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1 **EEIO efficiently sketches science-based environmental transition plans: illustration by**

2 **Canada's road industry**

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9

10 **ABSTRACT**

11 Industries struggle to build robust environmental transition plans as they lack the tools to quantify their  
12 ecological responsibility over their value chain. Companies mostly turn to sole greenhouse gas (GHG) emissions  
13 reporting or time-intensive Life Cycle Assessment (LCA), while Environmentally-Extended Input-Output  
14 (EEIO) is more efficient on a wider scale. In this article, we illustrate EEIO's efficiency while assessing the  
15 impacts of Canada's road industry. OpenIO-Canada, a new EEIO database developed for Canada, coupled with  
16 the IMPACT World+ impact assessment method, provides a multicriteria environmental diagnosis of Canada's  
17 economy. The construction sector carries the second-highest environmental impacts of Canadian people (10 to  
18 31% of the impact depending on the indicator) after the manufacturing industry (20-54%). The road industry  
19 generates a limited impact (0.5-1.8%), and emits 1.0% of Canadians' GHGs, mainly due to asphalt mix  
20 materials purchases (28%), bridges and engineering structures materials (24%), and direct emissions (17%). The  
21 industry must reduce the environmental burden from material purchases - above all concrete and asphalt  
22 products - through green buying plans and eco-design and invest in new machinery powered with cleaner  
23 energies such as low-carbon electricity. EEIO also captures impacts often neglected in process-based pavement  
24 LCAs - amortization of capital goods (machinery, buildings, infrastructure), staff consumptions, and services –  
25 and shows their substantial impact: from 15% on marine eutrophication to 73% on freshwater eutrophication.  
26 Yet, pavement construction and maintenance only explain 5% of the life cycle carbon footprint of Canada's road  
27 network. The roads' use stage emits 95% of the life cycle GHGs. Vehicle tailpipes release 72% of the GHG  
28 emissions while manufacturing vehicles bring the 23% left. Thereby, a carbon-neutral pathway for the road

1 industry must firstly focus on reducing vehicle consumption and wear through better design and maintenance of  
2 roads.

3 **Keywords:** industry; environmental transition plan; Environmentally-Extended Input-Output;  
4 road sector; multicriteria assessment; key drivers; greenhouse gas emissions.

## 5 **1 Introduction and background**

6 The rise of environmental threats calls for a drastically hurried industrial environmental  
7 transition. Building an efficient action plan at the industry level requires a deep multicriteria  
8 understanding of environmental life-cycle impacts to determine the most effective levers. But  
9 the tools and data to reach sufficient knowledge seem unsatisfying for the industry.  
10 First, the compilation of sectoral national greenhouse gas (GHG) inventories can be an  
11 interesting source of data to understand the carbon structure of an economy and its industry.  
12 Nevertheless, they are not suitable for industries as they only consider the emissions of  
13 production taking place on the territory - an approach known as "production-based" or  
14 "territorial" (Caro et al., 2014). Territorial approaches tend to push governments to shift the  
15 emissions outside the country by relocating polluting practices (Peters and Hertwich, 2008)  
16 or by importing the most carbon-intensive products, which can lead to increases in the global  
17 emission levels of GHGs and degrade the national economy (Rieber and Tran, 2008).  
18 Therefore, the territorial approach should not be the optimal method for managing a global  
19 transition. Conversely, national "consumption-based" environmental assessments – i.e.  
20 accounting for the impact from cradle-to-consumer, disregarding the production location -  
21 remain limited (Harris et al., 2020), even though they seem particularly suitable to orientate  
22 sustainable purchases and productions accounting for the entire supply chain.

1 Given the methodological choices made for national accountings, industrial sectors and  
2 companies, therefore, face three important challenges to determine their impact on the  
3 environment. First, because national inventories follow the territorial approach, companies do  
4 not have easy access to data on their indirect emissions - called "scope 3" assessment  
5 according to the GHG protocol (World Business Council for Sustainable Development and  
6 World Resources Institute, 2004) - as most of these indirect emissions occur beyond the  
7 borders of one single territory. Yet, the assessment of the so-called scope 3 is crucial to  
8 implementing comprehensive impact reduction procedures, such as green purchasing policies  
9 and environmental research and development (R&D) plans. For instance, in pavement  
10 construction, bitumen constitutes a major environmental contribution (de Bortoli, 2020)  
11 although it falls within scope 3. Second, the governmental services responsible for national  
12 GHG inventories often perform aggregations of the emissions by broad categories before  
13 releasing environmental information (Government of Canada, 2021a). This further hinders  
14 the potential use of this data by companies. Indeed, data is too aggregated to allow specific  
15 industrial sectors to access a representative footprint of their activities. As an example, to our  
16 knowledge, the road construction sector is not considered as such in national inventories, and  
17 even less the more specific sectors of materials it produces or consumes (i.e. aggregates,  
18 cement, binders, etc.). Third, national inventories only provide a footprint. It does not  
19 describe intersectoral links which would allow companies to identify the main sources of  
20 impact in their supply chain.

21 While national inventories are mostly focused on GHG emissions, as well as water and  
22 energy use, some countries also register other pollutant emissions by economic sector, such  
23 as the US EPA through its Chemical Data Reporting (US EPA, 2011), or the French CITEPA  
24 (CITEPA, 2021). However, these environmental matrices only report flows, i.e. masses of  
25 substances emitted which need further analyses before being usable by companies, to

1 determine what the environmental impact of these pollutants is. These flows thus need to be  
2 transformed from emissions to impacts, through characterization factors that model fate,  
3 exposure, and effect of these pollutants in the natural environment.

4 Two environmental quantification methods overcome the limitations previously raised: Life  
5 Cycle Assessment (LCA) and Environmentally Extended Input-Output (EEIO). Both carry  
6 out multi-criteria appraisals adapted to industry transition plans, from cradle-to-gate, i.e. from  
7 the extraction of materials to the products leaving the factory. However, using LCA to  
8 analyze the environmental impact of a sector at the national level requires a massive amount  
9 of data. The intensive time consumption of data collection is one of the main obstacles to the  
10 large-scale use of LCA. Moreover, the lack of digitization in certain sectors such as  
11 construction can hinder access to the required data. On the other hand, EEIO allows for such  
12 large-scale analyses, and databases to perform them become more numerous (Agez, 2021;  
13 Stadler et al., 2018; Yang et al., 2017; Andrew and Peters, 2013; Lenzen et al., 2013).

14 EEIO is already used within academia to quantify the environmental contributors to national  
15 economic sectors with a consumption-based approach. However, EEIO applications either  
16 focus on the consumption of final demand sectors (e.g. households, government) (Castellani  
17 et al., 2019; Cellura et al., 2011), or the impact of a whole economy without going into  
18 intersectoral details (Dawkins et al., 2019; Moran et al., 2018; Xia et al., 2022). Regarding  
19 applications to specific industrial sectors, the literature has so far mainly focused on food  
20 (Reutter et al., 2017) or tourism (Sun et al., 2020). But to our knowledge, there is no  
21 application in the road industry, only one EEIO analysis focusing on the GHG emissions  
22 from the entire construction sector in Ireland (Acquaye and Duffy, 2010).

23 EEIO is therefore a powerful decision support tool but is often overlooked outside of  
24 academia. It could be used more widely to allow industries to build environmental transition  
25 plans by identifying major environmental contributors, selecting relevant sets of

1 environmental indicators to monitor, prioritizing R&D topics, building green purchasing  
2 policies, and identifying major improvement levers for production sites.

3 The overall objective of this article is to illustrate the possible uses of EEIO to build  
4 environmental transition plans for industries on a national scale. This illustration will be  
5 based on the example of the road industry in Canada. We will first present the EEIO method  
6 and the database used for the Canadian context (section 2), before detailing the calculations  
7 that will be carried out (section 3) to obtain our results (section 4): a cross-sectoral vision of  
8 Canada's environmental impacts and the contribution of construction, then an intra-sector  
9 environmental picture of the road industry highlighting direct transition levers, and finally an  
10 overview of its impact by scope to give a perspective on these levers. The results will finally  
11 be discussed to lead to some recommendations to decision-makers before detailing the  
12 benefits and limits of using EEIO instead of LCA on such a large scale (section 5).

## 13 **2 Method and material**

### 14 ***2.1 The EEIO method***

15 EEIO is a method that links monetary transactions to environmental consumptions or  
16 releases. Data (both economic and environmental) are obtained and compiled by national  
17 statistics agencies, often through surveys sent to companies. Academics then integrate this  
18 data to form tables that can be readily used to estimate emissions and impacts on the  
19 environment. This quantification accounts for the whole life cycle of products. Hence, it  
20 includes scopes 1 and 2, as well as upstream scope 3. Although generally focused on the  
21 climate change issue, it can cover a large range of pollutants (i.e., 35 pollutants in the  
22 EXIOBASE EEIO database (Stadler et al., 2018)) and thus can be used to study other  
23 environmental issues, such as acidification or eutrophication.

1 Impacts on the environment linked to a given final demand are determined using the  
2 following equation:

$$\mathbf{q} = \mathbf{C} \cdot \mathbf{B} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{y} \quad (3)$$

3 Where vector  $\mathbf{q}$  presents the different potential impacts on the environment,  $\mathbf{C}$  is a matrix  
4 regrouping characterization factors translating emissions to potential impacts on the  
5 environment, matrix  $\mathbf{B}$  regroups the environmental extensions linking estimated  
6 consumptions and/or emissions for 1\$ of each category of product,  $\mathbf{I}$  is the identity matrix,  $\mathbf{A}$   
7 is the technology matrix describing the normalized monetary exchange between sectors of the  
8 economy, and vector  $\mathbf{y}$  being the final demand.

