Comparative Life-Cycle Assessment of Cement Concrete Pavement and Asphalt Pavement for the Purposes of Integrating Energy and Environmental Parameters into the Selection of Pavement Types

ENVIRONMENT

ÉTUDES ET RECHERCHES EN TRANSPORT

Québec

COMPARATIVE LIFE-CYCLE ASSESSMENT OF CEMENT CONCRETE PAVEMENT AND ASPHALT PAVEMENT FOR THE PURPOSES OF INTEGRATING ENERGY AND ENVIRONMENTAL PARAMETERS INTO THE SELECTION OF PAVEMENT TYPES

Karine Kicak, Eng. Jr
Jean-François Ménard, Eng.
Département de génie chimique
École Polytechnique de Montréal

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The opinions expressed in this report are those of the authors and do not necessarily reflect the views of the ministère des Transports du Québec.

Collaborators

Renée Michaud, Eng. and Réjean Samson, Eng., Ph. D., Department of Chemical Engineering, École Polytechnique de Montréal.

Édouard Clément, Eng., M. Sc. A, Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG).

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Note de traduction	Translation notice
Le rapport original a été traduit en anglais à l'exception de certaines annexes. La version anglaise de ce rapport a été validée et approuvée par le CIRAIG.	The original report has been translated in English, at the exception of some appendices. This English version has been validated and approved by CIRAIG.
Pour les annexes, la situation est la suivante :	Detail on the translation of Appendix is as follows:
Annexe A : Méthodologie ACV (Texte disponible en anglais)	Appendix A : LCA methodology (available in english)
Annexe B : Revue de littérature (Non traduite)	Appendix B : Literature Review (not translated)
Annexe C : Schéma des systèmes étudiés (Traduite)	Appendix C : Diagrams of analysed systems (translated)
Annexe D : Méthode d'évaluation des impacts (texte en version originale anglaise)	Appendix D : Method for Assessing Life-Cycle Impacts (original English version)
Annexe E : Description des systèmes produits et des hypothèses du modèle d'ACV (Non incluse au rapport)	Appendix E : Description of the LCA Model's Product System and Assumptions (not included in the report)
Annexe F : Résultats (Non inclus au rapport sauf certains graphiques importants traduits en anglais)	Appendix F : Results (not included in the report at the exception of key graphics translated in English)
Annexe G : Rapport du comité de revue critique et réponses du CIRAIG aux questions du comité - Partiellement traduit : • Note de revue critique (20 pages, non traduites); • Rapport de revue critique (3 pages, traduites); • Réponses aux commentaires (9 pages, non traduites).	Appendix G : Report of the Critical Review Committee and CIRAIG's Responses to the Committee: • Note de revue critique - Critical review note, (20 pages, not translated) • Rapport de revue critique - Critical review report (3 pages, translated); • Réponses aux commentaires - Responses to comments (9 pages, not translated).
Le graphique Figure 22.2.1B a été ajouté à l'Annexe F du rapport original à la suite de la Figure 22.2.1, afin d'illustrer la contribution que représente l'opération de 1% des véhicules.	Figure 22.2.1B was added to the original report Appendix F following Figure 22.2.1 to show the contribution of the operation of 1% of the vehicles.

Ministère
des Transports
Québec

ANALYTICAL INDEX

Report title and subtitle	Transports Québec report no.	
Comparative Life-Cycle Assessment of Cement Concrete Pavement and Asphalt Pavement for the Purposes of Integrating Energy and Environmental Parameters into the Selection of Pavement Types	RTQ-12-01 Date of publication of report (Year-Month) 2012-07	
Title of research project	**File no.**	**Project no.**
Comparative Life-Cycle Assessment of Cement Concrete Pavement and Asphalt Pavement for the Purposes of Integrating Energy and Environmental Parameters into the Selection of Pavement Types	2520-05-RF01	R592.1
Chief researcher	**Research start date**	**Research end date**
Réjean Samson, Eng., Ph.D. Report author(s) Karine Kicak and Jean-François Ménard	March 2006	September 2009
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Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG) Department of Chemical Engineering École Polytechnique de Montréal C. P. 6079, succ. Centre-ville Montréal (Québec) H3C 3A7	Direction de l’environnement et de la recherche Ministère des Transports 930, chemin Sainte-Foy, 6e étage Québec (Québec) G1S 4X9	

Issue

The Departmental Policy on Pavement Type Selection came into effect in 2001. An update was scheduled after five years. The Policy is a decision support process that aims to determine the best investment—cement concrete or asphalt—for the network based on a 50-year life cycle cost analysis. The update was intended to take into account the operational reality of the Policy in the various territorial branches. During the process, the policy steering committee engaged in updating the costs and traffic figures used in the decision-making process, as well as incorporating parameters that could not initially be factored in due to a lack of data or recognized method. Work has resumed in order to integrate energy and environmental parameters into the decision making. This complex issue has been examined from the angle of an environmental life-cycle assessment (LCA), an increasingly recognized method to account for environmental stressors linked to industrial processes. With the feasibility of the LCA proven, CIRAIG has been mandated to complete a full comparative LCA with the contribution of the involved industries.

Goals The study's aim is to provide for the first time an environmental assessment comparing asphalt pavement and cement concrete pavement by adapting the LCA to a framework previously defined by an economic life-cycle cost analysis. The study uses primary data provided by industrial associations that participated in the policy update, including the Cement Association of Canada, Bitume Québec, the Québec Road Builders and Heavy Construction Association, as well as the Petro-Canada refinery in Montréal and the ministère des Transports du Québec. The results must apply to the entire road network and take into account 16 functional classes of road design that correspond to road conditions.
Methodology The comparative LCA used for the pavement types was first examined in the context of a feasibility study (Martineau et al., 2005). Questionnaires were prepared in order to ascertain the availability of the data and the expertise required to set up the extensive inventory involved. Work undertaken here followed the rules established by the International Organization for Standardization (ISO 14 040 and 14 044): the reference life-cycle functional unit is defined as a 5 km segment of road in service for 50 years after initial construction. The analyzed systems include the extraction of raw materials (from quarries and sandpits), their transformation (in cement factories, pavement plants, refineries or asphalt plants, or at the work site), their transportation and the disposal or recycling of materials at the end of their useful life. Results were verified through a sensitivity analysis of the main assumptions and an uncertainty analysis of the data. Lastly, the study was submitted to an independent third party for critical review.
Results and recommendations First, for each pavement type, the LCA inventoried: 1) flows of energy and raw materials extracted from the environment, and 2) flows of residual materials and pollutants emitted to the environment. The inventory makes it possible to compare cement concrete pavement and asphalt pavement on the basis of mass. Secondly, the LCA makes it possible to extend the assessment further by weighting the inventoried flows according to their potential environmental impacts on human health, ecosystems and resources. The comparative inventory analysis shows that asphalt pavement requires more natural resources, but cement concrete pavement almost always emits more pollutants and residues. The results were analyzed using a potential impact assessment providing with 16 midpoint impact indicators, which were all, except two, aggregated into 4 endpoint damage indicators. Those results are presented as follows: three damage indicators (human health, ecosystem quality and global warming) favour asphalt pavement, while one damage indicator (resource consumption) favours cement concrete pavement. These results apply to all 16 functional classes of pavement. The impact indicators are only slightly different: the human toxicity indicator favours cement concrete pavement, but this indicator is aggregated as part of the human health damage indicator, which favours asphalt pavement as a whole. Aquatic eutrophication, one of the non-aggregated indicators, favours cement concrete pavement, but only for 3 of the 16 functional classes.

Key words	Number of pages	Number of bibliographical references	Language of document
LCA, assessment, life cycle, policy, pavement selection, pavement types, impacts, damages, environment	203 with appendices	29	☒ French ☒ English

ERRATUM

Authors: Ministère des Transports du Québec and CIRAIG

Date: June 28, 2011

While the following corrections do not change the report's findings, this erratum was added to the final version dated September 28, 2009, in order to avoid any misunderstanding of data and results following the report's publication.

Section 5.3.7

Page 81

The sensitivity analysis considered the operation of **100%** of vehicles over the life cycle of both types of pavement. In the second and third paragraphs of section 5.3.7, 1% should be replaced with 100%.

Section 5.3.8

Page 82

The term ρ_{cement} in equation (5-3) represents the mass of Portland cement per cubic metre of concrete and not the density of concrete. Based on the content of Portland cement in concrete used on Québec roads, its value is approximately **240 kg/m³** rather than 2,350 kg/m³, which modifies results by a factor of 10. The amount of CO_2 absorbed over the pavement life cycle for functional class 16 is therefore **135 tonnes** rather than 1,310 tonnes.

Page 83

Second paragraph: The first two sentences should be replaced by the following statement:

The amount of CO_2 absorbed through carbonation represents a decrease of less than 2% of the CO_2 equivalent inventoried over the life cycle of cement concrete pavement for functional class 16.

SUMMARY

Background

As part of the update of its Departmental Policy on Pavement Type Selection (hereinafter the “Policy”), the ministère des Transports du Québec (MTQ) wishes to integrate life cycle assessment (LCA) into the decision-making process for the selection of pavement types. The current decision-making process is based on an overall life cycle cost analysis (LCCA) for all monetizable parameters. This **LCA**’s objective is to integrate environmental parameters into the selection of pavement types. It is a **methodological tool to assess**, using internationally recognized methods, **the potential environmental impacts** of a product or activity over its entire life cycle. The MTQ thus commissioned the Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG) to perform an environmental comparison of cement concrete pavement and asphalt pavement.

This document is a summary of the final project report submitted following a critical review process that was carried out by an independent review committee, which confirmed the validity of methods used, results and findings.

Method

LCA is a method to assess the potential environmental impacts of a product or activity over its entire life cycle (“cradle to grave” concept). It is therefore a holistic approach that takes into consideration the extraction and processing of raw materials; manufacturing processes; transportation; the distribution, use and reuse of the final product; as well as end-of-life recycling and waste management. The main objective of this method is to reduce the impacts of products and services on the environment while providing environmental data to guide decision making and avoid possibly displacing environmental problems.

LCA involves identifying and quantifying the inputs (materials and energy) and outputs (emissions to air, water and soil) related to the life cycle of a product or activity (i.e., the product system), as well as assessing the potential impacts of those inputs and outputs.

Study Objectives

More specifically, this project’s objective is to assess and compare, using the LCA methodology, the potential environmental impacts of new cement concrete pavement (hereinafter “CC system”) made of Jointed Plain Concrete Pavement (JPCP) and those of new asphalt mix pavement (hereinafter “AM system”), considering different configurations (or functional classes) that are representative of Québec’s road system.

An initial literature review showed that a few studies have compared the environmental impacts of cement concrete pavement and asphalt pavement built in the last few years. CIRAIG’s review first led to a preliminary profile of the life cycle of cement concrete and asphalt pavement, which guided the development of the LCA's methodological framework. This framework was designed so as to adapt the LCA to Québec's context and ensure data representativeness.

Function and Functional Unit

LCA does not focus on a product, but rather on one or several functions performed by that product. Therefore, the analysis seeks to determine the quantity of product required to perform the function being analyzed, which enables the comparison of options with different performance features. As for the functional unit, it implies the quantification of the analyzed function, while reference flows establish a link between a system's performance and the functional unit (i.e., they represent the quantity of product required to perform the function expressed by the functional unit).

The analyzed function consists in "allowing vehicle traffic over a given distance and over a given period of time."

A distance of 5 km and a period of 50 years were established by the MTQ. Since the demolition and reconstruction steps are not completed in the same year for the two different types of pavement, this 50-year period is based on the maximum useful life of both options being studied. In addition, since it is difficult to determine to what extent the next life cycles of rebuilt pavement will be identical to the first cycle following initial construction (for instance, in what context and under what conditions will the base and sub-base need to be replaced or modified?), the comparative analysis was carried out for the first 50-year span of the pavement's initial life cycle. More specifically, as part of this comparative study, the functional unit is expressed as follows:

"Allow vehicle traffic over a 5 km distance and over the first 50 years of life of cement concrete pavement, compared to asphalt pavement built in Québec in 2009."

Boundaries of Analyzed Systems

The system's boundaries include: 1) all relevant activities required for achieving the study's objectives and thus necessary to perform the studied function; and 2) all processes and flows that significantly contribute to the potential environmental impacts.

Also to be noted, by determining the number of vehicles travelling on a segment of the road network, especially the number of trucks, and the type of traffic (urban vs. rural), the MTQ is able to identify 16 functional classes. The classes are divided according to the number of lanes and the structural dimensions of the pavement itself, for both types of pavement, which means there are 32 pavement systems in total.

Figure I shows the boundaries of the analyzed systems. The life cycle of pavement therefore starts with the **initial construction** of a road segment. This includes the complete construction of the pavement, from the placement of base materials to the marking of the road. The **in-use stage** includes the spreading of de-icing salt in winter, while the **maintenance stage** includes the maintenance schedule over the 50-year period, as well as the restoration of markings.

At the end of its life time, the pavement's cement concrete slab or asphalt layer is completely replaced. The **reconstruction stage** therefore implies the complete demolition of traffic lanes and shoulders, followed by the placement and marking of a new concrete slab (or a new asphalt layer) of the same thickness.

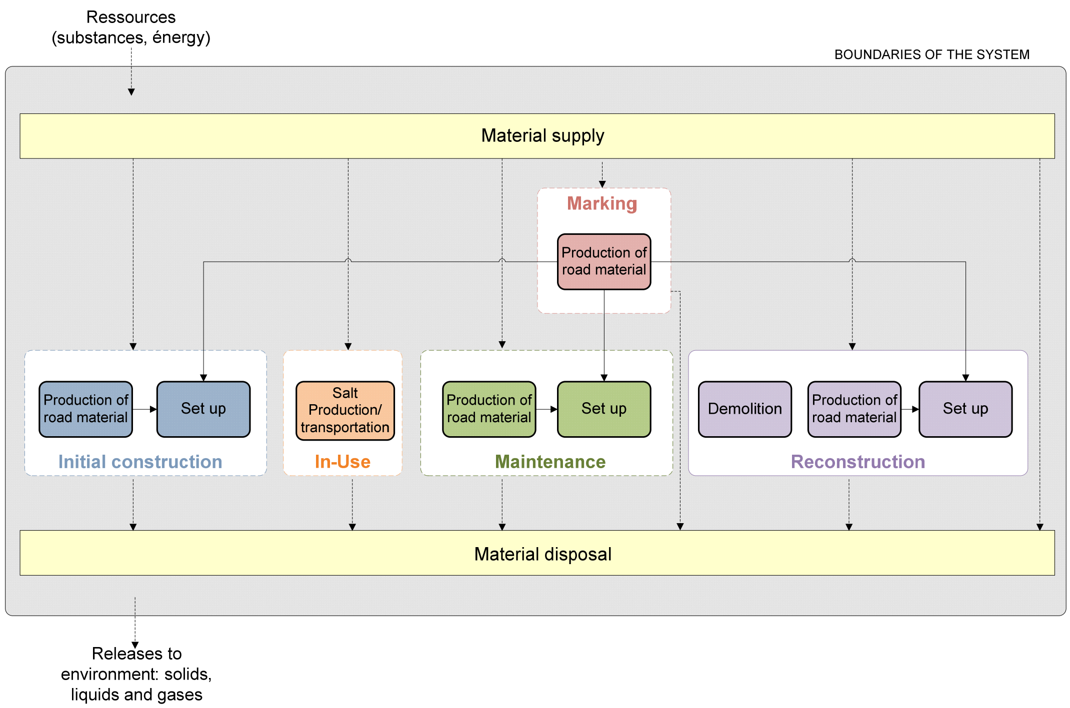


Figure I: System Boundaries

Assumptions

- The comparative LCA must pay special attention to the processes that are different between the compared systems. Thus, all processes deemed to be identical or that could not be differentiated between the two types of pavement were not considered. More specifically, the following elements were not included:
    - Initial deforestation;
    - Snow removal and curb maintenance (ditches, weed control, etc.) activities related to roadway operation;
    - Processes associated with the life cycle of fences and parapets, signs and the lighting system;
    - Traffic operations.

- Material loss during any interventions (initial construction, maintenance and reconstruction) is disregarded, as well as dust emissions from those same interventions.
- The useful live time of the bases and sub-bases were considered to be the same for both pavement types.
- No pavement materials are buried in Québec, which means all materials removed from pavement on the province's road system are recycled. They may be used on the same road construction site or another one.
- Due to a lack of data, the cleaning step performed following the demolition of pavement, during the reconstruction stage, is excluded. Also, the cleaning of trucks transporting cement concrete and asphalt is not taken into consideration, nor is the management of resulting liquid discharges.
- Tire wear and tear and particulate emissions from tires were not quantified or used in the study.
- The concrete carbonation process (carbonation of the lime contained in the concrete resulting from the following reaction: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$) was not taken into consideration in the LCA, but its influence on results was tested through a sensitivity analysis.
- Since no data on asphalt fumes (which contain polycyclic aromatic hydrocarbons [PAHs], among other things) from asphalt manufacturing and placement could be determined, this factor was not taken into consideration. A sensitivity analysis was nevertheless completed to verify the influence of those emissions on results.
- While technologies may very well evolve over the 50 years being considered, no one is currently in a position to accurately characterize the evolution of production techniques and road behaviour. Therefore, the technological system being analyzed is considered to be static.
- The most recent life cycle impact assessment (LCIA) methods are clear on a particular issue: any non-renewable energy source taken from the earth's energy capital is a potentially lost resource that has to be taken into consideration in the impact assessment (Goedkoop and Spriensma, 2001b; Bare et al., 2003; Jolliet et al., 2003; Toffoletto et al., 2007). Thus, if oil extracted to produce asphalt is not intended to be used as an energy source, but rather as a raw material, the consequence for energy resources is no different than if the same oil was intended to produce a fuel: the resource stock decreases, along with the available energy potential. Therefore, it is essential to consider asphalt inherent energy in the assessment of the potential impacts of pavement. This consideration comes into play only with regard to the use of non-renewable energy and has no bearing on other impact categories. However CO_2 emissions associated with the potential combustion of asphalt are not calculated until the asphalt is actually burnt.

