obtain further data on the flows of heavy trucks and refine our methodology to determine these flows.

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