## 9 *2.2 Sources of Canadian data*

10 OpenIO-Canada is the EEIO database used in this article (Agez, 2021). It is the first open-  
11 source EEIO database developed for Canada. The database represents the whole Canadian  
12 economy while providing details at the provincial level, for years from 2014 to 2017. Hence,  
13 the model includes economic exchanges between the different provinces as well as specific  
14 polluting emissions for each economic sector of each province. The economic data of  
15 openIO-Canada comes from the Supply and Use tables provided by Statistics Canada  
16 (StatCan) (Statistics Canada, n.d.), using a classification breaking down each province's  
17 economy in 492 commodities. GHG emissions and water use data are derived from the  
18 physical flow accounts of StatCan, while all other pollutants come from the National  
19 Pollutant Release Inventory (NPRI) (Government of Canada, 2021b).

# 3 Calculations

## 3.1 Overview

**Erreur ! Source du renvoi introuvable.** gives an overview of the calculation process used to understand the sources of the environmental impacts of Canada and its road sector in 2017, based on the latest data made available by the Canadian Government. A consumption-based approach is adopted throughout this paper, i.e., impacts stemming from international exports are excluded while international imports, local production, and consumption are included.

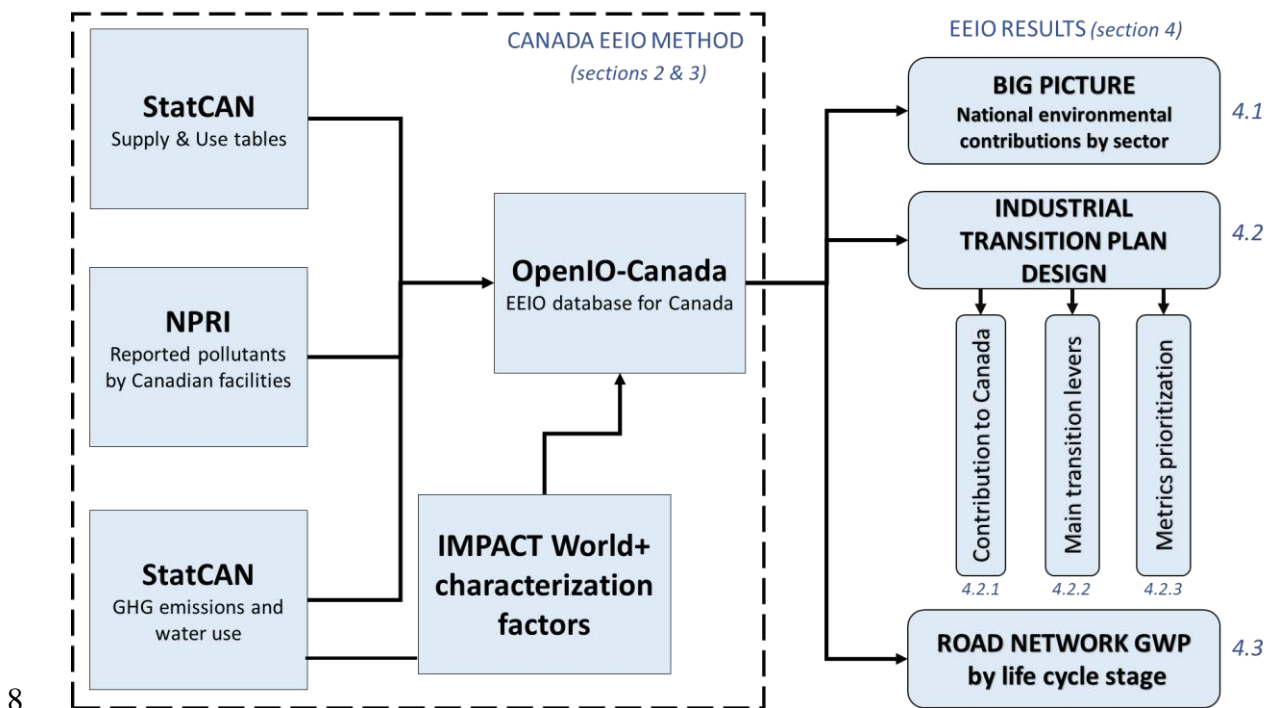


Figure 1 Illustration of the calculation method framework and presented results

## 3.2 Characterization method and indicators

The life cycle impact assessment method IMPACT World+ (IW+) v1.30/1.48 was selected as it was deemed the most scientifically up-to-date and relevant method for Canada (Bulle et al., 2019). Both midpoint and endpoint indicators were calculated. At the midpoint level, indicators calculated were short-term climate change (also called Global Warming Potential



1 (GWP)), freshwater acidification, eutrophication and ecotoxicity, marine eutrophication,  
2 ozone layer depletion, particulate matter (PM) formation, photochemical oxidant formation,  
3 terrestrial acidification, carcinogenic and non-carcinogenic human toxicity resp. “cancer” and  
4 “non-cancer”). As for the endpoint indicators, the damage to ecosystem quality and human  
5 health are considered. Both the long- and short-term effects of climate change on these  
6 damages are considered in IW+. Due to the lack of available national data, some IW+  
7 indicators were not considered, such as ionizing radiations, resources (mineral and fossil),  
8 land transformation and occupation, as well as water scarcity. Nevertheless, an indicator of  
9 water use was calculated, using the data reported by Statistics Canada (n.d.).

### 10 **3.3 *Aggregation of sectors by category***

11 This study relied on the “Detailed level” of openIO-Canada which describes the Canadian  
12 economy in 492 sectors. An additional category for direct emissions from final demands  
13 (e.g., coming from the use of personal vehicles by households) is also included. However, a  
14 492-sectors classification being too much for a meaningful interpretation, contributions were  
15 aggregated. This aggregation was deemed necessary to make the results readable and usable  
16 for the orientation of road industry environmental transition plans, and it was made based on  
17 industrial road expertise. The aggregation work was incremental, and the different  
18 aggregations tested are reported in the SM. Disaggregated results (i.e., with the 492 sectors  
19 detail) are also available in SM.

## 1 **4 Results and interpretation**

### 2 **4.1 Canada's environmental impacts**

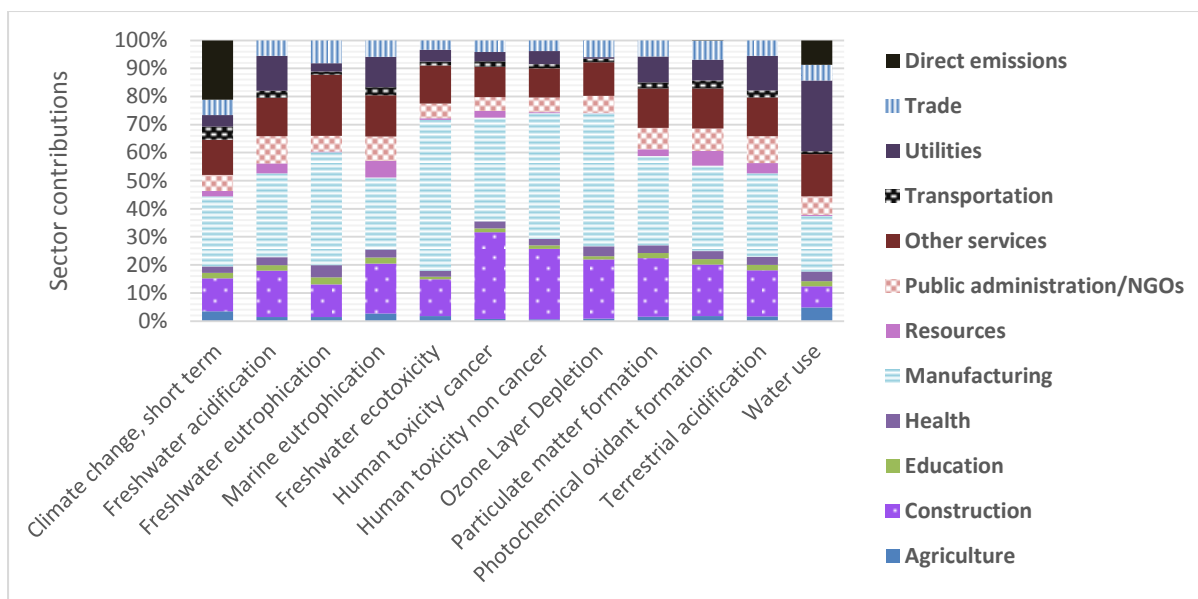
#### 3 *4.1.1 Environmental footprint contributions*

4 Our analysis first focused on the diagnosis of the Canadian economy as a whole to get an  
5 overview of the environmental impact contributors in Canada and the environmental footprint  
6 of Canada and Canadians on a consumption-based approach. In 2017, Canada's consumption  
7 was responsible for the release of 692 million tons of CO<sub>2</sub>eq (MtCO<sub>2</sub>eq). Considering a  
8 population of 38.4 million inhabitants (Statistics Canada, 2021), the average Canadian emits  
9 around 18.0 tCO<sub>2</sub>eq-GWT100 per year and 16.6 tCO<sub>2</sub>eq-GTP100/year. This is consistent  
10 with the values published by Friedlingstein et al. who reported a 15.66 tCO<sub>2</sub>eq/capita carbon  
11 footprint in Canada in 2017 (Global Carbon Project, 2020) and EXIOBASE which leads to  
12 17tCO<sub>2</sub>eq/capita.