Data Sources

- The specific data was essentially collected so as to take advantage of the latest data on Québec facilities, in accordance with good practices and actual practices in Québec. This data was obtained from industrial associations that are stakeholders in the project (Bitume Québec [BQ], the Cement Association of Canada [CAC] and the Québec Road Builders and Heavy Construction Association [QRBHCA]), Petro-Canada's Montréal refinery and the MTQ. The timeframe for the collected data was essentially from 2005 to 2008.
- This data was supplemented by generic data modules (average data taken from commercial databases) available in the internationally renowned LCA database, ecoinvent version 2.0 (http://www.ecoinvent.ch/). This is the largest life cycle inventory database on the market, with modules containing data collected from a great number of European based industrial sectors. The modules were adapted to energy contexts prevailing in Québec and North America whenever required.

Environmental Impact Indicators

- The collected data was assessed based on the internationally recognized method known as IMPACT 2002+ (Jolliet et al., 2003). The results obtained were also compared to those obtained with two other methods: the European Eco-indicator 99 method (Goedkoop and Spriensma, 2001a); and the Canadian LUCAS method (Toffoletto et al., 2007).
- IMPACT 2002+ includes factors to convert the results of characterized impacts into damages. While this conversion brings about additional uncertainties, it has the advantage of simplifying the communication of results expressed in four categories of damages, as opposed to over 10 impact categories,.

Table I shows the impact categories considered under the IMPACT 2002+ method. Note that:

- These categories do not cover all the possible environmental impacts associated with human activity. Several types of impacts, such as noise, odours, radiation and electromagnetic fields, are therefore not included in this analysis, since little to no methodological advances have been made in those areas;
- Aquatic eutrophication and acidification are not taken into consideration by the damage indicators, since IMPACT 2002+ does not currently propose a way of converting those two impact categories into damages (ecosystem quality category). We therefore recommended considering the four damage indicator results along with the results for those impact categories.

Table I: Impact and Damage Categories of the IMPACT 2002+ Method

IMPACT 2002+	
Damage Category	**Impact Category**
Human health	Human "cancer" toxicity
	Human "non-cancer" toxicity
	Respiratory effects (inorganic)
	Ionizing radiation
	Thinning of the ozone layer
	Respiratory effects (organic)
Ecosystem quality	Aquatic eco-toxicity
	Terrestrial eco-toxicity
	Terrestrial acidification/eutrophication
	Land use
Global warming	Global warming
Resources	Non-renewable energy
	Mineral mining
Not related to a damage category (relation known, but no conversion model available)	Aquatic acidification
	Aquatic eutrophication

Results

Since this LCA is comparative and the elements common to both systems were excluded from the assessment (particularly traffic, lighting, earthwork, etc.), the results show only the differences between the two types of pavement. The presentation of results specific to each type of pavement is not appropriate in this case, especially considering that only differential quantities were collected for de-icing salts.

The results of the inventory and potential impact assessment are therefore presented in terms of relative difference between cement concrete (CC system) and asphalt mix (AM) pavement as follows:

$$\Delta_{Result}(\%) = \frac{\left(result_{CCsystem} - result_{AMsystem}\right)}{result_{AMsystem}} \qquad \text{(I)}$$

Inventory Analysis Summary

In light of the results of the inventory analysis, the **use of water and energy** and **discharges to the environment** (except for emissions to water for functional classes 8, 12 and 16) are higher for the CC system, while the AM system shows a higher **consumption of natural resources**. The analysis also identified the main contributors to the inventory, which included the production of cement, cement concrete, steel, de-icing salts, asphalt and asphalt mix.

Impact and Damage Indicator Results

Table II shows the system with the least potential impacts according to the results obtained with the IMPACT 2002+ method for each of the four damage categories and for each of the two impact categories.

Twelve of the 15 impact indicators favour the AM system. However, indicators related to human “cancer” toxicity, consumption of non-renewable resources and aquatic eutrophication (for functional classes 8, 12 and 16 only) favour the CC system.

Note that:

- What distinguishes functional classes 8, 12 and 16 from the others is the fact that asphalt pavement must be rebuilt earlier, which implies a larger quantity of asphalt and asphalt mix being required by the AM system and an increase in related emissions to water (and eutrophication);
- While the human “cancer” toxicity indicator favours the CC system, the overall damage to human health indicator favours the AM system;
- The indicator related to aquatic eutrophication poses significant uncertainty, which means there is a great likelihood that the system to be favoured for this impact could be reversed.

Table II: System with the Lowest Impact Score in Each Category			
Damage Category	**Impact Category**	**CC System**	**AM System**
Human health	Human “cancer” toxicity	√	
	Human “non-cancer” toxicity		√
	Respiratory effects (inorganic)		√
	Ionizing radiation		√
	Thinning of the ozone layer		√
	Respiratory effects (organic)		√
	Human health		√
Ecosystem quality	Aquatic eco-toxicity		√
	Terrestrial eco-toxicity		√
	Terrestrial acidification		√
	Land use		√
	Ecosystem quality		√
--	**Aquatic acidification**		√
--	**Aquatic eutrophication**	√ (functional classes 8, 12 and 16)	√
Global warming	Global warming		√
	Global warming		√
Resources	Mineral mining		√
	Non-renewable energy		√
	Asphalt inherent energy	√	
	Resources	√	
(red)	Negative numbers occur when a decrease in the damage/impact indicator score is obtained by replacing asphalt with concrete pavement. **Favours the concrete pavement (CC).**		
(green)	Positive number occurs when an increase in the damage/impact indicator score is obtained by replacing asphalt with concrete pavement. **Favours the asphalt pavement (AM).**		

To simplify the presentation of graphic results, a comparative analysis for those six indicators (four damage indicators and two impact indicators) was carried out for functional classes and 1 and 16 only, which represents one class for which the aquatic eutrophication indicator favours the CC system and one class for which this indicator favours the AM system (even though results are presented only for two functional classes, the consistency of trends was verified for all classes).

Figure II shows the comparative damage indicators (CC results – AM results) for the four damage indicators, as well as the comparative impact indicators (CC results – AM results) for the two impact indicators, for functional classes 1 and 16.

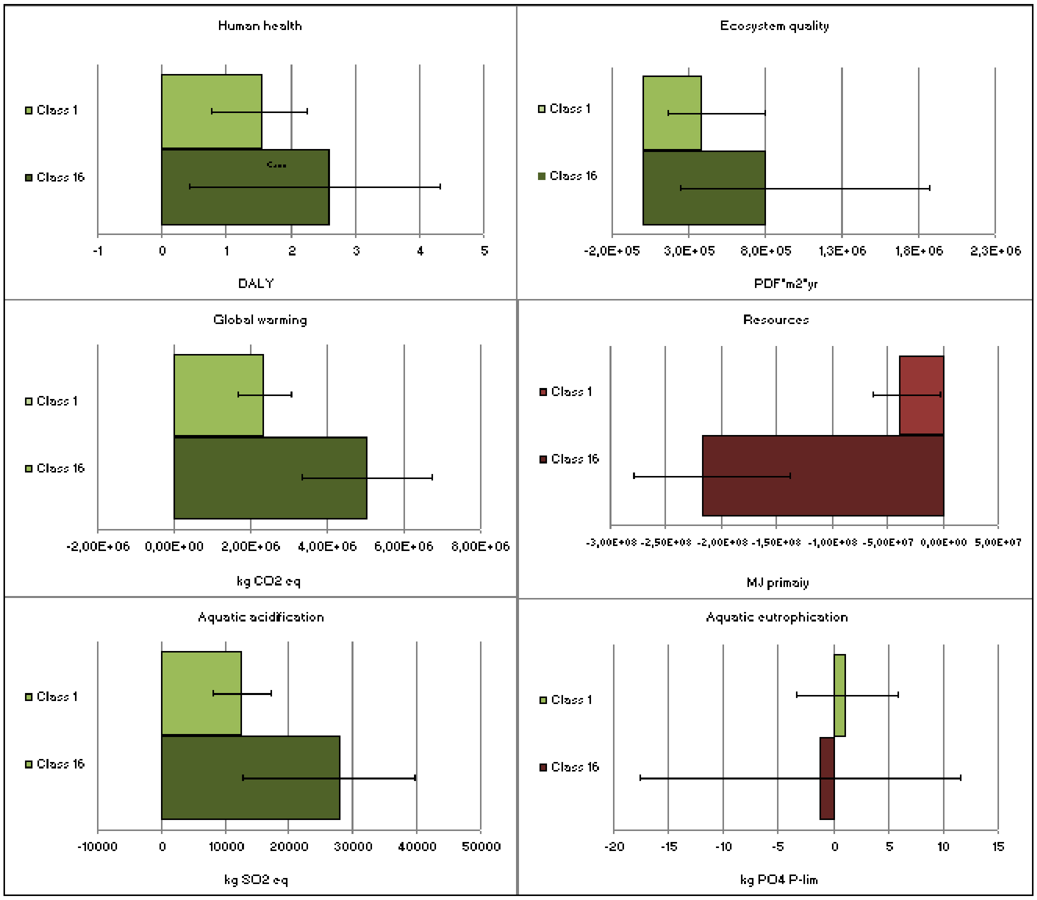


Figure II: Damage and Impact Indicator Results of the Comparative Life Cycle of Pavement Types (CC System – AM System) for Functional Classes 1 and 16[1]

Negative numbers (in red) indicate a higher damage or impact score for the AM system, while positive numbers (in green) indicate that the CC system shows a greater damage or impact score. For all functional classes, the human health, ecosystem quality, global warming and acidification indicators favour asphalt pavement.

As for aquatic eutrophication, functional classes 8, 12 and 16 favour the CC system, while the other 13 classes favour the AM system.

[1] DALY = Disability-Adjusted Life Years; PDF = Potentially Disappeared Fraction (of species)

The graphic also shows uncertainty intervals for the indicators, along with minimum and maximum values. These intervals show that there can be no overlap between a positive value and a negative value for any of the indicators, except in the case of aquatic eutrophication, for which no clear results emerge.

The damage indicator for non-renewable resources consumption can be broken down into primary non-renewable energy attributable solely to asphalt (through its inherent energy) and other primary non-renewable energy and minerals attributed to the rest of the system (not including asphalt inherent energy). Figure III shows the comparative results (CC damage – AM damage) for the broken down indicator of resource use for functional classes 1 and 16.

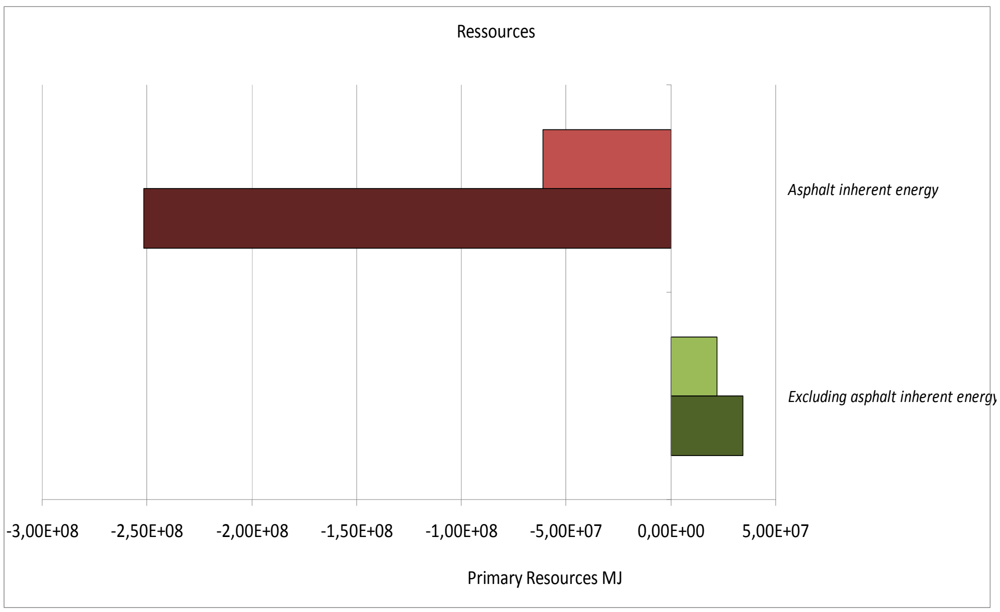


Figure III: Resource Use Indicator Result of the Comparative Pavement Life Cycle (CC System – AM System) for Functional Classes 1 and 16 (Showing Separately the Asphalt Inherent Energy)

However, since IMPACT 2002+ does consider the total primary energy, when the asphalt inherent energy is included the CC system is clearly favoured. In fact, the asphalt inherent energy represents an average of 76% of total primary energy across all 16 classes for the AM system, whereas it represents only 30% for the CC system, which explains the decisive difference between the two types of pavement for this indicator.

Sensitivity Analyses

The sensitivity analyses measure the sensitivity of the conclusions to a variation in:

1. Transportation distances for materials between their supply site to the road construction site;
2. The environmental profile of asphalt production;

3. The asphalt fume emissions in the asphalt production data;
4. The environmental profile for constructing Continuously Reinforced Concrete Pavement (CRCP) instead of Jointed Plain Concrete Pavement (JPCP) (only for functional class 16);
5. The impact assessment method;
6. The environmental profile of cement production;
7. The amount of fuel consumed by vehicles according to the type of pavement (although this parameter was excluded from the boundaries of this study, it appears important over the life cycle of a road, especially in a comparative context where there could be a significant difference between the two options);
8. The carbonation process over the entire life cycle of cement concrete, absorbing a portion of CO_2.

Theses sensitivity analyses have shown the findings are not likely to be changed, while the choice of the LCIA method could, on the contrary, influence some of the findings. More specifically, according to the individualist approach of the European Eco-indicator 99 method, the four damage indicators unanimously favour the AM system. It is important to note, however, that under Eco-indicator 99's individualist approach, only proven effects are taken into consideration, and the use of non-renewable resources is not included (a value choice that needs to be considered in a transparent manner).

As for the analysis carried out on asphalt fume emissions, the addition of PAH emissions does not change the study's findings. Although the difference between the two systems on the human health indicator decreases, the AM system is always favoured in this damage category, and the other indicators remain unchanged.

The sensitivity analysis on CRPC showed that the four damage indicators are higher for the CRCP CC system than for the reference JPCP CC system. This is partly due to the increased amount of cement and steel and to the composite, which is not included in the JPCP CC system. However, compared to the AM system, the findings of the study have not changed, i.e., all indicators are lower for the AM system, with the exception that the resource consumption indicator is always higher.

Conclusions and Recommendations

With regard to damages, the human health, global warming and ecosystem quality indicators all favour the AM system for each of the 16 functional classes, while the resource consumption indicator always favours the CC system. The acidification impact indicator favours asphalt pavement, while the aquatic eutrophication indicator, which introduces significant uncertainty, does not allow us to determine the system to be favoured for this impact.

As indicated by the literature review, over the life cycle of pavement, road traffic is responsible for most of the total impacts, in all categories. Thus, any fuel savings, even marginal, could clearly favour one type of pavement over another (assuming the type of pavement significantly influences fuel consumption, which remains to be validated).

Considering these results, it is difficult to favour one option without being able to validate the influence of the type of pavement on fuel consumption or without making a value choice so as to weigh the different impact indicators.

According to the ISO standard (2006), when the results obtained based on natural sciences do not clearly favour one option of the LCA, a decision can be made by making a value choice. By using weighting factors, several indicators can be aggregated into a single score in order to be able to decide between the options. These value choices are up to the entity that commissioned the study (the MTQ) and should be presented in a transparent way. For information purposes, a simulation showed that the favourable option can be targeted through different combinations of possible weightings for the four damage indicators. This data will be taken into consideration as part of decision making.

It is also important to note that the results obtained through this study were a function of a technological system that remains static over the 50-year period being considered. No one is currently in a position to accurately characterize the evolution of techniques for producing construction materials, pavement design and construction technologies or environmental regulations, although the market's competitiveness will most likely change the analyzed system and, therefore, the results of this study. As such, several new pavement technologies are emerging, such as cold mix, improved recycling techniques, polymer-modified asphalt which extends the pavement's useful life, etc. It would therefore be advisable for the MTQ to look at the environmental relevance of those pavement innovations.

Finally, as mentioned in the literature review, several road construction elements can reduce the environmental and social impacts of pavement: the choice of materials, road design, site design and intrinsic impacts of construction. From a sustainable development perspective, these considerations are factors that could possibly be integrated into MTQ transportation-related policies, regardless of the type of pavement.

In sum, since any decrease in fuel consumption represents a significant decrease in the life cycle impacts of any type of pavement, the focus should be on reducing fuel consumption by encouraging the use of greener vehicles or carpooling, for instance.

Limitations

The results presented for the damage and impact indicators stem from calculations made by essentially using the models of the IMPACT 2002+ assessment method. <u>Assessed damages (and impacts) are potential damages (and impacts), since they are the result of modelling, which implies a simplification of the real environment.</u> LCIA results are relative expressions that cannot predict effects on final impacts by category, exceeded thresholds, safety margins or risks. As such, these results should not be used as the sole basis for a comparative statement intended to be publicly disclosed, given that additional data would be required to remedy certain limitations inherent in LCIA. The results could potentially be refined through the use of other tools such as risk assessment, or following potential methodological improvements.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

BOD5	Biological oxygen demand (5 day)
BQ	Bitume Québec
CAC	Cement Association of Canada
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CIRAIG	Interuniversity Research Centre for the Life Cycle of Products, Processes and Services
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CRCP	Continuously reinforced concrete pavement
DALY	Disability-adjusted life year
DOC	Dissolved organic carbon
EAPA	European Asphalt Pavement Association
EPD	Environmental Product Declaration
GENI	Global Energy Network Institute
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
JPCP	Jointed Plain Concrete Pavement
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
ISO	International Organization for Standardization
IVL	Swedish Environmental Research Institute
LCCA	Life cycle cost analysis
LUCAS	LCIA method used for a Canadian-specific context
MTQ	Ministère des Transports du Québec
NaCl	Sodium chloride
NO_x	Nitrogen oxides
NPRI	National Pollutant Release Inventory
PAH	Polycyclic aromatic hydrocarbon
PaLATE	Pavement Life cycle Assessment Tool for Environmental and Economic Effects

PCR	Product Category Rule
PDF	Potentially disappeared fraction
PG	Performance grade
QRBHCA	Québec Road Builders and Heavy Construction Association
SO_2	Sulfur dioxide
TOC	Total organic carbon
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compound

1. INTRODUCTION

As part of the update of its Departmental Policy on Pavement Type Selection (the "Policy"), the **ministère des Transports du Québec** wishes to integrate life cycle assessment (LCA) into the decision-making process for the selection of pavement types. The current decision-making process is based on an overall life cycle cost analysis (LCCA) for all monetizable monetized parameters. The LCA's objective is to integrate environmental parameters into the selection of pavement types. It is a methodological tool to assess, using internationally recognized methods, the potential environmental impacts of a product or activity over its entire life cycle. It is therefore a holistic approach to identify the "hot spots" in a system and ensure that the decisions taken do not displace pollution from one life cycle stage or impact category to another.

A feasibility study carried out in 2005 for the MTQ by the Interuniversity Research Centre for the Life Cycle of Products, Processes and Services[2] (Martineau et al., 2005) found that:

[Translation]

"… a high-quality comparative LCA is feasible. The results of the inventory (quantity of materials and energy vectors entering into the life cycle of both types of pavement) and the assessment of the associated potential impacts (such as the potential contribution of both types of pavement to global warming, ozone depletion, smog formation, acidification, etc.) are clear and transparent environmental parameters that could be integrated into the decision-making process for selecting pavement types."

CIRAIG was then commissioned by Ronald Collette, an engineer with the Service de l'environnement at the MTQ's Direction du développement durable, de l'environnement et de la recherche, to carry out an environmental comparison of cement concrete and asphalt pavement.

The objectives of this study and the methodology employed are detailed in Chapter 3, while Chapters 4 and 5 discuss the results of the subsequent LCA phases, in accordance with the International Organization for Standardization (ISO 14 040 series).

The methodological framework outlined in Chapter 3.0 was established based on, among other things, a review of the available literature on the subject, which is summarized in the next chapter (Chapter 2).

Finally, Appendix A sets out the LCA methodology in greater detail, complete with a section defining various subject-specific terms.

[2] Known as CIRAIG

2. LITERATURE REVIEW

A literature review was first conducted to take stock of the research carried out around the world on the environmental life cycle assessment of road pavement. The objective of this review was to compare the different methodological choices made and the main results achieved, which in turn facilitated the development of the study design.

This chapter gives an overview of cement concrete and asphalt pavement built in Québec, followed by a review of available studies on the environmental impact of both types of pavement.

2.1 Profile of the Québec Road Network

Québec's road network includes approximately 185,000 km of roads of all categories (motorways, main roads, secondary roads, streets and local roads). The portion of the road network that falls under MTQ responsibility spans 29,100 km, including all motorways, of which twenty-five percent (25%), or 1,239 km, are built in cement concrete (covered or not in asphalt),. Those are found in the greater Montréal area in 75% of the cases, and serve 35% of all motor vehicle traffic in Québec (MTQ, 2001).

2.2 Review of Environmental Life cycle Studies of Pavement

Several studies comparing the environmental impacts of cement concrete pavement to those of asphalt pavement were completed in recent years. However, many of them are private reports or academic studies that are difficult to get access to. Nevertheless, some of those studies or bibliographic reviews summarizing their content were obtained. This literature review was based on those documents and on articles published in academic journals and conference reports.

A certain number of the articles identified deal indirectly with LCA applied to road pavement, by focusing for instance on the use stage (Eriksson et al., 1996; Pereira et al., 1998) or on the use of industrial by-products or recycled materials for road construction (Broers et al., 1994; Eskola et al., 2000; Mroueh et al., 2001; Roth and Eklund, 2003; Ventura et al., 2004). Another study proposes a method to include the noise and health effects of road traffic into LCAs (Muller-Wenk, 2004), while Treloar et al. (2004) worked to develop a partially simplified, hybrid LCA method that can apply to road construction as well as vehicle manufacturing, maintenance and use. These studies are not discussed further here. Instead, the focus was on studies that deal directly with comparative LCAs of cement concrete and asphalt pavement. The main parameters and findings of those studies are shown in Table 2-1 and in Appendix B.

2.2.1 Perspective on the Impacts of Road Traffic

It should be noted that all studies identified by Pereira et al. (2001) came to the same conclusion: it is the use stage—the road traffic—that represents 95 to 99% of environmental impacts associated with pavement life cycle. In addition, the report published by the Eurobitume and European Asphalt Pavement Association (EPEA) working group on fuel efficiency finds that fuel consumption is more influenced by the general state of the road than by the type of pavement (Beuving et al., 2004).

Despite these results, the MTQ wanted an environmental indicator for its Policy that 1) is based on a comparison of the environmental performance of both types of pavement, and 2) assumes that the road traffic stage is similar for the different options considered (therefore, by excluding this stage from the boundaries of the study).

Table 2-1: Main Parameters and Findings of the Reviewed Studies

Parameter	Swedish National Road Administration Stripple (1995, 2001)	Athena Sustainable Materials Institute Trusty (1999, 2005)	Transportation Research Board Horvath and Hendrickson (1998)	Eurobitume Blomberg (1999)
Type of study	Analysis and comparison of the life cycle inventory of pavement	Comparative LCA of pavement with regard to intrinsic energy and GHG emissions	Extremely simplified inventory analysis of pavement, carried out solely based on publicly available data	"Partial" life cycle inventory of asphalt and "eco-profile" of asphalt
Materials studied	Cement concrete and asphalt	Cement concrete and asphalt	Cement concrete and asphalt	Asphalt
Function	Allow motor vehicle traffic	Allow motor vehicle traffic	Overlay a section of pavement	Produce asphalt for road covering
Functional unit	Allow motor vehicle traffic over a 1 km long and 13 m wide road segment, assessed over a 40-year period	Allow motor vehicle traffic over a 1 km long and 3.75 m wide road segment, assessed over a 40-year period (50 years in the 2005 update)	Overlay a 1 km long and 7.2 m wide road section	Produce 1 kg of asphalt for road covering
Geographic context	European context	Canadian context	American context	European context
Time period	The time period considered is 40 years. Most data is for the period from 1990 to 1998.	The time period initially considered was 40 years. Following an update of the study in 2006, the period was changed to 50 years.	Not specified	Not specified
Included processes and flows	• Extraction of raw materials • Production of construction materials • Construction of pavement • Maintenance of pavement and curbs (ditches, lawn mowing, etc.) • Operation (lighting systems, signs and signals, salt spreading) • End-of-life management	• Extraction of raw materials • Production of construction materials • Construction of pavement (including the sub-base and base surface) • Maintenance of pavement and curbs	• Extraction of raw materials • Production of construction materials	• Extraction of crude oil • Transportation to Europe • Refining • Asphalt storage
Excluded processes and flows	• Vehicle traffic	• Activities deemed common to both types of pavement: • Construction of the right-of-way, marking, construction of barriers, restoration of the right-of-way • Initial deforestation • Transportation of asphalt or cement concrete to the construction site • Initial construction …	• Activities deemed common to both types of pavement: • Base and sub-base • Transportation of materials • Pavement maintenance • Vehicle traffic • Lighting, signs and signals	None

Table 2-1: Main Parameters and Findings of the Reviewed Studies

Parameter	Swedish National Road Administration Stripple (1995-2001)	Athena Sustainable Materials Institute Trusty (1999-2006)	Transportation Research Board Horvath and Hendrickson (1998)	Eurobitume Blomberg (1999)
Main assumptions	• The energy, resources and emissions related to traffic are not included; however, the mechanical effect of traffic on the road is considered in the maintenance steps	• The pavement contains 0% and 20% recycled materials (2 scenarios) • The data is adapted to regional particularities (production of electricity, production process)	• Only the surface layer was taken into consideration, as the rest was considered identical for both types of pavement	• Inputs and outputs are allocated on a mass basis • Asphalt is a 100% recyclable construction material
Asphalt inherent energy calculated?	Yes	Yes	Not specified	No
LCIA method	Not applicable (inventory analysis only)	Not specified	Not applicable (inventory analysis only)	Not applicable (inventory analysis only)
Main findings	• The total energy associated with the construction, operation and maintenance of 1 km of road over 40 years is 23 TJ for asphalt pavement and approximately 27 TJ for concrete pavement • Road operation is the main contributor (12 TJ to light traffic signals) • NO_x, SO_2 and CO_2 emissions are mainly associated with road construction	• Energy consumption is much greater for asphalt pavement than for concrete pavement (increase of around 200 to 300%) • If we exclude the asphalt inherent energy, the difference is less significant (3 to 30%) • Asphalt pavement represents potential GHG emission reductions of 41 to 82% compared to concrete pavement • Transportation represents only a small portion of the primary energy consumed and GHG emissions	• Considering the uncertainties, the quantity of raw materials required for the construction of both types of pavement is about the same • The asphalt scenario seems to generate more toxic waste than cement concrete pavement	• Eco-profile of 1 kg of asphalt (energy consumption, main air emissions, liquid and solid materials discharged, quantity of raw materials required) • About 50% of the primary energy consumed and CO_2 emitted is caused by the extraction of oil (about 25% for the production of asphalt) • Around 60% of NO_x emissions are caused by transportation • The storage of asphalt represents about 7% of CO_2 and SO_2 emissions

3. STUDY DESIGN

The next sections describe the first phase of LCA, which consists in defining the study's objectives and scope, in accordance with the ISO standard. This chapter describes the study design used to define the methodological framework guiding the subsequent LCA phases.

3.1 Study Objectives

3.1.1 Purpose of the Study

The purpose of this study was to compare the potential environmental impacts of the life cycle of cement concrete pavement made of Jointed Plain Concrete Pavement (JPCP) to those of asphalt pavement. In both cases, the configurations were representative of the infrastructure.

3.1.2 Intended Application

The study's goal was to allow the MTQ to gain a better understanding of the potential environmental impacts related to the life cycle of both types of pavement used on Québec's road network. Ultimately, the study aimed to compare the potential environmental impacts related to the construction of new cement concrete pavement to those of new asphalt pavement in order to provide an environment indicator for the Policy. This study does not cover the reconstruction of existing roads.

3.1.3 Targeted Audience

While the study is intended for internal use by the MTQ, its results could be made available to contributing stakeholders, namely the following three industrial associations:

- Bitume Québec;
- Cement Association of Canada (CAC);
- Québec Road Builders and Heavy Construction Association (QRBHCA).

In addition, while public disclosure of the results is not foreseen, these results will support a comparative statement used for an MTQ decision-making process. They will therefore undergo a critical review by a stakeholders committee (see sub-section 3.2.7).

3.2 Study Scope

3.2.1 Functions, Functional Unit and Reference Flows

The following paragraphs outline the analyzed function, as well as the secondary functions, the functional unit and the reference flows for the case under study.

3.2.1.1 Functions

The main function for both types of pavement analyzed is as follows:

"Allow vehicle traffic over a given distance and over a given period of time."

It should be noted that, in some cases, for instance when pavement is under repair, materials can be collected and reused elsewhere. The production of such secondary materials is therefore considered to be a second function of the system, and the system is considered multifunctional.

For multifunctional systems examined under a comparative LCA, all the elementary processes that give the systems their multifunctional character must be identified. It is then required to establish in what proportion the impacts of these processes should be allocated to the analyzed systems and to the other systems that benefit from the secondary functions of the multifunctional processes (in this case, the materials that are collected and reused elsewhere).

The treatment of secondary functions is discussed in sub-section 3.2.3.

3.2.1.2 Functional Unit

The functional unit results from the quantification of the analyzed function, namely allowing motor vehicle traffic over a given distance and over a given period of time.

A distance of 5 km and a period of 50 years were established by the MTQ. Since the demolition and reconstruction steps are not completed in the same year for the two different types of pavement, this 50-year period is based on the maximum useful life of both options being studied. In addition, since it is difficult to determine to what extent the next life cycles of rebuilt pavement will be identical to the first cycle following initial construction (for instance, in which context and under which conditions will the base and sub-base need to be replaced or modified?), the comparative analysis was carried out for the first 50-year span of the pavement's initial life cycle. More specifically, as part of this comparative study, the functional unit is expressed as follows:

"Allow vehicle traffic over a 5 km distance and over the first 50 years of life of cement concrete pavement, compared to asphalt pavement built in Québec in 2009."

3.2.1.3 Reference Flows

Reference flows for this study represent the fractions of system inputs and outputs attributable to the first 50 years of life of 5 km of pavement.

3.2.2 System Boundaries and Description

The following paragraphs provide a general description of the systems being analyzed and specify the processes and flows initially excluded from the boundaries, as well as geographic and time boundaries.

3.2.2.1 General System Description

Figure 3-1 shows the boundaries of the analyzed systems (this graphic representation is further detailed in Appendix C). It should be recalled that this was a complete, "cradle-to-grave" comparative analysis, which included each pavement life cycle stage, from the initial construction of a new road segment to the complete end-of-life reconstruction.

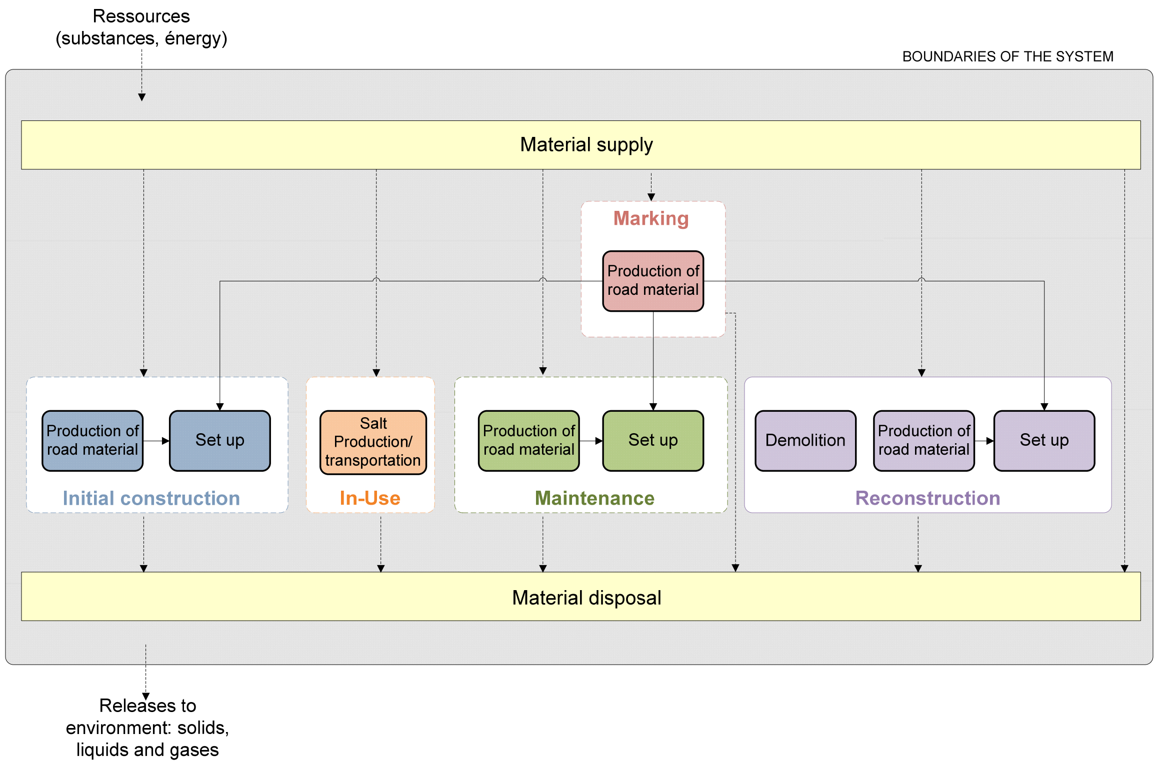


Figure 3-1: System Boundaries

Also note that by determining the number of vehicles travelling on any segment of the road network, especially the number of trucks, and the type of traffic (urban vs. rural), the MTQ is able to identify 16 functional classes (as defined in Table 3-1). The classes are divided according to the number of lanes and the structural dimensions of the pavement itself, for both types of pavement, for a total of 32 road designs (as shown in Table 3-2).

Table 3-1: Pavement Functional Classes Specified by the MTQ

	TYPE OF TRAFFIC	URBAN		RURAL	
	% TRUCKS	5	10	10	25
Number of lanes	Traffic (000)[1]	Functional Class Number			
2	20	#1	#2	#3	#4
	40	#5	#6	#7	#8
3	50	#9	#10	#11	#12
	90	#13	#14	#15	#16

[1] Daily highway traffic (total number of vehicles).

Table 3-2: Pavement Layers Thickness for the Functional Classes Specified by the MTQ

		TYPE OF TRAFFIC	URBAN		RURAL	
		% TRUCKS	5	10	10	25
No. of lanes	Traffic (000)	Layer thickness (mm)				
Cement concrete pavement						
2	20	Cement concrete	162 150	190 150	217 150	275 150
		MG-20 base[1]	150 162	150 190	150 217	150 275
		MG-112 type A[1] sub-base	929 929	885 885	843 843	756 756
2	40	Cement concrete	186 150	214 150	242 150	304 150
		MG-20 base	150 186	150 214	150 242	150 304
		MG-112 type A sub-base	890 890	847 847	805 805	713 713
3	50	Cement concrete	187 150	214 214	242 242	305 305
		MG-20 base	150 187	150 150	150 150	150 150
		MG-112 type A sub-base	889 889	847 847	805 805	712 712
3	90	Cement concrete	198 198	225 225	254 254	318 318
		MG-20 base	150 150	150 150	150 150	150 150
		MG-112 type A sub-base	872 872	830 830	788 788	693 693
Asphalt pavement						
2	20	Asphalt	184 90	209 90	237 105	293 143
		MG-20[1] base	281 375	293 412	298 430	324 474
		MG-112 type A[1] sub-base	776 776	723 723	675 675	564 564
2	40	Asphalt	206 90	233 103	263 120	318 164
		MG-20 base	293 409	304 434	305 448	345 499

Table 3-2: Pavement Layers Thickness for the Functional Classes Specified by the MTQ

		TYPE OF TRAFFIC	URBAN		RURAL	
		% TRUCKS	5	10	10	25
No. of lanes	Traffic (000)	Layer thickness (mm)				
		MG-112 type A sub-base	727 727	674 674	629 629	504 504
3	50	Asphalt	207 90	234 234	263 263	319 319
		MG-20 base	291 408	301 301	310 310	343 343
		MG-112 type A sub-base	728 728	676 676	624 624	505 505
3	90	Asphalt	217 217	245 245	274 274	330 330
		MG-20 base	297 297	306 306	311 311	356 356
		MG-112 type A sub-base	706 706	654 654	607 607	475 475

For each class, the first figure refers to traffic lanes, while the second one (underlined) refers to shoulders.
Traffic lane width: 3.7 m.
Shoulder width: 2 lanes (1.3 m to the left, 3 m to the right), 3 lanes (3 m both side).
[1] For shoulders: unbound aggregate bases.