13 Figure 2 shows the contribution of the aggregated 12 sectors of the Canadian economy on 11  
14 impact categories of the IW+ LCIA method, as well as a "Water use" indicator.

15 It shows that the manufacturing sector is by far the most important contributor to the  
16 environmental impact of Canadians' consumption on all midpoint impact categories. It goes  
17 from a minimum of 20% of the total water use to 54% of the impact on freshwater  
18 ecotoxicity, and accounts for a quarter of the impact of Canada on climate change. The  
19 construction sector is then globally the second most important contributor with contributions  
20 higher than 10% of the total (excluding on water use) and reaching up to 31% of the total on  
21 carcinogenic human toxicity. 12% of Canadians' impact on climate change is due to the  
22 construction sector, 41% of it being due to residential buildings. Services other than public  
23 administration and Non-Governmental Organizations (NGOs) are then globally ranked the

1 third biggest contributor to the midpoint impacts, with a top contribution on water  
2 eutrophication (22%). Trade, as well as public administration and NGOs services, are two  
3 sectors that are visible contributors, explaining each 5 to 10% of the Canadians' impacts.  
4 Direct emissions related to Canadian consumption show negligible contributions apart from  
5 the climate change impact and the water use where it carries respectively 23 et 9% of the total  
6 impact. Direct GHG emissions of the Canadians' consumption represent 3.81tCO<sub>2e</sub>/capita.  
7 As the direct emissions of Canadian households covered only come from GHGs emissions  
8 and water consumption, it is within expectations that it only contributes to these two impact  
9 categories. Utilities present limited contributions (<5%) excluding on freshwater acidification  
10 (13%), marine eutrophication (11%), PM formation (9%), terrestrial acidification (12%) and  
11 water use (9%). Finally, agriculture, education, health, resources, and transportation sectors  
12 have low contributions, generally from 0 to 5%. Let's note that "Trade" covers wholesale,  
13 retail, and warehousing activities, while "Agriculture" accounts for agriculture, forestry,  
14 fishing, and hunting activities, and "Resources" encompass oil, gas, and mining.  
15 Transportation is a low contributor, including on GWP, because it only accounts for freight  
16 and public transportation directly bought by households. Indeed, household private  
17 transportation is encompassed within direct emissions. Besides, freight is not highly  
18 consumed by households and public transportation is rather low-emission. Finally, all other  
19 forms of transportation are included in the sector that buys them. For instance, impacts from  
20 freight services purchased by the construction sector are included in the environmental  
21 impact of this sector.

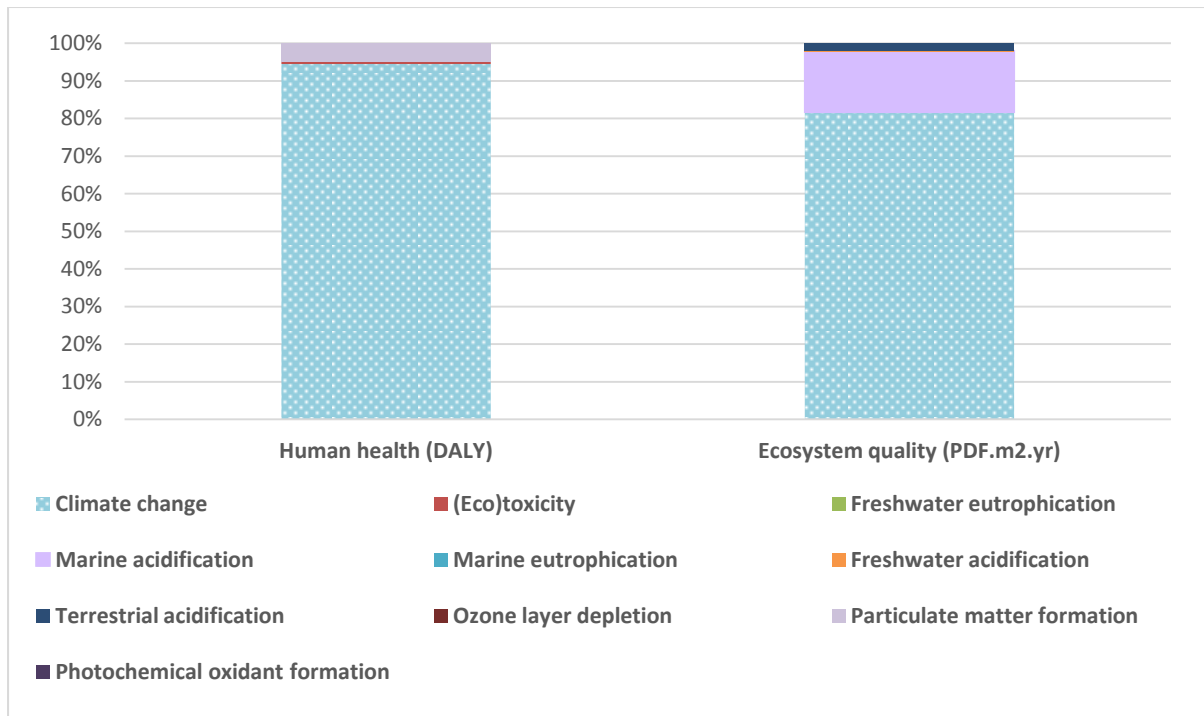


1

2 **Figure 2 Contributions of industrial sectors to the different IW+ environmental impacts of Canada at the**  
 3 **midpoint level, consumption-based approach**

4 *4.1.2 Most important environmental issues*

5 Based on the IW+ methodology, climate change – cumulating long- and short-term effects –  
 6 is by far the most important midpoint contributor to the two damages: it brings respectively  
 7 95 and 82% of the human health and ecosystem quality damage (Figure 3). The rest of the  
 8 human health damage is mainly brought by PM formation due to electricity consumption,  
 9 while the ecosystem quality is otherwise mostly damaged by marine acidification, generated  
 10 at 98% by CO<sub>2</sub> solubilization.



1

2 **Figure 3 Contributions of the different IW+ environmental impacts of Canada at the endpoint level,**  
 3 **consumption-based approach**

4 ***4.2 Environmental transition plan for the road industry in Canada***

5 In this section, we want to answer two main questions: what the contribution of the road  
 6 industry to the national environmental impacts of Canadians is (section 4.2.1), what the main  
 7 potential levers to the environmental transition plan of the road industry are (section 4.2.2),  
 8 and how to reduce the multicriteria dimension of green purchase strategies for decision-  
 9 makers by prioritizing metrics (4.2.3).

10 ***4.2.1 National burden from the road industry***

11 Table 1 shows the contribution of the road sector to the total impact of Canada. It presents  
 12 contributions within 0.54% on water use to 1.80% on particulate matter formation. In the  
 13 climate change impact category, it accounts for 1.02%, which represents only 10% of the

1 GHG emissions from the construction sector. It is also responsible respectively for 1.07 and  
 2 1.10% of the damage to ecosystems and human health.

3

4

**Table 1 Contribution of the road sector to the total impact of Canada**

INDICATOR	CONTRIBUTION
ECOSYSTEM QUALITY	1.07%
HUMAN HEALTH	1.10%
CLIMATE CHANGE, SHORT TERM	1.02%
FRESHWATER ACIDIFICATION	1.52%
FRESHWATER EUTROPHICATION	0.68%
MARINE EUTROPHICATION	1.64%
FRESHWATER ECOTOXICITY	0.68%
HUMAN TOXICITY, CANCER	1.28%
HUMAN TOXICITY, NON-CANCER	1.67%
OZONE LAYER DEPLETION	0.78%
PARTICULATE MATTER FORMATION	1.80%
PHOTOCHEMICAL OXIDANT FORMATION	1.43%
TERRESTRIAL ACIDIFICATION	1.51%
WATER USE	0.54%