The life cycle of pavement therefore starts with the **initial construction** of a road segment. This includes the entire construction of the pavement, from the placement of base materials to the marking of the road.

The **in use stage** includes the spreading of de-icing salt in winter, while the **maintenance stage** includes the intervention sequence outlined in Table 3-3 over the 50-year period, as well as the restoration of markings.

At the end of its useful life, the pavement's cement concrete slab or asphalt layer is completely replaced. The **reconstruction stage** therefore implies the complete demolition of traffic lanes and shoulders, followed by the placement and marking of a new concrete slab (or a new asphalt layer) of the same thickness. It should be noted that reconstruction does not involve the base and sub-base. Since reconstruction can occur at different times for the 16 functional classes, the environmental impacts of reconstruction are allocated to the product systems on a pro rata basis according to the number of years remaining in the 50-year period considered under this study. For instance, with regard to class 16 for cement concrete pavement, reconstruction is multiplied by 4/46, i.e., the number of years remaining to complete the 50-year cycle, divided by the useful life of the concrete slab.

Finally, for each of the preceding four foreground sub-systems (construction, operation, maintenance and reconstruction), the background "**material supply**" and "**material disposal**" sub-systems respectively involves all activities associated with:

- Procurement of resources (water, energy, chemicals, materials), including extraction, treatment and processing of natural resources, as well as transportation to the site where resources will be used;
- Transportation and treatment of waste generated in any of the life cycle stages, considering different possible outcomes (ex: reuse, recycling, energy recovery).

Table 3-3: Intervention Sequence for the Functional Classes Specified by the MTQ

Intervention	#	Timing of work (year)			
		Classes 1, 2, 3, 5, 6, 9, 10, 13, 14	Classes 4, 7, 11, 15	Classes 8 and 12	Class 16
Cement concrete pavement (JPCP type)					
Cement concrete construction, JPCP type (compliant transverse grooving)*	1	0	0	0	0
Restore 25% of joints	2	10	10	10	10
Minor repairs (0.5%), restoration of all joints and grinding (25%)	3	19	19	19	19
Major repairs (4%), grinding (25%) and grit blasting (75%)	4	29	29	29	29
Asphalt correction (60 kg/m^2) and asphalt resurfacing (120 kg/m^2)*	5	39	39	39	39
Reconstruction of cement concrete slab only *	6	50	49	47	46
Asphalt pavement					
Construction using only asphalt	1	0	0	0	0
Levelling (40 mm) and resurfacing (100 kg/m^2)	2	14	12	10	9
Levelling (50 mm) and resurfacing (120 kg/m^2)*	3	27	23	19	17
Levelling (50 mm) and resurfacing (120 kg/m^2)*	4	39	33	27	25
Levelling (50 mm) and resurfacing (120 kg/m^2)*	5	---	---	34	32
Complete removal of road surface and placement of new asphalt *	6	49	42	40	38
Levelling (40 mm) and resurfacing (100 kg/m^2)*	7	---	---	---	47

* Shoulders included in the intervention

3.2.2.2 Processes and Flows Outside the Boundaries

The following elements were excluded from the boundaries right from the start:

- **Human activity** (e.g., daily worker commute);
- **Life cycle of the concerned capital goods** (e.g., manufacturing, maintenance and end-of-life management of road building machinery), except for those already included in the ecoinvent data modules used in the LCA model (see paragraph 3.2.4.1).

In addition, the comparative LCA must pay special attention to the processes that are different in the compared systems. Thus, all processes deemed to be identical or that could not be differentiated between the two types of pavement were not considered. More specifically, the following elements were not included:

- Initial deforestation;
- Snow removal and curb maintenance activities (ditches, weed control, etc.) related to roadway operation;
- Processes associated with the life cycle of fences and parapets, signs and the lighting system;
- Road traffic.

3.2.3 Attribution Approach

This sub-section outlines the rules followed to allocate the impacts associated with the system's secondary functions, namely the production of asphalt and diesel (any refinery produces several coproducts) and the generation of by-products reused outside the study boundaries (materials collected from the existing pavement).

Note that the attribution of impacts associated with secondary functions can be avoided by expanding the boundaries of the system so as to include the processes concerned by those functions (e.g., by crediting to the expanded system the impacts from the production of virgin materials that are avoided through recycling). The latter approach is normally reserved to "consequential" LCAs that are developed to assess the consequences of the analyzed system on other systems or to guide specific decisions. It could in fact have been used here to compare the results obtained according to various attribution approaches.

3.2.3.1 Refining

Refining is a multifunctional process that was broken down into single-function sub-processes. This implies that the refinery is made up of sub-refineries, each one processing a fraction of the crude oil. The asphalt production sub-process is thus considered a single-function system, and the production of one kilogram of asphalt can be tracked from beginning to end (from the oil well to its final processing at the refinery). More specifically, data on energy consumption and emissions has been provided for the production of one kilogram of asphalt rather than for all the refinery's activities. That in turn has permitted to avoid mass allocation over all the refinery products.

3.2.3.2 Materials Reused Outside the Boundaries

As for recycled materials, the processes to generate them are entirely allocated to their user. So in one hand, the processes for generating recycled materials that are used in the construction of the sub-base and the asphalt surface (crushing, grinding, milling, etc.) are taken into consideration in the analyzed system itself. While on the other hand, the processes generating recycled materials that are taken out of the road construction site are not considered in the system because they fall under the responsibility of another user.

3.2.4 Life cycle Inventory (LCI) Data

This sub-section gives an overview of data sources relied upon and of the quality requirements that apply to the data used. These requirements guided the collection of the data and also supported its validation.

3.2.4.1 Data Sources

The goal of this LCA is to provide environmental data for the comparison of the life cycle of two types of pavement in Québec. It was carried out so as to take advantage of the latest available **primary data**, i.e., recent data from Québec based industries in accordance with good practices and actual practices in Québec. This data was obtained from industrial associations that are stakeholders in the project (BQ, CAC and QRBHCA), Petro-Canada's Montréal refinery and the MTQ.

Missing, incomplete or hard-to-access data was complemented with assumptions and **secondary data**, including generic or theoretical data taken from the literature and commercial LCA databases. The available secondary data included a few LCA databases that are recognized by the international scientific community, in particular the European ecoinvent database, version 2.0 (www.ecoinvent.ch). This database is currently the most complete available and by far surpasses the others, both in quantitative (number of processes included) and qualitative (quality of validation and documentation processes, completeness of data, etc.) terms.

3.2.4.2 Data Quality Requirements

The reliability of the LCA's results and findings depends on the quality of the inventory data used. Therefore, it is important to ensure this data meets the specified requirements, in accordance with the study's objective.

According to the ISO standard, data quality requirements should at least ensure the data's **validity**, which means, in this case, how representative the data is with regard to age, geographic origin and technological performance. The data used should be representative of:

- The time period defined by the functional unit, i.e., from 2009 to 2059;
- The geographic context of the analyzed systems;
- The technological characteristics of the unit processes that they describe.

It should be noted that current LCI databases are more or less representative of the context (Québec and Canada) in which the compared systems are located. These databases mostly contain technological averages that are representative of the European context. They can, however, be adapted to the extent that their data is sufficiently disaggregated and that the available information allows it. For instance, some European data on the production of different materials makes reference to other data (for the production of the required energy, for example). This other data can then be replaced by energy production data specific to Québec, thereby improving the geographic representativeness of the European data available on the production or processing of materials.

Thus, while most of the generic data modules used for this study come directly from the ecoinvent database, several of these modules were adapted to make them more representative of the actual products and context being analyzed. In particular, for all activities taking place in Québec (production of: diesel, cement, asphalt, cement concrete and asphalt mix; and pavement construction, operation and maintenance), the ecoinvent modules were adapted by replacing the European energy procurement mixes (or electricity grid mixes) with:

- The Québec grid mix for foreground processes, i.e., processes directly related to the analyzed systems (e.g., electricity consumed for producing cement, asphalt, cement concrete, asphalt mix, diesel and granular materials);
- The North American grid mix for background processes, i.e., all processes directly and indirectly related to foreground processes (e.g., all resources consumed to produce the electricity required for making pavement construction materials). The North American grid mix is more appropriate here, considering that procurement and the management of waste generated at the various life cycle stages are not carried out solely in Québec. Also, all foreground processes taking place in Québec (including transportation) rely on background processes that are adapted to the North American energy context;
- As specified by Petro-Canada's Montréal refinery and described in Appendix E, crude oil used for producing the asphalt and the diesel used by all mechanical equipment and for road transportation in Québec, was modelled as being Mexican. Electricity consumed during loading on board the oil tanker in Mexico was therefore modelled based on the Mexican grid mix, as presented by the National Energy Grids library of the Global Energy Network Institute (www.geni.org). Electricity consumed during transportation along the pipeline from Portland to Montréal is 60% based on the New England grid mix, as shown on the site of the United States

Environmental Protection Agency (USEPA) (www.epa.gov), and 40% based on the Québec grid mix.

Finally, while no particular method is currently prescribed by ISO concerning the **completeness** and **accuracy** of data, the following recommendations should be considered:

- Data should be collected in the least aggregated form possible (aggregations by technology type or area to be avoided);
- Data should be documented (metadata) in accordance with available best practices.

Applying these recommendations will ultimately allow an assessment of the completeness and accuracy of data used in the LCA.

3.2.5 Assessment of Life cycle Impacts

It was initially proposed to assess life cycle impacts on the basis of the LUCAS Canadian method (Toffoletto et al., 2007). However, it was instead decided to conduct the life cycle impact assessment (LCIA) based on the internationally renowned method known as IMPACT 2002+ (Jolliet et al., 2003) and to verify whether the use of LUCAS led to variations in results. The latter method is limited to the characterization step, i.e., the conversion and aggregation of inventory results based on their contribution to each of the impact categories. Thus, unlike IMPACT 2002+, LUCAS does not propose any factors to convert the characterized results into damages. While the conversion of impacts into damages brings about additional uncertainties, analyzing four categories of damages, as opposed to over 10 impact categories, has the advantage of simplifying the communication of results.

Table 3-4 shows the impact categories considered under each of the two methods (which are detailed in Appendix D). Note that:

- These categories do not cover all the possible environmental impacts associated with human activities. Several types of impacts, such as noise, odours, radiation and electromagnetic fields, are therefore not included in this analysis, since little to no methodological advances have been made in those areas;
- Aquatic eutrophication and acidification are not taken into consideration by the damage indicators, since the IMPACT 2002+ method does not currently propose a way of converting those two impact categories into damages (ecosystem quality category). We therefore recommended considering the four damage indicator results along with the results for those two impact categories.

Finally, it should be noted that IMPACT 2002+ allows us to standardize damage indicators based on the average European equivalent, then to aggregate them into a single score (by implicitly applying an identical weighting factor of 1). Although such a weighting is prohibited by ISO in the case of publicly released comparative statements (given the importance of the value choices involved), some weighted results are presented here so as to facilitate their communication (in particular, the results of sensitivity studies attached to the report).

Table 3-4: Damage Categories and Impact Categories of the IMPACT 2002+ and LUCAS Methods

IMPACT 2002+		LUCAS
Damage Category	**Impact Category**	**Impact Category**
Human health	Human “cancer” toxicity	Human “cancer” toxicity
	Human “non-cancer” toxicity	Human “non-cancer” toxicity
	Respiratory effects (inorganic)	None
	Ionizing radiation	
	Thinning of the ozone layer	Ozone layer depletion
	Respiratory effects (organic)	Photochemical smog
Ecosystem quality	Aquatic eco-toxicity	Aquatic eco-toxicity
	Terrestrial eco-toxicity	Terrestrial eco-toxicity
	Terrestrial acidification/eutrophication	Terrestrial eutrophication
	Land use	None
Global warming	Global warming	Global warming
Resources	Non-renewable energy	Fossil fuels
	Mineral mining	Mineral mining
Not related to a damage category (relation known, but no conversion model available)	Aquatic acidification	Aquatic acidification
	Aquatic eutrophication	Aquatic eutrophication

3.2.5.1 Notes on Asphalt Inherent Energy

The decision to consider or not the asphalt inherent energy is a recurring question in LCAs. However, the most recent LCIA methods are clear on one thing: any non-renewable energy source taken from the earth’s energy capital is a potentially lost resource that has to be taken into consideration in the impact assessment (Goedkoop and Spriensma, 2001b; Bare et al., 2003; Jolliet et al., 2003; Toffoletto et al., 2007). Thus, if oil extracted to produce asphalt is not intended to be used as an energy source, but rather as a raw material, the consequence for the energy resources is no different than if the same oil was intended to produce fuel: the resource stock decreases, along with the available energy potential.

It is important to note that this reasoning applies to all oil derivatives whose function is not to produce energy, such as asphalt, plastics, aromatic extracts, perfumes, etc. Therefore, the heating value (or inherent energy) remains contained in these different products throughout their life cycle. Even though that energy seems “lost,” it is actually being stored and could eventually be reused. So the fact that asphalt can be recycled time and time again in a material form does not influence its calorific power, which remains intact.

Therefore, it appears essential to consider asphalt inherent energy in the assessment of the potential impacts of pavement. This consideration comes into play only with regard to the use of non-renewable energy and has no bearing on other impact categories. CO_2 emissions associated with the potential combustion of asphalt are not calculated until the asphalt is actually burnt.

In order to test the robustness of the results obtained with IMPACT 2002+, a sensitivity study was carried out using the Eco-indicator 99 method (Goedkoop and Spriensma, 2001a), which is presented in detail on the PRé Consultants website (http://www.pre.nl/download/EI99_methodology_v3.pdf). Although they are similar, the two methods treat non-renewable energy consumption differently, namely:

- Total primary energy, calculated based on the higher heating value of the energy resource (IMPACT 2002+);
- "Surplus" energy, i.e., by calculating the additional effort required to extract a resource whose quality is diminished (Eco-indicator 99). In this case, the characterization factors are calculated taking into consideration the long-term effects of the resource's reduced quality.

It is also important to note that Eco-indicator 99 is a "damage-oriented" method that considers 11 impact categories, but which:

- Does not consider aquatic acidification and eutrophication (even as impact indicators);
- Characterizes the impact of global warming in terms of potential damages to human health. This method thus presents three damage indicators, rather than four under the IMPACT 2002+ method.

This method also has the advantage of being available in three versions based on the Cultural Theory concept. This concept is used to address difficulties related to subjectivity in modelling and proposes five value systems based on the influence society has on individuals. In the Eco-indicator 99 method, the following three approaches are considered, which enables the user to choose the method most suited to his needs:

- Egalitarian (E): Long-term approach that considers all effects;
- Hierarchist (H): Medium-term approach where a scientific consensus determines whether effects are included or not;
- Individualist (I): Short-term approach that considers only proven effects.

3.2.6 Method for Calculating and Presenting Results Based on a Modular Approach

Once all required data were obtained, the systems were modelled using a commercial LCA software. The SimaPro software, developed by PRé Consultants (www.pre.nl), was used to calculate the inventory and assess the potential environmental impacts associated with inventoried flows.

At the request of the MTQ, a matrix of impact indicator results by unit process (or life cycle stage) was also developed. As shown in Appendix F (in Tables F-3.1.1 and F-3.2.1), each module (or matrix line):

- Allows essential pavement parameters to be specified upon entry (i.e., the amounts of materials consumed and the related transportation distances, as well as the intensity of pavement placement processes);
- Provides, for each of those parameters, an indicator result by impact and damage category.

The environmental profile of a functional class is then obtained, for each type of pavement, by adding the indicator results for all the included modules. This way, potential impacts of a variety of configurations and possible situations on the road network can be quickly assessed. However, it is important to mention that, in this comparative analysis where elements common to both systems were excluded from the study, it is not appropriate to present individual profiles for each type of pavement, especially considering that only differential quantities were collected for de-icing salt. Thus, only the comparative profiles between the two options should be used (as presented in Appendix F in Table F-4.1, tab 4).

3.2.7 Critical Review

A critical review is a procedure carried out to ascertain that the LCA meets international standards. Generally speaking, critical reviews of LCAs are optional, except in the case of publicly released comparative assertions. An LCA conducted in order to support a comparison intended for public release requires particular attention, given the risks associated with the misinterpretation of its results by the various stakeholders. Critical reviews also increase the credibility of the assessment.

Since this study involves various stakeholders and its results will be used as part of the MTQ's Policy, a critical review was carried out by a review committee with the required skills to validate assumptions, data and study procedures. This committee is under the responsibility of Yannick Le Guern, manager at BIO Intelligence Service S.A.S. and holder of a specialized masters of eco-design and environmental management from the École Nationale Supérieure d'Arts et Métiers.

In accordance with ISO 14 040, the objectives of the critical review were to ensure that:

- The methods used by CIRAIG to complete the life cycle assessment were consistent with the ISO 14040 international standard;
- The methods used by CIRAIG to complete the life cycle assessment were technically and scientifically sound;
- The data used by CIRAIG was appropriate and reasonable considering the study's objective;
- CIRAIG's interpretations reflected the study's identified limitations and objective;
- The detailed report was transparent and coherent.

In addition to those objectives, the critical review includes an in-depth verification of certain key results and of the product system modelling made with the SimaPro LCA software. The results of the review (comments and questions of the review committee and responses from CIRAIG) are presented in Appendix G.

3.2.8 LCA Applications and Limitations

This LCA, which seeks to improve the MTQ's understanding of the environmental impacts of the life cycle of both types of pavement found on Québec's road network, was carried out for a strictly comparative purpose. Readers should therefore avoid drawing conclusions from this study out of its original context.

The study's results may be used to target the relative strengths and weaknesses of both types of pavement according to different functional classes, so as to be able to determine in which conditions one option is preferable to the other.

The following main limitations apply to the findings obtained:

- Applicability of the different assumptions related to the life cycle of cement concrete pavement and asphalt pavement in Québec from 2009 to 2059: It should be noted that while technologies may very well evolve over the 50 years being considered, no one is currently in a position to accurately characterize the evolution of production techniques and road behaviour. Therefore, the technological system being analyzed is considered to be static;
- Completeness and validity of inventory data: In particular, the use of secondary data from European LCA databases may influence the validity of results in a North American and Québec context;
- Completeness and validity of impact assessment methods used, in particular because they do not cover all inventoried substances nor all environmental impacts associated with human activities. Also of note:
    - The human "cancer" and "non-cancer" and eco-toxicity impact categories are not a measure of the risk associated with the systems being assessed. The different emissions are aggregated in time and space to create an inventory in which a single flow is associated with each of the identified substances (i.e., the total mass emitted or released by all processes that generate the substance). Therefore, it is not possible to know where or when emissions are being released, and consequently, it is not possible to determine the amount to which a given region is exposed, which is the information needed to assess the risk for a given population;
    - Contrary to an environmental risk analysis conducted in a regulatory context using a conservative approach, LCA seeks to provide the best estimate possible (Udo de Haes et al., 2003). LCIA seeks to represent the most likely situation, which means that fate, exposure and effect models used to determine how contaminants

are transported and released in the environment and what are their toxic effect on biologic receptors, do so without maximizing exposure and environmental damage (as in a worst-case scenario), but rather try to represent an average situation;

- The fact that some parameters may not have any influence on the environmental profile of either type of pavement but could be important elements from the users' viewpoint was not taken into consideration in this LCA (e.g., noise caused by road traffic, tire wear and tear, the urban heat island effect and pavement reflectance).

4. LIFE CYCLE INVENTORY ANALYSIS

This chapter presents the second phase of the LCA: the inventory analysis. It explains the data collection methodology and sources that were used, describes the systems studied and the assumptions made, and includes an analysis of inventory results.

4.1 Data Collection Methodology and Sources

As indicated in sub-section 3.2.4, **primary data** were mainly collected from the MTQ, industrial associations involved in the project and Petro-Canada's Montréal refinery (hereinafter the "partners"). In particular,

- Consumption and transportation data for **asphalt and diesel production** representative of all refineries in Montréal were calculated based on data for the Petro-Canada refinery in Montréal (provided by Mr. René Dufresne). Refinery emissions were taken from Environment Canada's National Pollutant Release Inventory (NPRI) for the year 2006, with the scaling factors used to reduce annual emissions to values per kilogram of asphalt provided by Mr. Dufresne. More precisely, the total annual energy consumption for the refinery and the amount of energy consumed to produce 1 kg of asphalt were provided, which allowed the conversion of the annual emissions data to emissions per kilogram of asphalt produced;
- **Cement and cement concrete production** data were provided by the CAC based on its three Québec-based cement factories and taken from Athena Sustainable Materials Institute (2005), CANMET and Radian Canada Inc. (1993) reports. Cement factory emissions were also taken from the NPRI site for the year 2006, with the scaling factors used to reduce annual emissions to values per kilogram of cement provided by Mr. George Venta of the CAC;
- **Asphalt production** and **road construction site activity** data were provided by the QRBHCA;
- Detailed functional class descriptions (types and quantities of materials used, interventions taken during the **initial construction, operation, maintenance and reconstruction stages**) were provided by Mr. Denis Thébeau, and road marking data were provided by Mr. Michel Tremblay of the MTQ.

Data were collected from emailed questionnaires, telephone discussions and face-to-face meetings. Partners transmitted their data directly to CIRAIG. The information provided is shown in Appendices E and F.

In addition, several assumptions were made, particularly based on information provided by the MTQ. These assumptions are also documented in Appendix E.

Lastly, all of the processes included in the various pavement life cycle stages for which primary data was not obtained were modelled on available

secondary data. A summary of the secondary data used is provided in Appendix F.

Because most of the elementary processes included in the systems being analyzed were available in the ecoinvent LCI database, and in order to make the data used to model the processes as uniform and coherent as possible, this database was selected and adapted whenever possible (more specifically for the North American energy context, as discussed in paragraph 3.2.4.2). It should be noted, however, that several processes that had no exact equivalent in the ecoinvent database had to be modelled using proxy data or other sources.

In particular, the machinery required for the various construction, maintenance and reconstruction steps was characterized using data provided by the QRBHCA (for power and operating hours). However, data for certain equipment could not be obtained from the QRBHCA, and was instead modelled using the pavement modelling software PaLATE (http://www.ce.berkeley.edu/~horvath/palate.html) developed by the University of California, Berkeley. This software is able to identify the equipment used for certain pavement life cycle sequences and determine the amount of power and number of operating hours required by the equipment based on road parameters.

Combustion emissions from the equipment were calculated using the non-road equipment model NONROAD (http://www.epa.gov/otaq/nonrdmdl.htm) designed by the USEPA. This model requires that the power and operating hours be input for each device modelled. Emissions for trucks were modelled by adapting the corresponding ecoinvent database process to the indicated consumption values.

4.2 Description of LCA Systems and Assumptions

The systems, i.e., the list of included elementary processes, were determined based on data provided by the partners, various assumptions and available generic data.

Tables F.3.1 and F.4.1 in Appendix F present the elementary processes for cement concrete pavement and asphalt pavement, respectively. Appendix E describes these elementary processes as well as the assumptions related to the inventory calculation, particularly regarding transportation distances, machinery operating time, quantity of material and consumables used for the construction, operation, maintenance and marking steps, as well as the manufacturing processes for the main construction materials used, such as asphalt and cement production.

4.3 Summary of Data Sources

Table 4-1 summarizes the data required for the LCI of both types of pavement, as well as the various data sources used. Table 4-2 shows the processes that were taken from the ecoinvent database and adapted or modified to be more representative, because certain European material production data relies on other data (for example, to produce the required energy). The latter data had to be replaced with energy production data more relevant to the context being analyzed in order to increase the geographical representativeness of the available European data for material production or transformation.

The various data sources are outlined in Appendix E.

Table 4-1: Summary of Data Sources

Data		Data sources	
		Resources consumed	Emissions generated
Material and fuel production			
Construction materials — cement concrete	Cement concrete	Canada Centre for Mineral & Energy Technology and Radian Canada Inc. + Athena Sustainable Materials Institute	
	Cement	Canada Centre for Mineral & Energy Technology and Radian Canada Inc. + Athena Sustainable Materials Institute	Québec Cement Plants – GHG and NPRI AP Emissions, 2006
	Sand	ecoinvent *(Sand, at mine/CH U)*	
	Stone	ecoinvent *(Gravel, crushed, at mine/CH U)*	
	Water	ecoinvent *(Tap water, at user/RER U)*	
	Silica fume	Not considered as resource (considered as a recycled waste)	
	Fly ash	Not considered as resource (considered as a recycled waste)	
	Slag	Not considered as resource (considered as a recycled waste)	
	Steel	ecoinvent *(Reinforcing steel, at plant/RER U)*	
	Pre-formed compression seals	ecoinvent *(Synthetic rubber, at plant/RER U)*	
	Hot-pour sealant	Asphalt production data from Mr. Dufresne (Petro-Canada)	Montréal refinery – GHG and NPRI AP Emissions,
Construction materials — asphalt	Asphalt mix	Data from Mr. Bouchard (QRBHCA) + Natural Resources Canada	Data not available
	Asphalt	Mr. Dufresne (Petro-Canada)	Montréal refinery – GHG and NPRI AP Emissions,
	Sand	ecoinvent *(Sand, at mine/CH U)*	
	Stone	ecoinvent *(Gravel, crushed, at mine/CH U)*	
Base and sub-base materials	New aggregate	ecoinvent *(Gravel, round, at mine/CH U)*	
Salts	NaCl	ecoinvent *(Sodium chloride, powder, at plant/RER U)*	
	$CaCl_2$	ecoinvent *(Calcium chloride, $CaCl_2$, at plant/RER U)*	
Road marking	Epoxy	ecoinvent *(Epoxy resin, liquid, at plant/RER U)*	
	Black aggregate	ecoinvent *(Carbon black, at plant/GLO U)*	
	Micro-beads	ecoinvent *(Glass fibre, at plant/RER U)*	
	Polymer tape	ecoinvent *(Epoxy resin, liquid, at plant/RER U)*	
	Alkyds	ecoinvent *(Alkyd paint, white, 60% in H_2O, at plant/RER U)*	
Fuel (diesel for machinery and road transportation in Québec)		Mr. Dufresne (Petro-Canada)	Montréal refinery – GHG and NPRI AP Emissions, 2006
On-site machinery use			
Various machinery required for interventions		Data from Mr. Bouchard (QRBHCA) + the pavement modelling software PaLATE	Non-road equipment emissions model from the
Material and fuel transportation			
Road transportation		ecoinvent *(Transport, lorry > 16 t, fleet average/RER U)*	
Transportation by pipeline, offshore		ecoinvent *(Transport, crude oil pipeline, offshore/OCE U)*	
Transportation by pipeline, onshore		ecoinvent *(Transport, crude oil pipeline, onshore/RER U)*	
Marine transportation, tanker		ecoinvent *(Transport, transoceanic tanker/OCE U)*	
Marine transportation, barge		ecoinvent *(Transport, barge tanker/RER U)*	
Marine transportation, ship		ecoinvent *(Transport, transoceanic freight ship/OCE U)*	
Rail transportation		ecoinvent *(Transport, freight, rail, diesel/US U)*	

Table 4-2: Summary of Data Adapted to Increase the Representativeness of ecoinvent Datasets

Data	ecoinvent dataset	Modified sub-process
Transportation	*Operation, lorry > 16 t, fleet average/RER U*	Diesel production
Crushed stone production	*Gravel, crushed, at mine/CH U*	Diesel production + Québec grid mix electricity
New aggregate production	*Gravel, round, at mine/CH U*	Diesel production + Québec grid mix electricity
Sand production	*Sand, at mine/CH U*	Diesel production + Québec grid mix electricity
Cement production	*Limestone, at mine - cement/CH U*	Diesel production
Cement production	*Clay, at mine/CH U*	Diesel production
Cement production	*Gypsum, mineral, at mine/CH U*	Diesel production + North American grid mix electricity
Cement production	*Sand, at mine/CH U*	Diesel production + Québec grid mix electricity
Cement production	*Iron ore, 46% Fe, at mine/GLO U*	Diesel production + North American grid mix electricity
Cement concrete production	*Light fuel oil, at regional storage/RER U*	Québec grid mix electricity
Asphalt production	*Light fuel oil, at regional storage/RER U*	Québec grid mix electricity
Cement production	*Light fuel oil, at regional storage/RER U*	Québec grid mix electricity
Cement concrete production	*Natural gas, burned in industrial furnace > 100 kW/RER U*	North American grid mix electricity
Asphalt production	*Natural gas, burned in industrial furnace > 100 kW/RER U*	North American grid mix electricity
Transportation by pipeline	*Transport, crude oil pipeline, onshore*	Québec grid mix electricity + New England grid mix electricity

4.4 Inventory Calculation Results

Using the information presented in the previous sections, inventory flows (inputs and outputs) were calculated per functional unit for each process that falls within the boundaries set for the systems being studied. These flows are presented in terms of both:

- Intermediate product flows, representing material and energy requirements (for transportation and equipment) as well as waste generated (disposed of or recovered) within the technological system (technosphere);
- Elementary flows, representing resources extracted from the natural environment and substances released into this environment (ecosphere).

All of these flows, i.e., the detailed inventory results, are presented in Appendix F (Table F-5.1, tab 5).

Note that seeing as this LCA is comparative and the elements common to both systems were excluded from the assessment (particularly traffic, lighting, earthwork, etc.), the results show only the differences between the two types of pavement. The presentation of results specific to each type of pavement is not appropriate in this case, especially considering that only differential quantities were collected for de-icing salts.

The results are therefore presented in terms of relative difference between cement concrete (CC system) and asphalt mix (AM) pavement as follows:

$$\Delta_{inventory}(\%) = \frac{\left(inventory_{CCsystem} - inventory_{AMsystem}\right)}{inventory_{AMsystem}} \qquad (4\text{-}1)$$

Table 4-3 presents the increase (in green) or decrease (in pink) in various elementary flows (grouped by ecosystem compartment) that would result from replacing asphalt pavement with cement concrete pavement.

In light of these results, the life cycle of cement concrete pavement consumes less natural resources ($\Delta_{resource\ inventory} < 0$) but requires more water ($\Delta_{water\ inventory} > 0$) and generates more emissions ($\Delta_{emission\ inventory} > 0$) than that of asphalt pavement (except when it comes to emissions to water for functional classes 8, 12 and 16). These differences are explained in the next subsection.

Table 4-3: Relative Difference Between the Elementary Flows of Comparative Pavement Life Cycles (CC system – AM system)

Functional Class	Relative Difference (%) for Each Compartment of the Ecosystem					
	Natural Resources Used	Water Consumption	Energy Consumption	Total Emissions to Air	Total Emissions to Water	Total Emissions to Soil
1	−8.4	65.2	66.5	100.9	25.8	86.4
2	−8.6	69.6	70.9	105.8	24.5	89.8
3	−8.8	71.8	73.1	107.0	21.3	92.5
4	−11.9	68.0	69.4	97.4	8.8	88.2
5	−8.6	68.9	70.2	105.0	24.5	89.0
6	−9.0	71.5	72.9	107.1	21.8	92.4
7	−11.2	66.2	67.5	96.9	12.0	86.1
8	−16.9	57.2	58.4	82.7	−3.6	77.7
9	−8.6	69.0	70.4	106.3	27.6	89.3
10	−9.4	71.2	72.6	103.0	16.5	90.9
11	−12.5	67.0	68.4	94.2	5.8	86.2
12	−17.9	65.2	66.5	89.7	−4.4	85.6
13	−9.3	67.9	69.3	100.2	17.6	87.5
14	−9.6	73.0	74.4	104.9	15.8	93.2
15	−12.5	69.3	70.7	96.2	5.3	88.4
16	−19.7	63.2	64.5	86.6	−7.6	83.6
(red)	Negative difference or decrease in flows (inputs or outputs) by replacing an asphalt pavement with a concrete pavement. **Favours the concrete pavement.**					
(green)	Positive difference or increase in flows (inputs or outputs) by replacing an asphalt pavement with a concrete pavement. **Favours the asphalt pavement.**					

4.4.1 Contribution Analysis

For each category of elementary flow, the next table summarizes:

- The main substances (resources and emissions) which are consumed or generated in different quantities for cement concrete and asphalt pavement;
- The main processes responsible for the consumption and emission of these substances (defined according to the results obtained for functional class 16).

In order to facilitate the presentation of results, the percentage that each of the main substances contributes to each ecosystem compartment was also calculated based on the average value obtained for all 16 functional classes.

Table 4-4: Contribution (%) of Main Substances to Each Environmental Compartment and Main Unit Processes Involved

Main substances[1]	Contribution[2] (%)	Contributing system	Main processes involved
Natural resources			
Sand and gravel (in ground)	68.6	AM	Granular material production for the road base and sub-base, crushed stone and sand production for new asphalt mix
Calcite (in ground)	13.2	CC	Cement production (limestone)
Oil (crude, in ground)	6.4	AM	Asphalt production
Sodium chloride (in ground)	5.1	CC	De-icing salt[4] production
Coal (in ground, not specified)	2.4	CC	Cement production, steel production, de-icing salt[4] production
Clay (in ground, not specified)	1.8	CC	Cement production (clay)
Emissions to air			
Carbon dioxide (calcination)[3]	98.1	CC	Cement production
Emissions to water			
Dissolved solids	25.2	AM	Asphalt mix production
Silicone	22.0	CC	De-icing salt[4] production, steel production
Suspended solids, not specified	9.5	AM	Asphalt production
Chloride	7.2	CC	Cement production, epoxy paint production
Sulphate	6.6	CC	Cement production, de-icing salt[4] production, steel production
Calcium ions	5.3	CC	De-icing salt[4] production, cement production, steel production
Chemical oxygen demand (COD)	4.3	CC	Cement production, cement concrete production, steel production, de-icing salt[4] production
Sodium ions	3.6	CC	Cement production, epoxy paint production
Barite	3.0	AM	Asphalt production
Biological oxygen demand (BOD5)	2.7	CC	Cement production, cement concrete production
Dissolved organic carbon (DOC)	1.6	CC	Cement production, cement concrete production, steel production, de-icing salt[4] production
Total organic carbon (TOC)	1.5	CC	Cement production, steel production, de-icing salt[4] production, cement concrete production
Aluminum	1.4	CC	De-icing salt[4] production, steel production, cement production
Emissions to soil			
Oils, not specified	72.4	CC	Cement production, cement concrete production
Iron	10.9	CC	De-icing salt[4] production, cement production, steel production, rail transportation
Carbon	7.1	CC	De-icing salt[4] production, cement production
Calcium	3.7	CC	De-icing salt[4] production, cement production
Sodium	1.1	CC	Cement production, cement concrete production
Silicone	1.0	CC	De-icing salt[4] production

(pink)	Main processes associated with the AM system and responsible for the consumption or emission of the main substances. **Favours the concrete pavement.**

Table 4-4: Contribution (%) of Main Substances to Each Environmental Compartment and Main Unit Processes Involved

Main substances[1]	Contribution[2] (%)	Contributing system	Main processes involved
	Main processes associated with the CC system and responsible for the consumption or emission of the main substances. **Favours the asphalt pavement.**		

[1] Substances that contribute more than 1% (on average, for all 16 functional classes) to the difference between the two types of pavement (i.e., to the Δ inventory).
[2] Contribution (%) of the substance to the Δ inventory.
[3] The inventory distinguishes the relative contribution of carbon dioxide depending on whether it was emitted during cement production (specifically during calcination) or during other steps. This distinction is made because the contribution from the cement production step is so significant.
[4] The inventory above does not account for sodium (Na) emissions to water and chlorine (Cl) emissions to soil generated from de-icing salt use in the CC system because there was not enough data available (see section 5.4, Study Limitations).

4.4.1.1 Natural Resources

As mentioned above, the CC system consumes less natural resources overall than the AM system. This is explained in part by sand and gravel consumption, which contributes significantly (68.6%) to the difference between the two types of pavement, and which can be attributed to the larger quantity of granular material that is required to build the base and sub-base of asphalt pavement, as well as to the crushed stone and sand required for new asphalt mix production. In addition, the crude oil (consumed in the form of asphalt) that is required to produce asphalt mix constitutes a second resource that is attributable to the AM system and contributes significantly (6.4%) to the difference between the systems.

Lastly, the other main resources are attributable more to the CC system. These resources include calcite (13.2%) and clay (1.8%), which are used as raw materials in cement production; sodium chloride (5.1%), which is used for de-icing salt production; as well as coal (2.4%), which is used as an energy resource for cement, steel and salt production. The AM system actually consumes less salt than the CC system and does not require any cement or steel.

4.4.1.2 Emissions to Air

As indicated, emissions to air are more significant for cement concrete pavement than for asphalt pavement, which can be explained by the carbon dioxide (CO_2) that is emitted during the calcination step of the Portland cement production.