5

6 *4.2.2 Main potential levers for the transition*

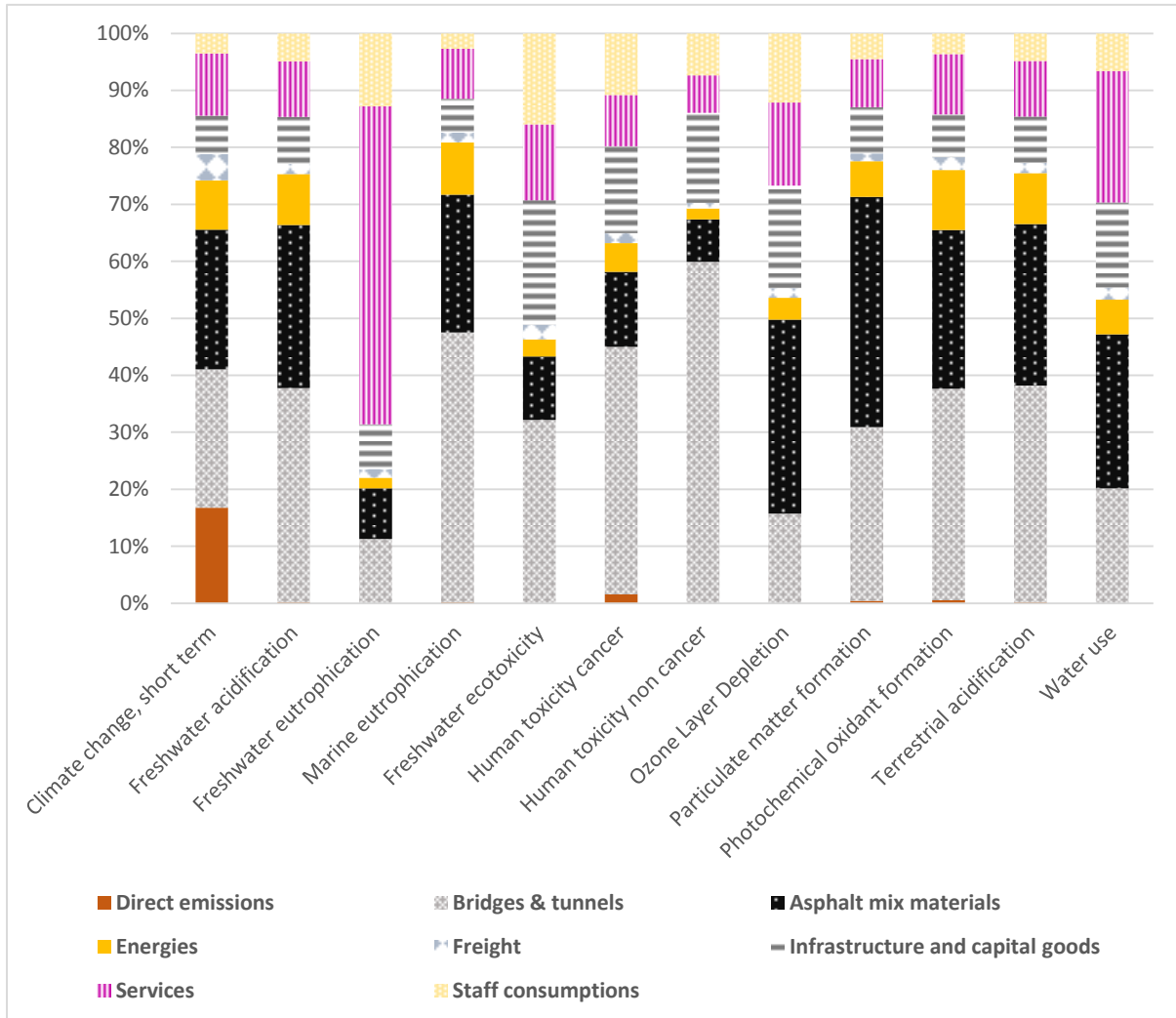
7 **Midpoint contribution analysis**

8 Figure 4 offers a first overview of the drivers of the environmental burdens generated by the  
 9 road industry. We created categories based on road industry expertise to aggregate the 492  
 10 sectors of openIO-Canada. The results illustrate how direct emissions are a low contributor to  
 11 the cradle-to-gate impacts of the road industry, except for climate change where they  
 12 represent 17% of the total impact. These low contributions might be due to a low number of  
 13 road industry facilities reporting to NPRI.

1 The results also highlight that the category “bridges & tunnels” – a category including  
2 purchases of concrete, cement, steel, and aluminum – weighs heavily (from 11 to 60%) on  
3 most of the environmental impacts of the road industry. Asphalt mixture materials purchases  
4 - in which we included the purchases in asphalt products, asphalt binders, aggregates, and  
5 other minerals as well as chemicals – highly affect 2/3 of the impact categories, particularly  
6 climate change (25%), freshwater acidification (29%), marine eutrophication (24%), ozone  
7 layer depletion (34%), PM formation (40%), photochemical oxidant formation (28%), and  
8 terrestrial acidification (28%). Energy purchases – including electricity, natural gas, and other  
9 fuels – account for 2% to 11% of the impacts (resp. for freshwater eutrophication and smog).  
10 On climate change, fuel purchase accounts for 9% of the impact and direct emissions for  
11 17%, meaning a upstream scope 3 accounting for 32% of the climate change impact from  
12 energies, a higher contribution than the 10 to 15% usually highlighted in European databases  
13 (e.g. ADEME, 2019), probably due to the major supply from Canadian oil sands, known for  
14 their higher extraction and transformation impact (Charpentier et al., 2011; Chen et al., 2019;  
15 Masnadi et al., 2018). Infrastructure and capital goods – covering the maintenance/repairs of  
16 machinery, buildings, and infrastructure, as well as other metals than steel, plastic, and rubber  
17 – mainly have a significant impact (>10%) on freshwater ecotoxicity, human cancer, and  
18 non-cancer toxicities, ozone layer depletion and water use where they represent respectively  
19 22, 15, 16, 18 and 15% of the contributions. Services – encompassing intragroup and external  
20 services as well as upstream sales –, have a prevalent role on the impact of freshwater  
21 eutrophication where they represent 56% of the impact. On other environmental indicators  
22 they contribute by 7 to 23%, thus being one the major contributors across all environmental  
23 indicators. Staff consumption – combining paper and paperboard purchases, other goods  
24 purchases, and staff transportation only has a significant impact (>10%) on freshwater  
25 eutrophication, freshwater ecotoxicity, human cancer and ozone layer depletion. Finally,

1 freight services have negligible impacts except on climate change where they bring 5% of the  
 2 emissions.

3



4

5 **Figure 4 Contribution of different activities to the different IW+ environmental impacts of the road**  
 6 **industry at the midpoint level – overview**

7 **Midpoint contribution details**

8 Figure 5 shows the contributions of direct emissions and purchases of the road industry to the  
 9 different IW+ environmental impacts at the midpoint level. The figure illustrates the  
 10 significant number of different factors to account for in the road industry when adopting a  
 11 multicriteria approach. For instance, 3 different contributors need to be added together to



1 represent two-thirds of the climate change impact (53%). These three contributors are the  
2 asphalt products (18%), the concrete (18%) and the direct emissions (17%). The other 20  
3 sectors account for the rest of the impact (47%).

4 Asphalt (e.g. bitumen) and asphalt products as well as concrete are also major contributors to  
5 the impact of the road industry across multiple other impact categories: freshwater  
6 acidification (27 and 24%), carcinogenic human toxicity (8 and 21%), non-carcinogenic  
7 human toxicity (4 and 35%), marine eutrophication (17 and 39%), PM formation (19 and  
8 20%), photochemical oxidant formation (21 and 29%), terrestrial acidification (23 and 28%)  
9 and water use (15 and 10%). While asphalt products account for binders and asphalt mixtures  
10 purchases (i.e. asphalt binder and aggregate production as well as asphalt mixing and  
11 products' transportation on the upstream life cycle of these products) related to pavement and  
12 sidewalks construction, concrete mainly connects to the construction of bridges, tunnels, and  
13 other structures (e.g. sidewalks and rare concrete pavements). We can conclude from Figures  
14 4 and 5 that asphalt and asphalt products impacts must mainly be due to bitumen and asphalt  
15 mixing operations (e.g. burnt fuels).