Considering the relative importance of CO_2 emissions attributable to the cement production process, the inventory actually distinguishes between CO_2 emitted during this step (calcination CO_2) and CO_2 emitted during the other steps (fossil CO_2). The following energy sources are consumed during calcination: coal, natural gas, fuel oil, and coke from petroleum and residual materials such as tires. Calcination CO_2 is generated partly by the combustion of these energy sources, as well as by the thermal decomposition of calcium carbonate ($CaCO_3$) present in the limestone. Since fossil CO_2 emissions for both types of pavement are close to equal, this type of emission does not contribute very significantly to the difference between two systems. In fact, 98.1% of the difference is attributable to CO_2 emissions from calcination.

4.4.1.3 Emissions to Water

Several substances contribute more than 1% to the difference in aquatic emissions between the two systems, and most of them are attributable to the CC system, and more specifically to direct emissions from cement production, including chloride (7.2%), sulphate (6.6%), calcium ions (5.3%), COD (4.3%), sodium ions (3.6%), BOD5 (2.7%), DOC (1.6%), TOC (1.5%) and aluminum (1.4%). Some of the chloride is also released to water when producing epoxy for road marking material, and some of the sulphate is released to water after treating sewage during de-icing salt production.

However, the substance that contributes most to aquatic emissions from the CC system is silicone (22%). This emission are attributable in part to slag management at the plant when casting the nickel required for steel production, as well as to end-of-life management of electronic equipment used to operate the de-icing salt plant.

As for the AM system, it does not require cement or steel, and it uses less de-icing salt and epoxy than the CC system. The substances emitted in large quantities by this system are dissolved solids (25.2%) released while extracting natural gas used for asphalt mix production, as well as suspended solids (9.5%) and barite (3.0%), which are related to the life cycle of infrastructures and used to extract the crude oil required for asphalt production.

Lastly, note that the life cycle of cement concrete pavement generates more emissions to water than asphalt pavement, except when it comes to functional classes 8, 12 and 16. In fact, for these three classes, asphalt pavement requires earlier reconstruction (at year 40 for classes 8 and 12, and year 38 for class 16). Consequently, a larger quantity of asphalt is required for reconstruction for these three classes (the quantities of materials representing the last intervention are allocated to the product systems on a pro rata basis according to the number of years remaining in the 50-year period considered under this study). Aquatic emissions generated by producing the additional amount of asphalt and asphalt mix required for the AM system in these three classes therefore more than offset the large quantity of aquatic emissions generated by the CC system.

4.4.1.4 Emissions to Soil

Cement concrete pavement also generates more emissions to soil than asphalt pavement, with the substances that contribute most to the difference between the two types of pavement being attributable to the CC system. More specifically, these substances are oils (72.4%) generated largely from the production of crude oil required to produce the fuels that are consumed during cement and cement concrete production. In the Swiss ecoinvent database, this oil that generates emissions to soil is sourced mainly from Russia. It is therefore possible that this data is not representative of the Canadian context.

Iron emissions also contribute 10.9% to the difference between the two systems. These emissions are attributable to the spreading of sludge from de-icing salt production onto agricultural land, as well as the transportation of cement and steel by train. Again, the rail transportation data used is representative of European technology (trains operating on electricity and diesel). Also to be noted, according to the data used, no rail transportation of asphalt or asphalt mix is accounted for, and, contrarily to the CC system, the AM system does not include foreground rail transportation.

Lastly, the other main substances emitted to soil are carbon (7.1%), calcium (3.7%), sodium (1.1%) and silicone (1.0%). These emissions occur particularly after treating sewage during de-icing salt production and spreading, onto agricultural land, residues from the drilling of wells used to extract the fossil resources required for cement and cement concrete production (more specifically to produce petroleum coke and diesel fuel). Carbon, calcium and silicone are also emitted to soil through the spreading of wastewater treatment sludge from de-icing salt production onto soil. Sodium is also associated with the spreading of residues from well drilling for resource extraction, the treatment of wastewater generated by de-icing salt production, as well as the production of cement and cement concrete.

5. IMPACT ASSESSMENT AND INTERPRETATION OF RESULTS

The environmental impacts associated with the comparative life cycles of both types of pavement were assessed and interpreted in accordance with the methodological framework presented in sub-section 3.2.5.

5.1 Damage and Impact Indicator Results

Appendix F compares the impact indicators (Table F-10.4, tab 10) and damage indicators (Table F-11.6, tab 11) of cement concrete pavement and asphalt pavement life cycles for each of the 16 functional classes. Again, these results are presented in terms of relative difference between the CC system and the AM system as follows:

$$\Delta_{impact}(\%) = \frac{\left(impact_{CCsystem} - impact_{AMsystem}\right)}{impact_{AMsystem}} \qquad (5\text{-}1)$$

$$\Delta_{damage}(\%) = \frac{\left(damage_{CCsystem} - damage_{AMsystem}\right)}{damage_{AMsystem}} \qquad (5\text{-}2)$$

According to the results summarized in Table 5-1, the human health, ecosystem quality and global warming indicators all report a positive difference that favours the AM system (shown in green in the table). Negative values are reported, however, for resource consumption and aquatic eutrophication (for classes 8, 12 and 16), thereby favouring the CC system (shown in pink).

Recall that the distinguishing characteristic of classes 8, 12 and 16 is the fact that asphalt pavement must be rebuilt earlier (see paragraph 4.4.1.3). In these three classes, larger quantities of asphalt and asphalt mix are therefore required for the AM system, which increases the associated aquatic emissions (and eutrophication).

In addition, as indicated in Table 5-2, note that:

- The overall human health damage indicator favours the AM system, even though the human “cancer” toxicity impact indicator favours the CC system;
- The resources damage indicator favours the CC system because of the amount of inherent energy in the asphalt consumed as part of the AM system.

In fact, the damage indicator related to the consumption of non-renewable resources has been broken down into sub-categories to distinguish the portion of this consumption that is attributable to the asphalt inherent energy. The indicator therefore includes the use of non-renewable primary energy attributable solely to asphalt (only the asphalt inherent energy), as well as the use of minerals and non-renewable primary energy attributable to the rest of the system (not including asphalt inherent energy).

However, because the IMPACT 2002+ method of LCIA considers total non-renewable primary energy, when the asphalt inherent energy is included in the total primary energy associated with the system, the CC system is clearly favoured. In fact, the asphalt inherent energy represents an average of 76% of total primary energy across all 16 classes for the AM system, whereas it represents only 30% for the CC system (see Appendix F, Table F.11-2, tab 11), which explains the decisive difference between the two types of pavement for this indicator.

Table 5-1: Relative Difference Between the Damage/Impact Indicators of the Comparative Life Cycles of Pavement (CC system – AM system)

Functional Class	Relative Difference (%) for Each Damage/Impact Category					
	Human Health	Ecosystem Quality	Global Warming	Resource Consumption	Aquatic Acidification	Aquatic Eutrophication
1	43	104	101	−33	76	30
2	46	109	106	−35	81	28
3	46	111	107	−38	82	24
4	40	104	97	−47	76	7
5	45	108	105	−34	80	28
6	46	111	107	−37	82	25
7	40	103	97	−44	75	11
8	30	92	82	−55	64	−6
9	46	109	106	−35	81	27
10	44	108	103	−43	80	14
11	38	102	94	−50	74	2
12	33	99	89	−57	71	−8
13	42	105	100	−42	77	15
14	45	110	105	−44	82	13
15	39	104	96	−50	76	2
16	31	96	86	−59	69	−11
(red)	Negative numbers occur when a decrease in the damage/impact indicator score is obtained by replacing asphalt with concrete pavement. **Favours the concrete road (CC).**					
(green)	Positive number occurs when an increase in the damage/impact indicator score is obtained by replacing asphalt with concrete pavement. **Favours the asphalt road (AM).**					

Table 5-2: System with the Lowest Impact Score in Each Category

Damage Category	Impact Category	CC System	AM System
Human health	Human "cancer" toxicity	√	
	Human "non-cancer" toxicity		√
	Respiratory effects (inorganic)		√
	Ionizing radiation		√
	Thinning of the ozone layer		√
	Respiratory effects (organic)		√
	Human health		√
Ecosystem quality	Aquatic eco-toxicity		√
	Terrestrial eco-toxicity		√
	Terrestrial acidification		√
	Land use		√
	Ecosystem quality		√
--	**Aquatic acidification**		√
--	**Aquatic eutrophication**	√ (functional classes 8, 12 and 16)	√
Global warming	Global warming		√
	Climate warming		√
Resources	Mineral mining		√
	Non-renewable energy		√
	Inherent energy of asphalt	√	
	Resources	√	

(red)	Negative difference or decrease in the damage/impact indicator score by replacing an asphalt pavement with a concrete pavement. **Favours the concrete pavement.**
(green)	Positive difference or increase in the damage/impact indicator score by replacing an asphalt pavement with a concrete pavement. **Favours the asphalt pavement.**

5.1.1 Single-Score Analysis

As previously mentioned in sub-section 3.2.5, the IMPACT 2002+ method allows damage indicators to be normalized based on the average European equivalent, and then aggregated into a single score (by implicitly applying an identical weighting factor of 1). Yet, the use of such a weighting relies on value choices that are not backed by current science and is therefore explicitly prohibited by ISO in the case of publicly released comparative assertions (intended to affirm the superiority of one option over another).

However, in order to meet the MTQ's requirements, certain weighted results are presented in Appendix F so as to facilitate communication and interpretation (a single score effectively reduces the number of criteria that must be considered in the Policy). In that perspective, Figure F-11.1 and Table F-11.13 present the weighted damage indicators for the comparative profile (CC system – AM system) for the 16 functional classes. According to this figure, the CC system has a higher total impact score for all functional classes except classes 8, 11, 12, 15 and 16. For these five classes only, the CC system is favoured over the AM system because its "net" single score is negative. It should be noted that in Figure F-11.1, the resource consumption damage category is again divided into two sub-categories to distinguish the portion of consumption attributable to the asphalt inherent energy.

It is also important nonetheless to recall that these results presuppose an identical weighting factor of 1, in other words each damage category is given the same value, and that weighting the categories according to values and preferences defined by the MTQ (or other stakeholders) could potentially yield different results. **These results are therefore provided only as information for MTQ use, and the MTQ must be transparent about this fact when disclosing results on which it will base its future decisions. All communication of single-score results must therefore explicitly mention the choice of weighting factors used.** In addition, when a weighting is included in the LCA, the ISO 14044 (2006) standard states that:

"The value-choices and judgements within the grouping procedures are the sole responsibilities of the commissioner of the study (e.g. government, community, organization, etc.)."

It is therefore up to the MTQ to decide on the choice of values, using a weighting factor for example, in order to determine the most favourable option for each functional class.

Strictly for informational purposes, Appendix F presents the various results obtained using a weighting tool that calculates the weighted sum of normalized results using a set of weighting factors. More specifically, a simulation makes it possible to analyze a variety of possible weighting combinations for the four damage indicators and to list the combinations that favour one system over the other.

The results of this simulation are presented in Table 5-3, which reports the percentage of weighting combinations that favour the AM and CC systems for each of the 16 functional classes. As the table shows, a large majority of functional classes favour the AM system. In fact, for 5 of the 16 functional classes, 70% or more of the possible weighting combinations favour the AM system. For several classes, however, the values for each of the two systems are similar and do not really indicate which system to favour for most weighting sets.

Table 5-3: Possibility (%) that Weighting Factor Combinations Favour One System over the Other

Functional Class	AM System Favoured	CC System Favoured
1	73.0	27.0
2	72.3	27.7
3	69.6	30.4
4	58.7	41.3
5	72.3	27.7
6	70.0	30.0
7	61.0	39.0
8	47.3	52.7
9	72.3	27.7
10	63.4	36.6
11	55.2	44.8
12	47.4	52.6
13	63.7	36.3
14	62.8	37.2
15	55.3	44.7
16	45.0	55.0

NOTE: The percent possibility is based on a total of 1,771 weighting sets considered, with weighting factors set at 5% intervals.

5.1.2 Contribution Analysis

Figure F-12.1 in Appendix F presents the weighted damage indicator results for the comparative profile (CC system – AM system), for class 16, and breaks the indicators down by life cycle process (contrary to Figure F-11.1, which presents an aggregated indicator for each functional class). Since the general trend in results is consistent for all classes, the results for class 16 are considered fully representative. It is also worth noting that only foreground system processes (in other words, the processes included in the systems presented in Appendix C) are considered here, and that processes that are common to both systems do not appear because it is a comparative profile.

The horizontal axis indicates the number corresponding to each process as described in the processes diagram in Appendix C. Processes beginning with the number:

- "1" are initial construction activities;
- "2" are operational activities;
- "3" are maintenance activities;
- "4" are reconstruction activities;
- "5" refer to road marking.

According to the results, the processes that were found to contribute the most to the life cycle impact indicator results for cement concrete pavement compared to those for asphalt pavement are: cement production for initial construction (process 1.5) and reconstruction (process 4.1), cement concrete production (process 1.10) and steel production (process 1.13) for initial construction, asphalt production for initial construction (process 1.17) and for maintenance activities (process 3.13), asphalt mix production for initial construction (process 1.21) and for maintenance activities (process 3.16), and salt production (process 2.1). Note that the processes related to machinery use and road marking do not contribute very significantly, which can be explained by the fact that the values for these processes are about the same for both systems.

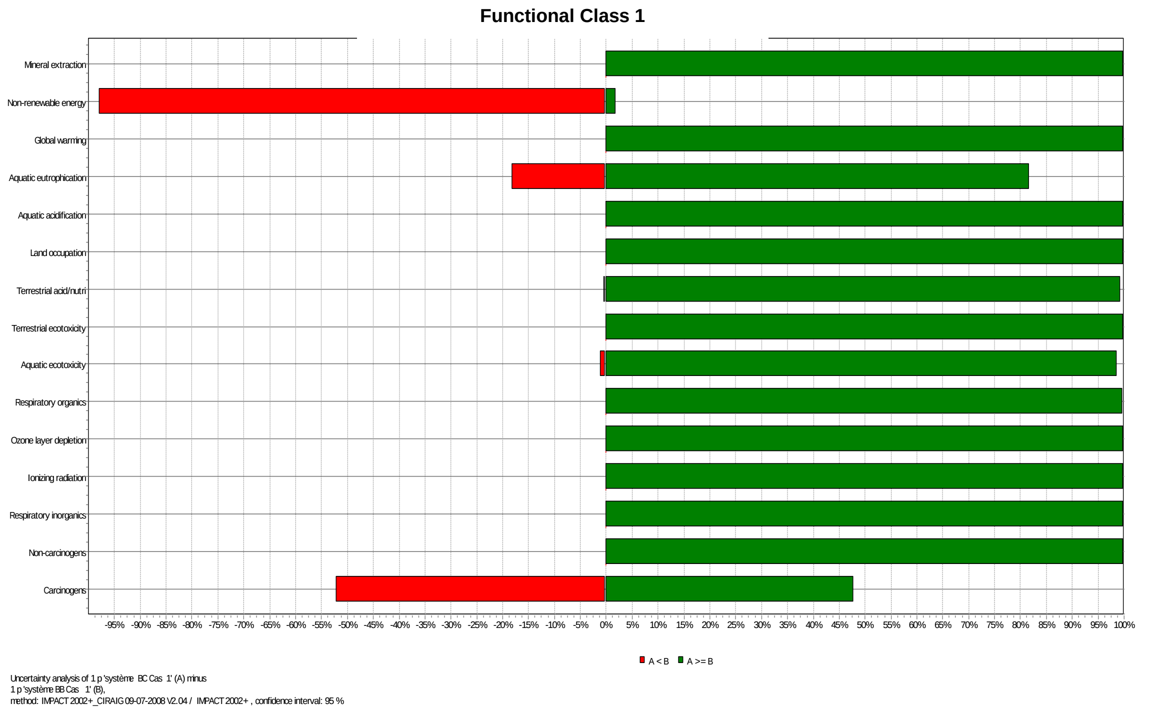
These results corroborate those obtained following the inventory flow analysis (see sub-section 4.4.1), with the exception of certain processes which are responsible for the consumption and emission of main substances, but which do not appear to contribute significantly to potential impacts (e.g., the production of granular material, crushed stone, sand and epoxy paint). This can be explained by the fact that no characterization factors were available to convert these inventory flows to impact indicators (see the limitations presented in section 5.4).

Once again, note that these results presuppose an identical weighting equal to 1, i.e., each damage category is given the same value.

5.2 Uncertainty Analysis

Of the thousands of individual elementary flows inventoried as part of the elementary processes of the various scenarios studied, the vast majority were taken from the ecoinvent database. The majority of these flows present some variability in the form of a log-normal distribution around a specified central value, also used in deterministic calculations, and characterized by its standard deviation. It is worth noting, however, that the variability incorporated in the secondary data by the creators of the ecoinvent database is not a measure of the real variability of processes (i.e., statistically determined using actual measures taken during data collection). It was instead estimated by applying a pedigree that describes the quality of data based on its origin, method of collection and representativeness, and is subjectively determined by the database creators. Similarly, the variability of most of the primary data collected was represented by a log-normal distribution that was also estimated by applying a pedigree (the results of this analysis are presented in Appendix F, Tables F-20.1.1 and F-20.1.2). It is therefore essential to understand that the purpose here is to emphasize that the conclusions are uncertain and that variability is provided for information purposes only because of a lack of better quality information.

An analysis was therefore completed to determine the degree of uncertainty attributable to the variability of inventory data. The software SimaPro 7 was used to complete a Monte Carlo analysis (i.e., a study of the propagation of inventory data variability in calculations, which are therefore probabilistic), with the number of iterations set at 1,000. The results for functional classes 1 and 16 are presented in Figure 5-1.



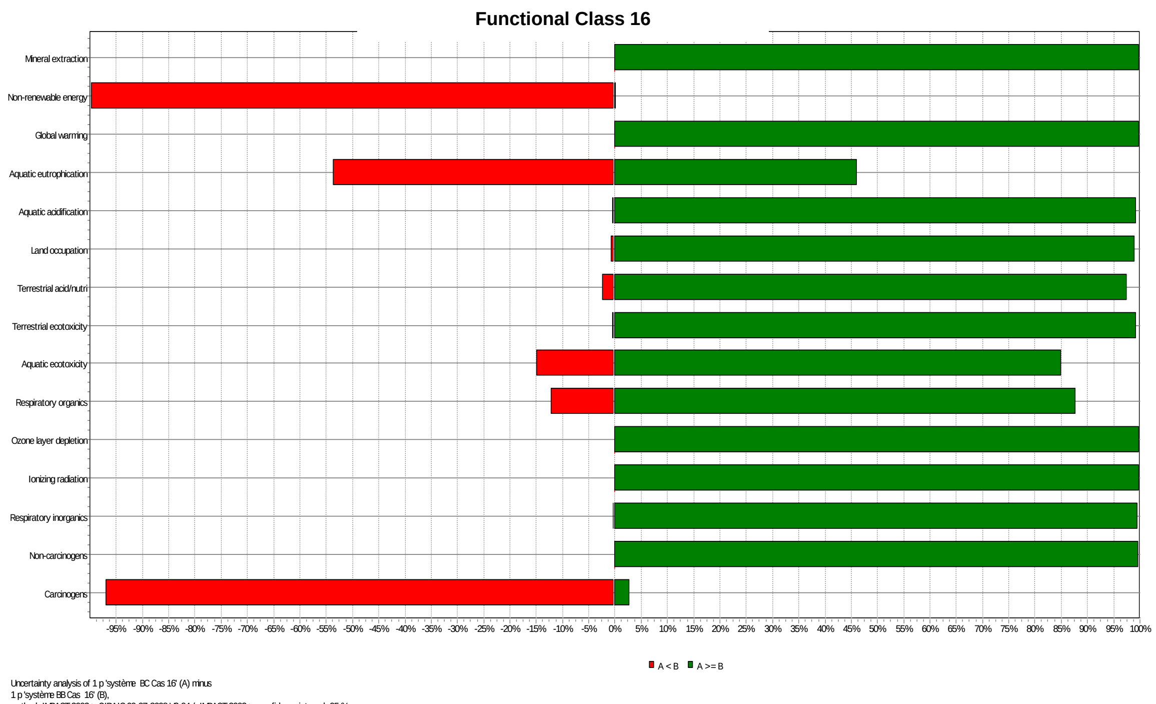


Figure 5-1: Probability of Occurrence of Results for Impact Indicators for Functional Class 16 (CC system – AM system).

This figure shows the results of subtracting system B (AM system) from system A (CC system). According to these calculations, when the impact calculated for system A (CC) is greater than that calculated for system B (AM), the iteration result is positive (shown in green). The iteration result is negative if system B (AM) has a greater impact (shown in red). It is then possible to see the probability of one system having a greater impact than the other.

Recall that, as illustrated in Table 5-2, the CC system has the highest indicators for the majority of impacts, with the exception of the categories related to human health ("cancer"), aquatic eutrophication (for functional classes 8, 12 and 16) and non-renewable energy. This is also confirmed by the results of the Monte Carlo simulation completed on the subtraction of damage indicators for each system (A − B), with small probabilities of occurrence of A < B (CC system < AM system) for the following categories:

- Aquatic acidification (less than 1% for class 16 only);
- Land use (less than 1% for class 16 only);
- Human health ("non-cancer") (less than 1% for class 16 only);
- Terrestrial acidification (less than 1% for class 1, and less than 5% for class 16);
- Terrestrial eco-toxicity (less than 1% for class 16 only);
- Aquatic eco-toxicity (less than 2% for class 1, and less than 15% for class 16);
- Respiratory effects (inorganic) (less than 1% for class 16 only);
- Respiratory effects (organic) (less than 13% for class 16 only).

Similarly, the results of the Monte Carlo simulation for non-renewable energy also reported small probabilities of occurrence of A ≥ B (CC system ≥ AM system) of less than 2% for functional classes 1 and 16.

For human health ("cancer") on the other hand, the probability of occurrence of an A ≥ B reversal (CC system ≥ AM system) is approximately 50% for functional class 1, which would further favour the AM system for the human health damage category.

Lastly, for the aquatic eutrophication category, the simulation results reported the following probabilities of reversal:

- A ≥ B (CC system ≥ AM system): approximately 46% for class 16;
- A < B (CC system < AM system): approximately 18% for class 1.

While strong probabilities of reversal can be observed for the human health ("cancer") and aquatic eutrophication categories for certain functional classes, the conclusions made as to the damage indicators (as they are presented in Table 5-1) would not change. For information purposes only, Figure F-.3.3 (Appendix F, tab 20.3) presents the Monte Carlo simulation results for class 16, this time using a "damage" approach. The simulation results effectively show that the human health, ecosystem quality and global warming indicators remain higher for the CC system, and the resource consumption indicator remains higher for the AM system. Moreover, while the "by indicator" conclusions may be different at the impact category level, the overall conclusions (as to the superiority of one type of pavement over the other) remain unchanged.

5.3 Sensitivity Analysis

As discussed in the previous section, several parameters used in modelling the systems have some degree of uncertainty, in particular those related to the choice of assumptions as well as generic data modules and impact (and damage) assessment models used. The results obtained are linked to these parameters, and their uncertainty is transferred to the conclusions drawn.

In order to test the robustness of certain parameters, sensitivity analyses were performed in which the values of the uncertain parameters were changed to different, though plausible, values. The resulting extent of the variation indicates the importance of the modified parameters and the range in which the results are likely the most valid.

The results of the sensitivity analyses are presented in the sub-sections below. They cover in particular the sensitivity of the conclusions regarding a variation in:

1. Different material transport distances between their supply site and the road construction site;
2. The environmental profile of asphalt production;
3. The asphalt fume emissions in the asphalt production data;
4. The environmental profile for constructing Continuously Reinforced Concrete Pavement (CRCP) instead of Jointed Plain Concrete Pavement (JPCP) (only for functional class 16);
5. The impact assessment method;
6. The environmental profile of cement production;
7. The amount of fuel consumed by vehicles according to the type of pavement (although this parameter was excluded from the boundaries of this study, it appears important over the life cycle of a road, especially in a comparative context where there could be a significant difference between the two options);
8. The carbonation process over the entire life cycle of cement concrete, absorbing a portion of CO_2.

Note that Appendix F presents the damage indicator results for the comparative profile (CC system – AM system):

- Weighted and, in certain cases:
- Grouped for each functional class (a single indicator rather than four indicators broken down for each functional class).

5.3.1 Material Transport Distances

The truck transport distances for construction, maintenance and reconstruction materials from the supply site to the road construction site as well as for de-icing salts and marking products from the supply site to the road surface have been fixed at 20 km—a value deemed to be a good estimate of the average transport distances. However, to fully validate this assumption, a sensitivity analysis was performed.

Figure 14.2.1 in Appendix F presents the results from comparing the two types of pavement with distances fixed at 100, 250 and 1,000 km.

By increasing road transport, the difference in score between the two types of pavement increases with the distance for all damage categories, except that the inherent energy in asphalt remains unchanged by an increase in transport distances. For distances of 100 and 250 km, the findings are nevertheless maintained, i.e., human health, ecosystem quality and global warming indicators are always higher for the CC system, while the resource consumption indicator is always higher for the AM system, for all functional classes.

However, when the distance is increased to 1,000 km, human health, ecosystem quality and global warming indicators favour the CC system for 7 of the 16 functional classes (i.e., classes 4, 7, 8, 11, 12, 15 and 16). This suggests a reversal of the results as to which system should be used in these classes.

This reversal caused by the increase in the truck transportation distance can be explained by the greater total mass of material to be transported to the construction site for the AM system—even up to 12% higher than the CC system for certain functional classes. Particularly, the amounts of sand and crushed stone transported to the construction site are larger for the AM system (detailed results of economic flows are presented in Tables 1.1 and 2.1 in Appendix F).

This sensitivity analysis confirms that the distance between the construction material suppliers and the construction site would have to be greatly increased to reverse the results. If the given road is far from major urban centers (e.g., James Bay), the preferred system may vary. However, even for remote sites, it is unlikely that sand and stone would be transported over very long distances.

5.3.2 Asphalt Production

Asphalt production data were provided by Mr. René Dufresne from the Petro-Canada's Montréal refinery. Although this information is accurate and comes from a reliable source, it is important to ensure that it is representative and more or less coincides with the published data, if this is available. As presented in the literature review in Appendix B, there are several studies on the life cycle of asphalt pavement, and consequently, several studies have documented consumption as well as emissions and discharges associated with asphalt production. It was therefore considered important to compare data provided by

Petro-Canada with other data. A sensitivity analysis was performed by modifying the asphalt production process data according to the following scenarios:

- Scenario 1: Using the Eurobitume report giving inventory data on asphalt production (in particular air and water emission data, as well as the total energy required for asphalt production including extraction, storage and refining). Infrastructure and transport modelling remain unchanged.
- Scenario 2: Multiplying the extraction energy of crude oil by a factor of 10 because the provided value is lower than the values from other sources. Emission and discharge data as well as infrastructure, transport and storage energy modelling remain unchanged.
- Scenario 3: Increasing refining energy, by cancelling out the credit given for energy recovered during the refining process. Petro-Canada has provided energy consumption attributable to asphalt production only (and not for the entire refinery). According to this data, in the vacuum distillation step, a portion of the energy can be recovered by the refinery. This energy recovery was subtracted from the total energy required for asphalt production. However, since it was not possible to verify whether the credit should actually be attributed 100% to asphalt production (and not to other products from refining crude oil), a scenario was established which excluded this refining energy credit. Data on asphalt extraction, storage and transportation energy as well as water and soil emissions remain unchanged.
- Scenario 4: Using the asphalt production data available in the ecoinvent database. The approach used to model this data by the creators of the database is significantly different from that used for this LCA. As we explained in sub-section 3.2.3.1, the data on asphalt production was actually collected without attributing the multifunctional process (i.e., refining). Conversely, the data from ecoinvent attributes the inputs and outputs of the refining process to the various coproducts from the refinery on a mass basis. In addition, the type of oil modelled using this generic data comes from Great Britain, so the sensitivity associated with the origin (in part due to different transport distances) and extraction techniques will also be evaluated.

Figure 15.2.1 and Table 15.2.1 present the comparative results for the various asphalt production scenarios for the two types of pavement. Note that since the trends in the results are the same for each functional class, this analysis was performed only for functional class 16.

Scenario 2, considering a higher extraction energy, is the scenario with the lowest (comparative) indicator result for the human health category and is therefore the scenario with the highest damage score for this category for the AM system regarding asphalt production impacts. This can obviously be explained by the greater amount of diesel fuel that must be burned. However, Scenario 1, using Eurobitume emission data, shows greater contributions for the global warming and resources categories for asphalt production. This effect can be explained by the greater amount of CO_2 released into the air according to the Eurobitume study (0.277 kg CO_2/kg asphalt) than the amount provided by Petro-Canada (0.0747 kg CO_2/kg asphalt), and by the greater total amount of energy needed for overall asphalt production.

The most important finding is that human health, ecosystem quality and global warming indicators are always higher for the CC system. Regarding resources, the amount of inherent energy[1] used does not change in relation to the scenarios. This is normal, considering that the same amount of crude oil must be extracted for each of the scenarios. The resource consumption indicator is always higher for the AM system, regardless of the asphalt production data used.

This sensitivity analysis demonstrates that regardless of the asphalt production data used for comparison, result reversal never occurs.

5.3.3 Asphalt Fumes

Asphalt fumes emitted while producing and laying pavement normally contain polycyclic aromatic hydrocarbons (PAHs) and may have an effect on the health of workers exposed to them. In this study, data on emissions that may occur in asphalt mix plants or at the road construction site could not be determined.

Since PAHs can have a significant impact on human health, it is important to study their influence on the total score and to analyze the sensitivity of the results based on this parameter.

Following a brief review of the available information on asphalt fumes, benzo[a]pyrene was found to be the most carcinogenic PAH to humans, and it can be found in asphalt in concentrations up to 5.53 µg/g (Huynh et al.). Therefore, the amount of benzo[a]pyrene was added to the air emissions associated with asphalt mix production (depending on the amount of asphalt contained in the mix).

According to Figure 16.2.1 in Appendix F, the addition of PAH emissions does not change the conclusions of the study. Although the difference between the two systems on the human health indicator decreases, the AM system is always favoured in this damage category, and the other indicators remain unchanged.

5.3.4 Continuously Reinforced Concrete Pavement

When the scope of this study were defined, the Policy was based on the choice between Jointed Plain Concrete Pavement (JPCP) and asphalt pavement. However, Continuously Reinforced Concrete Pavement (CRCP) was later integrated into the MTQ's overall life cycle cost analysis (LCCA). In order to

[1] Note that creators of the ecoinvent database did not separate out the asphalt's inherent energy in the inventory. This is why only the total consumption is indicated.

provide the MTQ with additional guidance, a sensitivity analysis was performed only on functional class 16 by adding a CRCP model.

The main differences between CRCP (hereinafter "CRCP CC system") and JPCP (hereinafter "JPCP CC system") are linked to the longer life cycle of CRCP and to the amount of construction materials required (i.e., a greater amount of steel and composite reinforcement for CRCP, among others). CRCP is considered over a period of 60 years in order to include roadway reconstruction that takes place at a later time given the durability of this type of pavement.

In order to compare the three types of pavement, both JPCP and asphalt pavement life cycle were extended by 10 years.

Given the durability of CRCP and to ensure the proper comparison, the functional unit was also modified specifically for this sensitivity analysis and the life cycle of JPCP and asphalt pavement was extended by 10 years. The modified functional unit is expressed as follows:

"Allow vehicle traffic over 5 km for the first **60** years of the cement concrete pavement's life, compared to asphalt pavement and continuously reinforced concrete pavement constructed in Québec in 2009."

The intervention sequence for these three types of pavement is presented in Table 5-4 for functional class 16.

Table 5-4: Intervention Sequence for Functional Class 16 Over a Period of 60 Years Including CRCP

Intervention	No.	Year
		Class 16
Cement concrete pavement (JPCP type)		
Cement concrete construction, JPCP type (compliant transverse grooving)*	1	0
Restore 25% of joints	2	10
Minor repairs (0.5%), restoration of all joints and grinding (25%)	3	19
Major repairs (4%), grinding (25%) and grit blasting (75%)	4	29
Asphalt correction (60 kg/m^2) and asphalt resurfacing (120 kg/m^2)*	5	39
Reconstruction of cement concrete slab only*	6	46
Restore 25% of joints	7	56
Continuously reinforced concrete pavement (CRCP)		
Complete reconstruction of the road* in CRCP	1	0
Minor CC repairs (0.5%), grinding (5%), restoration of longitudinal joints (100%) and marking	2	19
CC repairs (2%), grinding (10%) and grit blasting (75%)	3	29
CC repairs (4%), grinding (25%)	4	39
Correction* (60 kg/m^2) and asphalt resurfacing*	5	49
Reconstruction of CRCP only	6	56
Asphalt pavement		
Construction using only asphalt	1	0
Levelling (40 mm) and resurfacing (100 kg/m^2)*	2	9
Levelling (50 mm) and resurfacing (120 kg/m^2)*	3	17
Levelling (50 mm) and resurfacing (120 kg/m^2)*	4	25
Levelling (50 mm) and resurfacing (120 kg/m^2)*	5	32
Complete removal of road surface and placement of new asphalt*	6	38
Levelling (40 mm) and resurfacing (100 kg/m^2)*	7	47
Levelling (50 mm) and resurfacing (120 kg/m^2)*	8	55

*Shoulders included in the intervention.

The amount of materials required for additional interventions related to JPCP and asphalt pavement were calculated and adjusted in proportion to the years before the end of the 60-year life of the intervention. Additional machinery was also added.

With respect to CRCP, the amount of materials for initial construction was calculated based on layer thicknesses specified by the MTQ, as presented in Table 5-5.

Table 5-5: CRCP Layer Thickness for Functional Class 16

Layer	Layer Thickness (mm)
Cement concrete	272 272
Free-draining base	100 100
MG-20 base	150 150
MG-112 type A sub-base	557 557

Free-draining base is made up of crushed stone and cement in proportions specified by the MTQ. The life cycle of both the MG-20 base and the sub-base is supposed to be equivalent to that of asphalt pavement and JPCP.

The amount of steel and composite reinforcement (fibreglass-reinforced polymer) required was also provided by the MTQ and is presented in Table 5-6.

Table 5-6: Amount of Steel and Fibreglass-Reinforced Polymer Required for CRCP for Functional Class 16

Material	Amount (tons)		
	Initial Construction	Maintenance	Reconstruction
Steel	1,529.8	99.4	109.3
Fibreglass-reinforced polymer	550.8	35.8	39.3

In order to simplify the calculations for this analysis and to counter a lack of information, the following simplifying assumptions were made:

- The machinery required for intervention sequences on CRCP was modelled in the same way as for JPCP;
- Marking CRCP for years 1–50 is considered identical to that of JPCP. Marking for the three types of pavement was not taken into account for years 51–60;
- Only the amount of fibreglass contained in the traffic lanes was recorded and not the amount in the shoulders.

In light of the results presented in Figure 17.2.1 in Appendix F, the four damage indicators show higher results for the CRCP CC system than for the JPCP CC system. This is partly due to the increased amount of cement and steel and to the composite which is not included in the JPCP CC system.

However, compared to AM system, the findings of the study have not changed, i.e., all indicators are lower for the AM system, with the exception of the resource consumption indicator.

Although CRCP has the advantage of offering a longer lifespan, the sensitivity analysis performed in this regard does not demonstrate that choosing this pavement results in an environmental gain.

5.3.5 LCIA Methods

In order to test the robustness of the results obtained with the IMPACT 2002+ method, two other LCIA methods were used: the European Eco-indicator 99 method (Goedkoop and Spriensma) and the Canadian LUCAS method (Toffoletto et al., 2007).

5.3.5.1 Eco-indicator 99

Despite the modelling differences between these two methods (see sub-section 3.2.5.1), a comparison of the two types of pavement for the 16 functional classes with the Eco-indicator 99 method can show whether the results follow the same trends as with the IMPACT 2002+ method.

Figure 18.2 shows the comparative damage indicator results of the pavement life cycle (CC system – AM system) for functional class 16 using the IMPACT 2002+, Eco-Indicator's Egalitarian (E), Hierarchist (H) and Individualist (I) methods.

Given these results, comparative indicators for human health and ecosystem quality are always positive, thus favourable to the AM system, regardless of the method or perspective used.