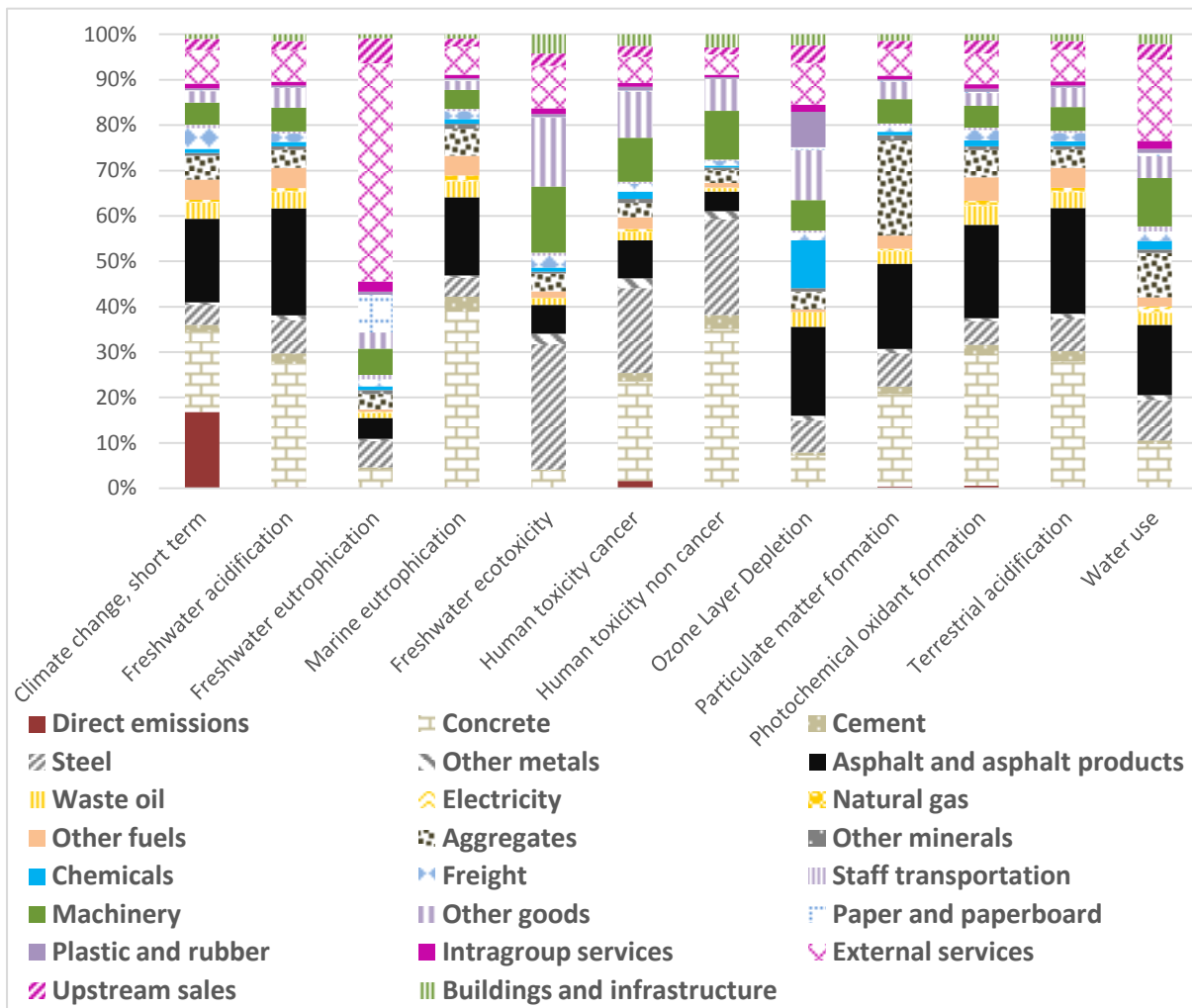
16 Paper and paperboard purchases appear to be a negligible contributor except on freshwater  
17 eutrophication (8%, Figure 5). While reducing paper consumption in companies is often  
18 promoted as an important environmental action, it appears insignificant for the road industry  
19 outside of freshwater eutrophication issues. Moreover, the crushing contribution of services  
20 on freshwater eutrophication (Figure 4) is brought by the purchase of external services, that  
21 accounts for 48% of the impact (Figure 5). Within the different external services bought,  
22 "Architectural, engineering and related services" and "Management, scientific and technical  
23 consulting services" contribute the most.

1 Steel purchases, machinery maintenance/repairs and other goods purchases (mainly wires and  
2 lighting fixtures) all significantly impact freshwater ecotoxicity and both toxicities (cancer  
3 and non-cancer).

4 Energy purchases by the road industry in Canada account around 10% of the contributions –  
5 summing natural gas, waste oil and other fuels. We note a negligible contribution from  
6 natural gas, while waste oil and other fuels – specifically heavy fuel oil – globally account for  
7 similar impacts. Waste oil does not appear particularly problematic on indicators accounting  
8 for the release of toxic substances such as human toxicities or ecotoxicity, while we know  
9 they constitute a serious risk (Government of Canada, 2018). This is probably because mostly  
10 small companies produce it, and that these small companies do not have to report to the  
11 NPRI. The direct emissions triggered by the combustion of fuels from production tools,  
12 machinery and company fleets, contribute specifically to climate change (17%) as specified  
13 previously.

14 Aggregates are particularly impacting on PM emissions (21%), despite the use of specific  
15 techniques to reduce dust, such as water spraying in some quarries especially close to densely  
16 populated areas.

17 Finally, concrete is an overall much higher contributor to the impacts than cement. It  
18 indicates that the industry mainly purchases concrete mixtures instead of manufacturing its  
19 own, as cement is the most carbon-intensive component of concrete. The cement bought is  
20 partly used in own-made concrete, and partly used to stabilize soils in pavement foundations.



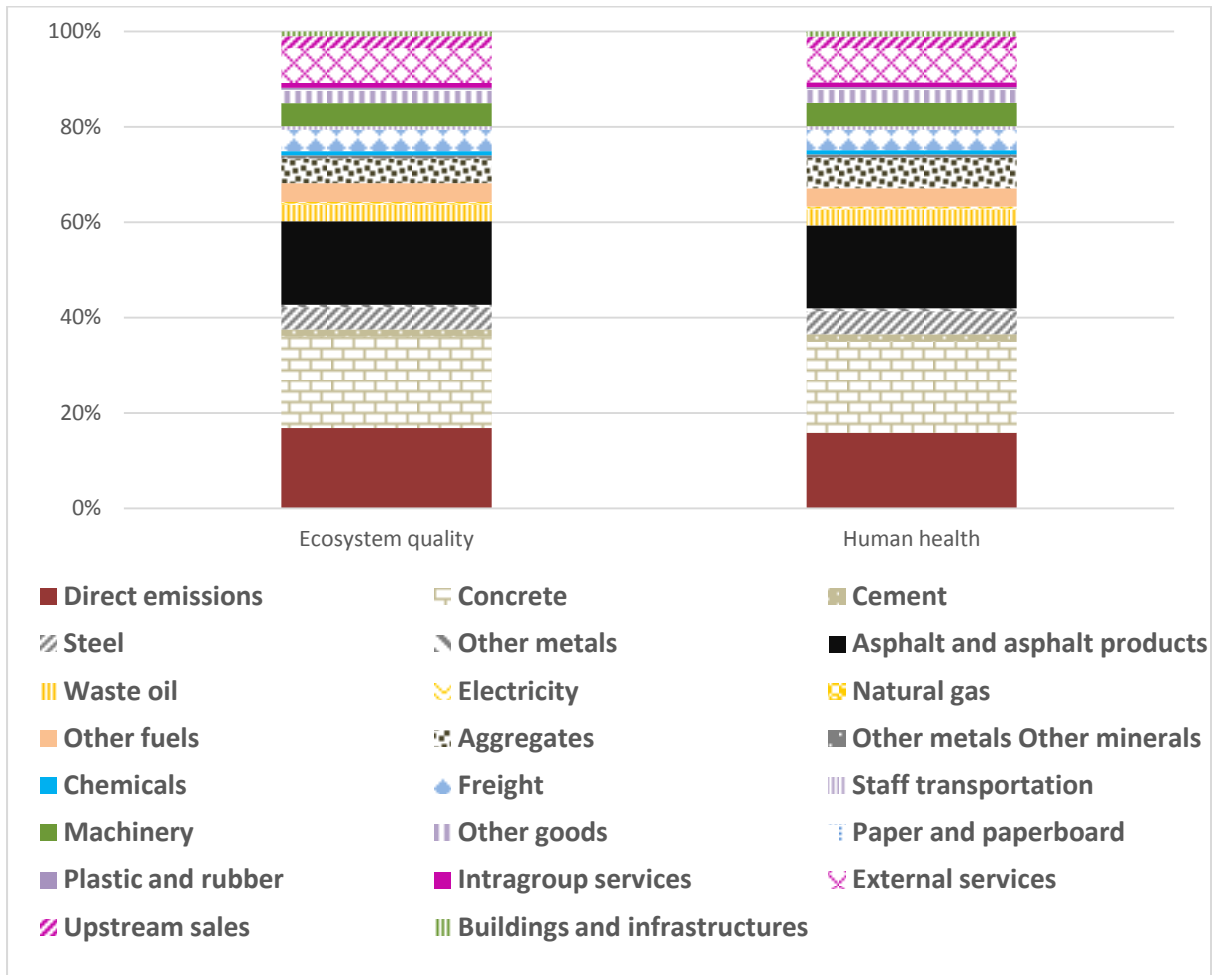
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3 **Figure 5 Contributions of different activities to the different IW+ environmental impacts of the pavement**  
 4 **industry at the midpoint level**

5 **Damage drivers**

6 Figure 6 shows the contribution of direct emissions and purchases by category of Canada's  
 7 road industry for endpoint indicators. The main contributors are almost identical between the  
 8 two kinds of damage. Contributors exceeding 5% are, by decreasing contribution: concrete  
 9 (19% on EQ and HH), asphalt products purchases (18% on EQ and 17% on HH), direct  
 10 emissions (17% on EQ and 16% on HH), as well as aggregates, freight, machinery, external  
 11 services purchases, and steel (~5% each on each damage). The last third of the damage is due  
 12 to the sixteen other kinds of purchases, with individual contributions equal to or lower than

1 4%. This analysis informs on which areas to focus the R&D topics and green purchases  
 2 efforts. From a larger point of view, it also informs which LCIs to regionalize in priority in a  
 3 road process-based LCA to enhance the quality of the results: the most important contributing  
 4 processes must be regionalized first.

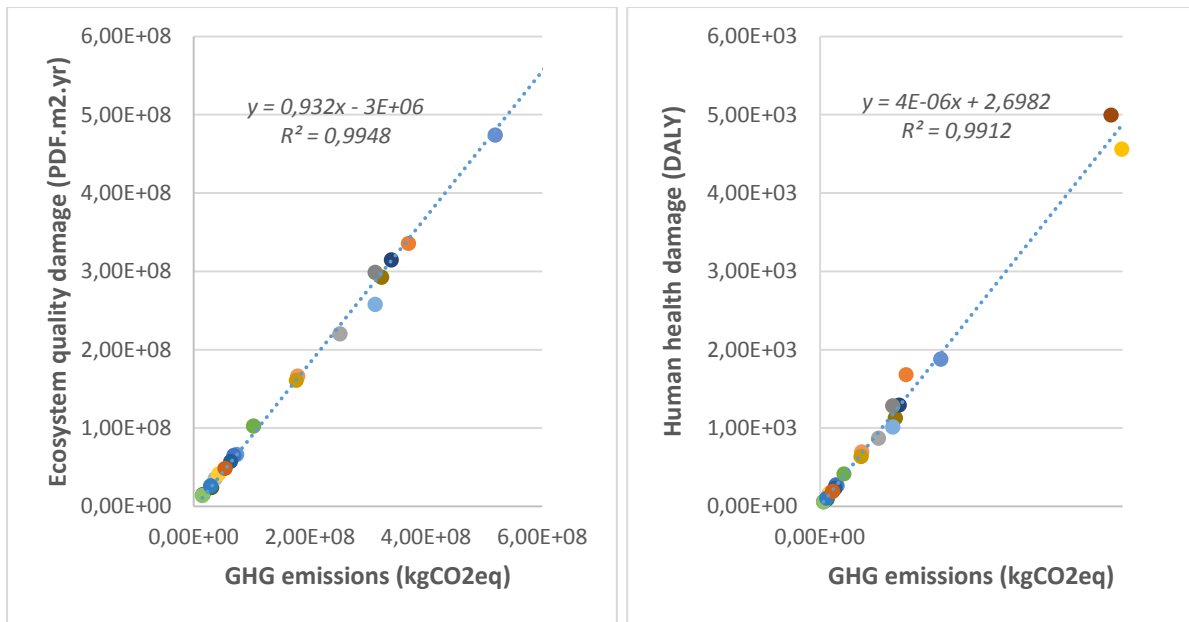


5  
 6 **Figure 6 Environmental drivers of Canada's road industry at the endpoint level**

7 *4.2.3 Metrics prioritization for green purchase plans*

8 Endpoint indicators in environmental quantification methods exist for decades (Steen and  
 9 Ryding, 1992), and the pros and cons of midpoint and endpoint indicators in LCA have been  
 10 largely debated, showing that both approaches have different adequate usages (Bare et al.,  
 11 2000). One major benefit of the use of damage indicators in LCA is to offer a concise but

1 complete overview of the environmental issues for non-LCA expert decision-makers.  
2 Nevertheless, damage indicators are rarely used, and an overwhelming number of studies  
3 only focus on a midpoint climate change impact, i.e. GHG emissions. Depending on cases,  
4 solely focusing on the climate change impact might still represent a decent estimate for  
5 endpoint categories, provided results are correlated. In Figure 7, this correlation is studied for  
6 the road industry case where the damage brought by each category of purchase by the road  
7 industry in Canada is plotted as a function of the corresponding GHG emissions of these  
8 purchases. A linear regression shows a very good correlation between the two in the case of  
9 the road industry, with a coefficient of determination  $R^2$  equal to 0.995 and 0.991 resp. for  
10 ecosystem quality and human health. The figure shows that other fuels purchases (blue dot  
11 under the regression line in the ecosystem quality graph) have a particularly higher  
12 contribution on climate change than on the ecosystem quality endpoint indicator, while the  
13 opposite is true for aggregates and concrete (orange and brown dots above the regression line  
14 in the human health graph), indicating that these purchases have a bigger contribution to  
15 damages on human health than on climate change. Direct emissions impact is excluded from  
16 the analysis presented but its inclusion gives a higher  $R^2$  (see SM). This analysis suggests that  
17 GWP is currently a good proxy to represent wider environmental impacts of Canada's road  
18 industry and support a global green purchase plan. These conclusions must not be directly  
19 extrapolated to other sectors or locations, and they still depend on the openIO-Canada  
20 database and the IW+ characterization method. Finally, this analysis method is useful to  
21 assess the redundancy of indicators in an environmental quantification study and reduce a set  
22 of indicators to be analyzed for instance in the LCA of a product or sector.



1

2 **Figure 7 Correlation between GWP (X-axis) and damages (Y-axis) per category of purchase from**  
 3 **Canada's road industry**

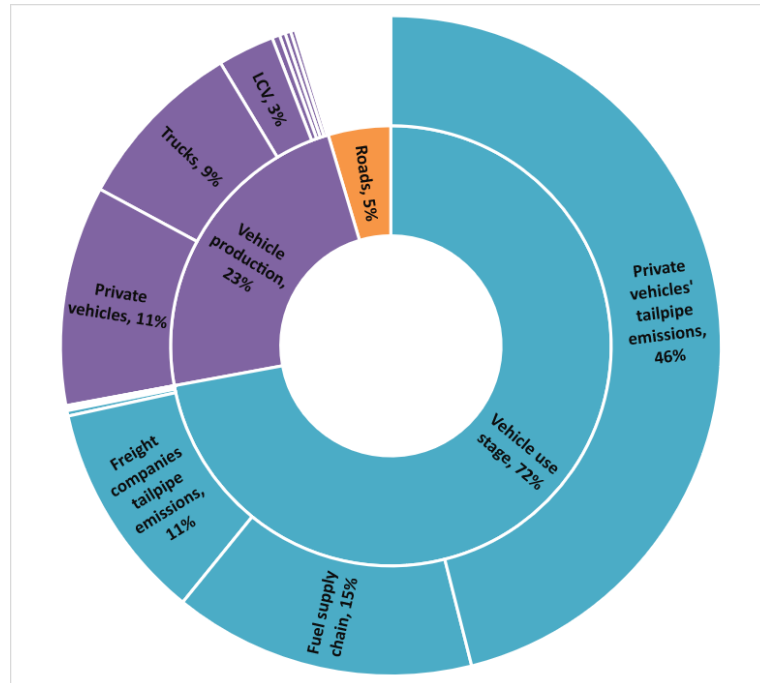
4 **4.3 Canadian roads' carbon footprint by life-cycle stage**

5 Previously, the breakdown by contributors of Canada's road industry was presented. In this  
 6 section, the impact of the production/maintenance/end-of-life of the road industry (shown  
 7 previously) is compared to the roads' usage by vehicles (downstream scope 3 according to  
 8 the GHG protocol (World Business Council for Sustainable Development and World  
 9 Resources Institute, 2004)), including vehicle tailpipe and fuel supply chain GHG emissions.  
 10 The relative contributions of this comparison are presented in Figure 8, and absolute values  
 11 are in Table 2. It shows that the construction, maintenance, and end-of-life of the Canadian  
 12 road network only represent 5% of its life cycle carbon footprint, i.e. 8 Mt CO<sub>2</sub>eq over the  
 13 total 179 Mt CO<sub>2</sub>eq from the Canadian road transportation system. Most of the carbon  
 14 footprint (95%) comes from the pavement use stage - 80% of it from private vehicles (PVs)  
 15 and 20% from freight services (see SM). PVs include private freight trucks as well as sport-  
 16 utility vehicles (SUVs) and pickup trucks. Private freight trucks would account for one-third

1 of the PVs emissions. SUVs and pickup trucks are very popular in Canada and would  
2 account for around 60% of the household PV's direct emissions (Government of Canada,  
3 2021c). Within the road network use stage, the vehicles' use stage accounts for 72% of the  
4 impact, while the manufacturing of vehicles represents 23% of it. Vehicles' maintenance  
5 shows negligible contribution. When looking at the contribution within the vehicles' lifecycle  
6 per category of vehicles, 85% of the PVs' life cycle emissions come from the vehicle use  
7 stage and 15% from the vehicle manufacturing amortization, while this stage accounts for  
8 44% of the freight services' life cycle emissions (see SM). Within the vehicles' amortization  
9 emissions, PVs account for 50%, freight services vehicles for 38%, and light commercial  
10 vehicles (LCV) for 12%. Finally, if vehicles' use stage emissions are further broken down,  
11 we see that providing vehicle fuel generates 15% of the road transportation system GHG  
12 emissions, while PVs' tailpipe emissions account for 46% of it, and tailpipe emissions from  
13 freight services' vehicle 11%. On average, tailpipe emissions bring 79 % of the vehicle's use  
14 stage emissions, while the fuel supply chain brings the other 21% (see SM). This contribution  
15 is a bit higher than the 10 to 15% contribution from the fuel supply chain that can be found in  
16 databases such as the French ADEME's database (ADEME, 2019). This could be explained  
17 by the higher impact of the fuel on the Canadian market - partly coming from high carbon-  
18 intensive oil sands – compared to the impact of the European market's fuel (Charpentier et  
19 al., 2011; Masnadi et al., 2018). To conclude, as the environmental carbon footprint of  
20 Canada's road network mainly comes from its use stage, the main lever of its decarbonization  
21 is better managing pavement-vehicle interactions (PVI) to reduce vehicle consumption and  
22 deterioration through optimally designed and maintained roads. This recommendation  
23 corroborates previous results at the road scale (de Bortoli, 2014; de Bortoli et al., 2022),  
24 showing that potentially higher environmental impacts from a more intensive maintenance  
25 scheme are completely offset by their consequential benefits on the use stage (de Bortoli et

1 al., 2022), some previous studies focusing on the fuel consumption benefits rather than on the  
 2 whole vehicle life cycle (Wang et al., 2014, 2012; Araujo et al., 2014).

3



4

5 **Figure 8 GHG emissions drivers on Canada's road network**

5

6 **Table 2 GHG emissions from the Canadian road transportation system**

6

Scope	Source	GWP (kg CO <sub>2</sub> eq)
Infrastructure	Roads	8.23E+09
Tailpipe emissions	Buses	4.46E+07
	LCVs	4.73E+08
	Freight services	1.92E+10
	Tourism	2.94E+07
	School buses	1.58E+08
	Taxis	2.19E+08
	Private vehicles	8.24E+10
	Fuel supply chain	Fuel
Manufacturing	Buses	1.58E+08
	Trailers	6.75E+08
	LCVs	4.96E+09
	Companies' trucks	1.52E+10
	Tourism vans	5.09E+08
	Other vehicles	4.13E+08
	Private vehicles	1.93E+10



	Maintenance	4.91E+08
TOTAL	<b>TOTAL EMISSIONS</b>	1.79E+11

1

## 2 **5 Discussion**

### 3 **5.1 *The environmental transition of the Canadian road industry***

#### 4 **5.1.1 *Insights for the road industry actors***

5 Our results highlight how EEIO can help quickly sketch an environmental transition plan by  
6 first understanding the multicriteria environmental responsibility of an industry at the  
7 national scale, also accounting for embodied emissions in the supply chain – including  
8 imports, revealing the main contributors to these impacts, and reducing the environmental  
9 dimensions to consider in R&D and green purchase plans. This case study shows the major  
10 roles of purchases of concrete and asphalt products, as well as direct emissions on the climate  
11 change midpoint indicator for Canada’s road industry (18, 18 and 17% of the impact). As  
12 regards direct emissions, and since the climate change midpoint indicator also brings a major  
13 contribution at the endpoint level, it calls for efforts on the energy consumed by production  
14 tools, machinery, and company fleets. As such, switching from heavy fuel to natural gas  
15 would for instance reduce these emissions by 31% per megajoule consumed due to lower  
16 carbon factors (Quebec Ministry for the Energetic transition, 2019). Moreover, electrification  
17 of construction machinery, company fleets, and production processes is a very promising  
18 avenue where electricity mixes are low-carbon such as in Quebec, yet subject to an increase  
19 in electric capacity respecting electricity decarbonization. Our results also emphasize the  
20 importance of engineering structures on the overall impact of infrastructure which  
21 corroborates railway process-based LCAs (de Bortoli et al., 2020; Chang and Kendall, 2011).

1 This contribution would mainly be due to the GHG emissions of concrete (and more  
2 specifically of cement) and metals, building machines having a limited contribution to this  
3 impact (de Bortoli et al., 2020). Moreover, this limited impact of the construction process  
4 compared to the provision of materials has also been demonstrated in many road LCAs (de  
5 Bortoli, 2020). More generally, the contributions of the different types of purchases made by  
6 the road industry in Canada will enable this industry to prioritize the development of a green  
7 purchasing charter for categories with a strong environmental impact, which concerns - apart  
8 from engineering structures – asphalt mixture and materials to produce them. When looking  
9 further at the environmental impact from the “Asphalt (except natural) and asphalt products”,  
10 EEIO results show that 43% of the carbon footprint comes from purchases in asphalt binder,  
11 22% from fuel purchases, 10% from aggregates, 9% from crude oil purchases (aiming at  
12 producing asphalt binders and fuels), and 5% from freight. This embodied carbon structure is  
13 consistent with previous studies (e.g. the meta-study by de Bortoli, 2020) and confirms the  
14 prevalence of asphalt binders and fuels for asphalt mixing and asphalt binder production in  
15 the emissions from asphalt mixture production.

16 Finally, we used EEIO at the national scale, but it can also be a powerful tool at the company  
17 scale to hierarchize environmental actions. Indeed, EEIO can also be used statically to screen  
18 environmental levers based on the buying reports of the company, or even dynamically to  
19 simulate the environmental impact of a change in the purchases of the company, relating to a  
20 change in the buying choice, the materials or services sold, or the production process. This  
21 process must involve all the departments of a company: R&D, material, buying, and  
22 production departments.

### 1 5.1.2 *The trifling contribution of road construction compared to their usage*

2 Quantifying the environmental contribution of each life-cycle stage of the road to its lifetime  
3 impact is a recurring question in the literature, especially to understand to which extent the  
4 pavement use stage is important, as it is often excluded from road LCAs scope (Santero et al.,  
5 2011). Several studies emphasized that the vehicle pipe emissions carry a crushing  
6 contribution to the road life-cycle impact (de Bortoli, 2018; Wang et al., 2014, 2012; Chappat  
7 and Bilal, 2003). When included, the impact of vehicle manufacturing and maintenance has  
8 shown to be also important in the rare studies accounting for it, for instance representing 21%  
9 of the primary energy consumed by a road system over 30 years (de Bortoli, 2014) or around  
10 15% of the carbon footprint of passenger car modes (de Bortoli and Christoforou, 2020;  
11 Chester and Horvath, 2009). However, these assessments were always carried out on a  
12 particular road or a particular mode (e.g. passenger car transportation), and a more global  
13 overview at the network level was missing. The environmental picture that we give for  
14 Canadian roads demonstrates that decarbonizing the road construction industry might not be a  
15 priority to tackle the impact of road transportation, contrary to building and maintaining roads  
16 to lower vehicle consumption and tear and wear, or directly reducing vehicle manufacturing  
17 and use' GHG emissions. Results show that fleet replacement is far from being a secondary  
18 question in terms of road's climate transition, which may be explained by the fact that cars in  
19 Canada are the second heaviest in the world, weighing 1717 kg on average in 2017 (IEA,  
20 2019). Fleet replacement is a particularly thorny question with the penetration of  
21 electromobility, as electric vehicles emit more at the manufacturing stage but less during the  
22 use stage than internal combustion engine (ICE) vehicles, which can lead to lowering GHG  
23 emissions on the entire life cycle as shown in Quebec (Roy and Ménard, 2016).

## 1 **5.2 *Limitations and future work on the openIO-Canada model***

### 2 **5.2.1 *Overview***

3 OpenIO-Canada has been designed with a few inherent limitations and assumptions that are  
4 made clear in this section. First, the physical flow accounts of Statistics Canada (used to  
5 quantify GHG emissions and water use) are provided at a more aggregated level (240 sectors)  
6 than the economic data that is used by openIO-Canada (492 sectors). Hence, an economic  
7 allocation approach was adopted to distribute GHG emissions and water use. For instance,  
8 physical flow accounts only provide GHG emissions for the “Crop and animal production”  
9 sector. OpenIO-Canada thus considers all more refined subsectors that belong to the broad  
10 “Crop and animal production” sector and uses the weighted average of their sales share to  
11 determine their emission level. In other words, if the “Wheat” sector represents 6% of the  
12 total sales of “Crop and animal production”, the “Wheat” sector will be attributed 6% of the  
13 total GES emissions of “Crop and animal production”.

14 Second, openIO-Canada does not provide a version with capital goods endogenized. Capital  
15 endogenization is a method used in EEIO to distribute the impacts of capital formation (e.g.,  
16 the construction of a machine) to the different sectors of the economy requiring the formation  
17 of capital. Using an example to make it clearer, openIO-Canada records the construction of a  
18 building (and its associated emissions) but does not link the construction of the building to  
19 the economic sector that required the building. Therefore, contribution analyses on sectors  
20 provided by openIO-Canada do not include the formation of capitals, but rather only include  
21 recurring operations such as maintenance and repairs.

22 Third, international imports are considered produced as in the importing province, as is  
23 typically done in many national EEIO tables (Eurostat : Statistisches Amt der Europäischen  
24 Gemeinschaften, 2008). An American car imported in Quebec will thus be considered

1 produced the same way as a car directly produced in Quebec, both for economic and  
2 environmental flows.

3 Fourth, the NPRI has some limitations. This readily available Canadian national emission and  
4 consumption database does not cover all the flows accounted for in LCA databases, such as  
5 ecoinvent. While NPRI covers a fair amount of 323 types of substances, some flows are  
6 nevertheless missing, such as land occupation/transformation, ionizing radiations, water  
7 consumption, as well as mineral and fossil resource use. Moreover, the NPRI covers  
8 emissions of the 8000 most important complying industrial sites across Canada. Pollutant  
9 emissions (other than GHG emissions) are thus underestimated, as many smaller industrial  
10 sites are not covered by the NPRI.

### 11 *5.2.2 Focus on the underestimated non-GHG direct emissions*

12 As specified in the limitations of openIO-Canada, the NPRI only covers a part of Canada's  
13 industrial sites. Indeed, according to the Canadian Environmental Protection Act, only the  
14 "owners or operators of facilities that meet published reporting requirements are required to  
15 report to the NPRI" (Government of Canada, 2020a). These requirements are a facility with  
16 more than 10 full-time employees - i.e. 20 000 hours of work per year – and carrying out  
17 specific activities, including quarry operations and operation of stationary combustion  
18 equipment (Government of Canada, 2021d). In Canada, around 8000 facilities report their  
19 pollutant releases in the 2017 NPRI, based on reporting requirements that mainly consider the  
20 type of activities, the total number of hours worked and substances manufactured  
21 (Government of Canada, 2011). But, in 2020 for instance, the manufacturing sector  
22 accounted for 90359 establishments, and the oil and gas extraction sector only 4125  
23 (Government of Canada, 2021a). Thus, the completeness of the activities covered by the  
24 NPRI database is rather poor in number of sites but may be good in the percentage of

1 production covered as it includes major producers. Nevertheless, we do not have access to  
2 this information yet, and this default in the coverage leads to an unknown underestimation of  
3 the substances assessed with the NPRI (i.e., all substances except GHGs, the latter being  
4 assessed with physical accounts). As a result, the estimation of the climate change indicator  
5 reliably covers the whole Canadian economy while the estimation for other impact categories  
6 may not. This, to date, limits somehow the robustness of some conclusions, for instance the  
7 correlation between climate change and endpoint categories shown in section 4.2.3. Indeed, if  
8 only climate change is characterized comprehensively, it creates a bias towards its  
9 contribution in both endpoint categories. Moreover, the overwhelming contribution of climate  
10 change on the damage to ecosystems and human health (section 4.1.2.) could result from the  
11 truncation of the NPRI data used in the current version of OpenIO-Canada. It could also  
12 explain the low contributions of direct emissions to midpoint indicators (section 4.2.2.).  
13 Assessing this bias will require improving the coverage of non-GHG emissions by openIO-  
14 Canada in the future, nonetheless, all the methodological aspects proposed to use EEIO to  
15 sketch environmental transition plans are totally valid.

### 16 ***5.3 Articulation between EEIO and LCA for transition plans***

#### 17 *5.3.1 EEIO as a screening tool to build upon for LCA*

18 EEIO can be a screening tool for transition plan development, but it can also be used to  
19 orientate LCA methodological choices such as system boundaries or LCI regionalization, by  
20 looking at the contribution of specific products and services calculated with EEIO, as detailed  
21 below.

22 What is usually considered outside the system boundaries of road process-based LCAs –  
23 namely staff consumptions, services, and sometimes infrastructure and capital goods  
24 amortization – accounts according to openIO-Canada for 15 to 73% of the impacts, resp. on

1 marine eutrophication and freshwater eutrophication. In particular, external services are  
2 always excluded from these studies and bring between 4 and 48% of the impacts, resp. on  
3 human non carcinogenic toxicity and freshwater eutrophication. EEIO is thus an interesting  
4 tool to rapidly screen the impact of time-consuming aspects to model in process-based LCAs  
5 and decide whether to include them in the system boundaries of an LCA in a more specific  
6 study. Amortization of infrastructure, machinery, and buildings is more often included,  
7 especially in the ecoinvent database. Yet the models are often very generic and/or outdated,  
8 as illustrated by the quarries: a single model for each type of site (loose rocks or solid rocks)  
9 was created between the end of the 90s and the beginning of the 2000s, based on 4 Swiss  
10 quarries (Kellenberger et al., 2007). However, the impact of the depreciation of infrastructure  
11 is even more important as the carbon intensity of energies decreases. If the contribution of  
12 this depreciation is already significant, it will undoubtedly be more and more so, which calls  
13 for improving the classic LCA models. Note, all the same, that our EEIO approach on this  
14 point has limits: we consider the impacts of the year 2017 to be representative, while there  
15 can be strong heterogeneities depending on the year of purchase. Capital goods should be  
16 endogenized in openIO-Canada as it has been done in Exiobase (Södersten et al., 2018) and  
17 US-EEIO (Miller et al., 2019).

18 It may also be interesting to use the major contributors to the environmental impacts  
19 highlighted through EEIO to prioritize the regionalization of life cycle inventories (LCIs) for  
20 a sector, particularly if the national market differs from the markets modeled in existing  
21 databases, or if national technologies do not coincide with existing models in the case of  
22 domestic production.

23 However, as EEIO is entirely based on economic allocations, the importance of the  
24 contributors found in EEIO could be distorted compared to LCA contributors, as LCA is  
25 more disaggregated than EEIO, and mainly uses non-economic allocation methods such as

1 mass or other physical allocations to deal with multifunctional systems. Thus, comparing  
2 EEIO and process-based LCA results, and using both types of methodologies to interpret and  
3 use results in decision-making support could bring more robustness on the environmental  
4 structure and levers of a system, or more insights on the uncertainties to deal with. EEIO and  
5 LCA must then be used complementarily to strengthen environmental decision processes.

6

### 7 *5.3.2 Uncertainty and data quality in EEIO versus LCA*

8 EEIO databases generally cover a more limited number of substances than LCI databases  
9 which typically consider more than a thousand substances. Nevertheless, there is great  
10 variability in the magnitude of the environmental consequences of substances. For instance,  
11 with only about 35 pollutants covered, EXIOBASE has been found to still reliably cover  
12 many impact categories apart from those related to toxicity (Muller, 2019).

13 Another potential drawback of EEIO pertains to the reliability of national pollutant  
14 inventories, used by EEIO databases and compiled by government agencies, which rarely  
15 stem from actual measurements on industrial sites. In the case of Canada for example, certain  
16 specific emissions must be measured on an annual or multi-year basis, e.g., the emissions of  
17 certain pollutants for facilities burning used oil in Quebec. Most emissions on the other hand  
18 are simply reported based on calculation methodologies prescribed by the Government of  
19 Canada which may be incomplete or obsolete. As an illustration, a calculator is made  
20 available for asphalt plants to estimate their pollutant emissions (Government of Canada,  
21 2020b). Parameters - such as annual production, fuel consumption, type of production, or  
22 asphalt mixing temperature to name but a few - are fairly comprehensive and make it possible  
23 to take into account technologies and specific equipment. However, according to this “hot  
24 mix asphalt plant” calculator's documentation, its emission factors are based on US EPA data



1 published between 1994 and 2005. Moreover, the calculator does not differentiate emissions  
2 from a boiler using waste oil and oil #6, while used oil facilities need to be tested regularly  
3 due to the risk related to specific metals and contaminants emissions. It, therefore, seems  
4 necessary to increase the consistency of emission reports, for example by providing updated  
5 calculators. The more so as a specific calculator also exists for waste oil combustion  
6 (Government of Canada, 2018), but the existence of this calculator is not pointed out in the  
7 section relating to the production of asphalt mixtures. Finally, efforts should be put on the  
8 quality of these databases, in terms of completeness, reliability, as well as technological,  
9 geographical, and temporal representativeness. Moreover, giving access to the information on  
10 the quality of these data could allow analysts to assess the robustness of their assessments.  
11 While this data quality problem also concerns LCA, they are already mathematically  
12 addressed in LCA through data quality characterization and various uncertainty propagation  
13 methods (Baker and Lepech, 2009), while it is not the case in EEIO.

## 14 **6 Conclusions**

15 EEIO must be used as one tool to orientate the environmental transition plans of industries as  
16 proved by the example of the pavement industry in Canada. First, it estimates faster than  
17 LCA the multicriteria environmental contribution of an industry for cradle-to-gate on a large  
18 scale such as a country: in our illustration, the road industry accounts for around 1.0% of  
19 most of the country's damages on a consumption-based approach, i.e. 10% of the construction  
20 sector impacts. It thus unearths industrial key drivers on which organizing the environmental  
21 transition through green purchase and R&D prioritization strategies. The road industry in  
22 Canada must reduce (1) its direct emissions through the investment in new machinery using  
23 cleaner energies such as low-carbon electricity, biomass, and natural gas, and (2) the impact

1 of material purchases, especially concrete and asphalt products. Second, EEIO spots the  
2 critical midpoint indicators explaining most of the damage to areas of protection such as  
3 ecosystems and human health, allowing for reducing the set of classical LCA indicators to  
4 monitor ecological transition plans, multicriteria assessments being less understandable for  
5 non-experts as the number of metrics rises. Climate change dominates the midpoint category  
6 contributions to damages in the pavement sector, followed by marine acidification, and PM  
7 formation due to aggregates. Third, EEIO rapidly seizes often neglected sources of impacts in  
8 traditional LCA: capital goods amortization, staff consumption, and services. It must be used  
9 to set the system boundaries adapted to specific LCAs. Finally, it helps estimate the impacts  
10 of some types of goods at a large scale on a cradle-to-grave perimeter: its application to  
11 Canada's road network confirms that the use stage of the roads is capital to its environmental  
12 impact (95% of the GHG emissions), mainly due to vehicle tailpipe emissions (72% of the  
13 total impact) but also to vehicle amortization (23%). The construction and maintenance of the  
14 roads contribute little over the life cycle (5%), and the major lever for decarbonization is  
15 expected from better managing PVI to reduce the use stage impacts through better designed  
16 and maintained roads.

17

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19 (Harmonized Environmental Assessment of Transportation Infrastructure) funded by the  
20 technical department of Eurovia – VINCI group. The work has been hosted at the Americas  
21 Technical Center of Eurovia Canada.

22

23 **Data statement:** OpenIO-Canada is accessible online: [https://github.com/CIRAIG/OpenIO-](https://github.com/CIRAIG/OpenIO-Canada)  
24 [Canada](https://github.com/CIRAIG/OpenIO-Canada). The case study calculation algorithm is available on Zenodo

1 (<https://doi.org/10.5281/zenodo.6505413>). Excel spreadsheets of category aggregation, as  
2 well as raw and worked results, are also made available in the supplementary material.

3

4 **Authors' contribution:** Conceptualization: ADB; Methodology: ADB, MA; Data curation:  
5 ADB, MA; Formal analysis: ADB; Software: MA; Validation: ADB; Visualization: ADB,  
6 MA; Roles/Writing - original draft: ADB; Writing - review & editing: MA; Funding  
7 acquisition: ADB.

8

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