For the resources damage category, the preferred system varies according to the perspective used. For the E and H perspectives, as well as for the IMPACT 2002+ method, the comparative indicator is always negative, indicating the AM system is the most damaging. However, according to the I perspective, only proven effects are considered. Therefore, the use of non-renewable resources is not included in the resource category (only ore consumption is included). The AM system is strongly favoured, since the consumption of crude oil required for asphalt production—a significant part of the inventory in terms of mass and the main building material of asphalt pavement—is not even translated into impact while cement has significant ore consumption for the CC system.

Since a trend reversal is induced in the resource category from the I perspective, it becomes clear from this approach that the AM system is preferred. However, as with the results obtained with IMPACT 2002+, if the E or H perspective is used as LCIA method, the indicators do not all point to the same conclusions. In those circumstances, there is no scientific approach to aggregate the damage categories into a single score and decisions can only be made based on value choices.

5.3.5.2 LUCAS

The Canadian LUCAS method was initially supposed be used to complete the LCIA. A verification was performed to determine whether using the LUCAS method resulted in variations in the results of the comparison of the two types of pavement for the 16 functional classes.

Table F-18.14 shows the comparative impact indicator results of the pavement life cycle (CC system – AM system) for the 16 functional classes according to the LUCAS method, and Table F-18.15 shows those comparative results in relative terms for the 16 functional classes according to the LUCAS and IMPACT 2002+ methods.

For all functional classes, the results for the aquatic eutrophication and consumption of non-renewable resources categories are negative, favouring the CC system, while the remaining 10 categories show positive results favouring the AM system. Excluding the “cancer” human health category, results obtained at the “problem” level are very similar to those for the IMPACT 2002+ method, which—as mentioned earlier—favoured the CC system for the “cancer” human health, aquatic eutrophication (classes 8, 12 and 16 only) and resource consumption categories.

The different conclusion for the “cancer” human health category can partly be explained by the difference in uncharacterized substances between the two methods. For example, air emissions of “aromatic hydrocarbons” contribute the most for the IMPACT 2002+ method, but they are not characterized by the LUCAS method. These emissions are considerably more important for the AM system than for the CC system (185% larger for functional class 16). Conversely, other substances are characterized by the LUCAS method but not by IMPACT 2002+.

5.3.6 Cement Production

As for the study on the consistency of asphalt production data, it is important to test specific cement production data in a sensitivity analysis. As mentioned above the data was directly provided by the CAC based on its three cement plants in Québec. Although no cement ecoprofile (other than that of Athena Sustainable Materials Institute [2005] and CANMET and Radian Canada Inc. [1993]) was listed in the literature review (presented in Appendix B), two sets of data about cement production from the ecoinvent database were studied. More specifically, the datasets represented class (Z) Portland cement of either 42.5 or 52.5 MPa strength[1].

Figure 19.2.1 and Table 19.2.1 show the results of the comparison of the different types of cement for the two types of pavement. It is to be again noted that, since the trends in the results are the same for each functional class, only functional class 16 is the subject of this analysis.

[1] Note that the strength class mainly influences the make-up of cement, more specifically the proportions of limestone, gypsum, sand, etc.

A reversal can be observed in regard to human health. By using ecoinvent cement production data, the comparative indicator result for this damage category is negative, favouring the CC system. This reversal is mainly due to the respiratory effects (inorganic) impact category and can be explained by higher emissions of SO_2, NO_x and particulates for the specific cement data. Clearly, the relative difference between the specific data and the two generic datasets is approximately 10% and 61% respectively for direct SO_2 and NO_x emissions to the air. In addition, unlike the ecoinvent data, particulate emissions are accounted for for the extraction of raw materials (limestone, gypsum, clay, etc.) in the data from the CAC.

The negative indicator for human health can also be influenced by the impact on “non-cancer” human health. Direct emission of hexachlorobenzene and dichloromethane into the air were not included by the creators of ecoinvent for both types of cement production although these values were inventoried and entered into the specific data.

The quality of ecosystems category also presents lower comparative indicator results when the ecoinvent datasets are used but still show positive values, indicating that the AM system is still favoured for this indicator.

As for the global warming and resource consumption categories, the conclusions remain unchanged.

Despite the changes to the human health and ecosystem quality categories, the fact remains that these reductions do not enable the identification of the most favourable system overall.

5.3.7 Impact of Reduced Consumption

Although the literature review (Chapter 2) indicates that traffic could contribute up to 90% of the total impacts for the entire life cycle of pavement, it is not included in this LCA, as specified in sub-section 3.2.2.2. Some studies have attempted to demonstrate that the type of pavement could influence fuel consumption.

Therefore, a sensitivity analysis was performed to verify whether including traffic (cars and trucks) would influence the findings. To do this, fuel consumption and direct emissions associated with 1% of the vehicles driving on the 5 km stretch over the 50-year period were added to both pavement types and compared to the baseline scenarios for which no traffic is considered.

Figure 22.2.1 presents the damage indicator results for the life cycle of pavement for functional class 16, assuming 1% of gasoline use for the life cycle of both types of pavement while also indicating the results for the baseline scenarios. In order to properly observe the influence of traffic on the total life cycle, these results are not presented as a differential.

The results obtained indicate that taking into account the traffic, even by a marginal amount (1%), could completely reverse the findings of the study. The relative difference between the scenario considering the traffic and the baseline is around 10,000% for both pavement types, indicating that all stages of construction, maintenance and reconstruction have very little impact compared to road traffic. It is traffic and not the pavement itself that generates impacts on the life cycle of pavement.

5.3.8 C0$_2$ absorption through the Carbonation

For this LCA, CO_2 emissions throughout the life cycle of the pavement are considered. Particularly for cement concrete pavement, the inventory analysis (sub-section 4.4.1) indicated that CO_2 emissions were mostly (98.1%) due to the calcination process of limestone during cement production. However, once cement is used to produce concrete, the carbonation process is started, resulting in the absorption of CO_2 by the concrete itself.

This sequestration of CO_2 by cement concrete pavement had been omitted while calculating the inventory for this study. To verify the influence of this process on the results, this sensitivity analysis takes in account the total amount of CO_2 that can be absorbed by the cement concrete pavement for functional class 16 over the 50-year period.

To do this, some simplifying assumptions were made:

- Recycled concrete (i.e., second generation) can also absorb CO_2 when used in the sub-base of the two types of pavement. While sub-base layers are thicker for concrete pavements, the absorbed CO_2 is calculated from the cement concrete surface and does not depend on the thickness. Since the lengths and widths of the roads are the same for both types, the absorption rate is considered equivalent. Thus, only the absorption of the concrete used for the cement concrete pavement surface (CC system) was considered for this analysis;
- The *Guidelines – Uptake of Carbon Dioxide in the Life Cycle Inventory of Concrete* (Pommer and Pade, 2005) were used to estimate the amount of CO_2 absorbed during the life cycle of the cement concrete pavement surface.

The authors Pommer and Pade (2005) state in their guidelines that, according to some studies, the fraction of calcium oxide (CaO) in the cement part of cement concrete which turns into $CaCO_3$ is at least 75%. The degree of carbonation of the concrete in the pavement surface depends on several parameters, including the pavement service life, the strength of the cement, the percentage of clinker in the cement, the composition of the concrete and the concrete surface.

The following formula is used to calculate the total amount of absorbed CO_2:

$$CO_2(kg) = 0.383 \cdot S \cdot \rho_{cement} \cdot X_{clinker} \cdot K \cdot \sqrt{t} \tag{5-3}$$

where:

S is the surface area which can undergo carbonation and is calculated according to the following equation:

$$S(m^2) = \frac{volume \cdot 2}{thickness} = length \cdot width \cdot 2 = 5000m \cdot 17.1m * 2 = 171{,}000m^2 \qquad (5\text{-}4)$$

ρ_{cement} is the density of the cement concrete, or 2,350 kg/m^3

$X_{clinker}$ is the percentage of clinker in the cement, or 92.5%

t is the service life of the pavement, or 50 years

K is a constant function of three factors, k_1, k_2 and k_3, using the following equation:

$$K = k_1 \cdot k_2 \cdot k_3 \qquad (5\text{-}5)$$

where:

k_1 is a factor that depends on exposure and concrete strength. For 43 years of the 50-year period, the cement concrete surface is considered to be exposed. The k_1 factor is therefore 1 mm·y$^{1/2}$. However, between years 39 and 46 (for functional class 16), a layer of asphalt is applied to the surface of the cement concrete. For these seven years, the cement concrete is considered not to be exposed and therefore k_1 factor becomes 0.75 m·y$^{-1/2}$.

k_2 is a correction factor that depends on the type of concrete structure. For pavement, k_2 is 1.0.

k_3 is also a correction factor and depends on the composition of cement concrete. Since the cement concrete used contains 5% silica, 25% fly ash and 22% slag, the k_3 factor is estimated to be 1.08.

The CO_2 absorbed can be calculated using equation (5-3:

$$CO_2(kg) = \left[0.383 \cdot 171{,}000m^2 \cdot 2350\frac{kg}{m^3} \cdot 0.925 \cdot 1 \cdot 10^{-3} m \cdot yr^{-1/2} \cdot 1.0 \cdot 1.08 \cdot (43yr\right.$$

$$\left[0.383 \cdot 171{,}000m^2 \cdot 2350\frac{kg}{m^3} \cdot 0.925 \cdot 7.5 \cdot 10^{-4} m \cdot yr^{-1/2} \cdot 1.0 \cdot 1.08 \cdot (7yrs)^{1/2} \right]$$

The total amount of CO_2 absorbed by the pavement over the 50-year period for functional class 16 is **1,310 t**.

Figure 23.2.1 presents the comparative results of the damage indicators for the life cycle of pavement for functional class 16 with and without the inclusion of the CO_2 absorbed by the CC system.

The total amount of CO_2 from the life cycle inventory of cement concrete pavement for functional class 16 was **6,060 t**. There is a decrease of 22% in the net amount of CO_2 emitted during the life cycle of the cement concrete pavement for this functional class, which results in a decrease of 26% in the total amount of CO_2 equivalent. The results are in agreement with the decrease of CO_2 equivalent, since the global warming damage indicator result indicates a decrease of the same proportion when considering the carbonation process. However, although there is a decrease in the impact score, it remains higher for the CC system than for the AM system. The other damage indicator results remain unchanged.

The carbonation process of cement concrete is important from a life cycle perspective and to give a representative picture of reality. However, for this comparative LCA, the amount of CO_2 absorbed by the pavement throughout its life cycle is not a sensitive parameter as the findings of this study are not modified by taking into account the carbonation process of cement concrete.

5.4 Study Limitations

5.4.1 LCI Limitations

The limitations of the inventory analysis are essentially related to the incompleteness and the validity of the inventory per se. Several processes that were initially within the study's boundaries had to be excluded or estimated during data collection, mostly due to lack of information. Those limitations concern notably the following:

- **Material truck transport distances to the road construction site:** This parameter is assessed with a sensitivity analysis which shows that the study's findings are not modified when the distance is less than 250 km (see paragraph 5.3.1);
- **Organic emissions from the production, transportation and placement of asphalt:** This parameter is assessed with a sensitivity study which shows that the addition of PAH emissions does not change the study's findings (see paragraph 5.3.3);
- **Asphalt production:** This inventory is assessed with a sensitivity analysis which shows that using production data from other sources does not change the findings obtained (see paragraph 5.3.2);
- **Cement production:** This inventory is assessed with a sensitivity study which shows that using production data from other sources changes the findings for certain damage indicators (human health and ecosystem quality) without, however, allowing the identification of an overall favourable system (see paragraph 5.3.6);
- **Life cycle of cement concrete and asphalt plants:** Since no generic data is available regarding the infrastructure of an asphalt mix plant as opposed to that of a cement concrete plant, those inventories are excluded;
- **Production of de-icing salts and marking products:** Those inventories are completed using proxy data;

- **Dust emissions from interventions:** This parameter is supposed to be equivalent for both systems and therefore should not influence the findings;
- **Direct emissions to water (Na) and soil (Cl)[1] related to the use of de-icing salts:** This parameter does not change the findings obtained since the CC system uses more de-icing salt (which puts it at a greater disadvantage with regard to the ecosystem quality category).

Thus, the inclusion and/or better representation of those processes within the inventory would surely change the analysis results, but most likely not to the point of reversing the findings. For information, Table 5-8 shows the quality indicators that apply to the comparative life cycle data in order to gauge the reliability of the data in relation to its potential influence over the findings. The criteria used for qualifying the data are identified in Table 5-7.

As for the qualification of "quantity" and "process" data, the data obtained from experts or published reports was assessed as being reliable and representative of the analyzed context. This means that data on the production of different road construction materials had a score of 1 or 2. However, some missing data had to be completed using assumptions or gross estimates. These data therefore received lower scores of 4 or 5.

Some particular sought-out specific data could not be integrated into the inventory, such as data on losses, dust and cleaning during interventions, asphalt fume emissions during the production and placement of hot mix, as well as various transport distances. For instance, no specific transport distances could be specified or determined during data collection, so a score of 4 was attributed to the "quantity" data. However, the different transport distances do not strongly contribute to the impact scores.

In addition, some generic data was missing and therefore had to be modelled using proxy data. This was the case for processes related to the production of marking products and preformed joints. As such, the score given to the "process" data was lower; however, their contribution to impact scores is small (score of 1).

[1] Since these substances are not characterized, excluding them from the inventory will not change the results of the impact assessment.

Table 5-7: Data Qualification Criteria

Score	"Quantity" qualification criteria
1	Rather reliable specific data or information showing little variation between sources (experts/reports, but not reviewed by a third party)
2	Rather uncertain specific data or information that varies between sources (experts/reports, but not reviewed by a third party)
3	Data estimated from other sources (generic)
4	Grossly estimated data
5	Missing data
Score	**"Process" qualification criteria**
1	Specific data (experts/reports, but not reviewed by a third party), or generic data with good geographic and technological representation of the selected process
2	Generic data partly adapted to the energy or technological context
3	Incomplete data (the process is only partially represented) or data with unknown geographic and technological representativeness
4	Data with inadequate geographic or technological representativeness. The data is not easily accessible, another process was used as a proxy.
5	Missing data
Score	**Criteria for qualifying potential contribution to impacts**
1	Potentially low or insignificant contribution (i.e., with no influence over results)
3	Potentially influential contribution
5	Potentially high contribution

Table 5-8: Data Qualification

Life cycle stage	Potential contribution to the differentiation of systems	Data quality	
		Quantity (involved in foreground processes)	Process (background)
1- Initial construction (IC), 2- Maintenance (M) and 3- Reconstruction (R)			
Granular materials for base and sub-base	1	1	2
Transport of base and sub-base materials	1	4	3
Asphalt for new asphalt pavement	5	1	2
Sand and crushed stone for new asphalt pavement	1	1	2
Pre asphalt mix transport	1	4	3
Production of new asphalt mix	3	3	3
Transport of new asphalt mix to road construction site	1	4	3
Cement for new concrete pavement	5	1	2
Sand and crushed stone for new concrete pavement	1	1	2
Water for new concrete pavement		1	2
Pre concrete transport	1	4	2
Additional concrete transport	1	1	2
Production of new concrete	1	1	1
Transport of new concrete to road construction site	1	4	3
Steel for joints	3	1	2
Pre-formed compression seals	1	1	4
Hot-pour sealant	1	1	3
Transport of auxiliary elements to road construction site	1	4	3
Machinery	1	3	3
2-Operation (O)			
De-icing salt for concrete pavement	3	1	3
5- Marking (M)			
Production of marking products	1	1	4
Transport of marking products	1	4	3

Note: The quality of “quantity” data refers to the reliability of inventoried quantities of materials and energy, as well as transport distances and quantity of emissions according to use (primary flows; see definition in Appendix A). The quality of “process” data refers to the geographic and technological validity of the selected generic data modules (secondary flows; see definition in Appendix A). Finally, the potential contribution to impacts refers to the potential influence of the values of the two systems over results (in light of contribution and sensitivity analysis results).

5.4.2 LCIA Limitations

The results discussed in the sections above (5.1 to 5.3) stem from calculations essentially using the models embedded in the IMPACT 2002+ assessment method. Assessed damages (and impacts) are only potential damages (and impacts), since they are the result of modelling, which implies a simplification of reality. LCIA results are relative expressions that cannot predict effects on final impacts by category, threshold exceedance, safety margins or risks. As such, these results should not be used as the sole basis for a comparative statement intended to be publicly disclosed, given that additional data would be required to remedy certain limitations inherent in LCIA. The results could potentially be refined through the use of other tools such as risk analysis, or following future methodological improvements.

More importantly, the interpretation of characterization results can only be based on the obtained results, i.e., it only considers substances for which the impact assessment method databases include characterization factors that convert the inventoried elementary flows into the impact or damage indicator units. Yet, many elementary flows (448) could not be converted into a category indicator because no characterization factor was available, such being the case for sand and gravel for producing granular materials (crushed stone and sand), and for chlorine and sodium emissions to water due to the production of epoxy paint. Those flows were therefore not considered in the assessment of impacts and damages. It should also be noted that the non-characterized elementary flows are the same for both types of pavement. However, on average, the comparative result for those non-characterized flows is mostly positive, which puts the CC system at a disadvantage. More specifically, the 340 flows favour the AM system for, while 108 flows favour the CC system. The associated impacts that would be assessed if characterization factors were available would probably be to the detriment of the CC system, which would support the findings obtained.

6. CONCLUSION AND RECOMMENDATIONS

The purpose of this project was to compare the potential environmental impacts of the life cycle of cement concrete pavement of the Jointed Plain Concrete Pavement type to those of asphalt pavement.

The inventory analysis showed that the **use of water and energy** and **discharges to the environment** (except for emissions to water for functional classes 8, 12 and 16) are higher for cement concrete pavement (CC system), while asphalt pavement (AM system) presents a higher **consumption of natural resources**. The analysis also identified the main contributors to the inventory, which included the production of cement, cement concrete, steel, de-icing salts, asphalt and asphalt mix.

According to the results of the impact assessment carried out using the IMPACT 2002+ method, 12 of the 15 impact indicators favour the AM system. However, indicators related to human "cancer" toxicity, consumption of non-renewable resources and aquatic eutrophication (for functional classes 8, 12 and 16 only) favour the CC system.

Let us recall that:

- What distinguishes functional classes 8, 12 and 16 from the others is the fact that the asphalt pavement must be rebuilt earlier, which implies a larger quantity of asphalt and asphalt mix being required by the AM system and an increase in the associated emissions to water (and eutrophication);
- While the human "cancer" toxicity indicator favours the CC system, the overall human health damage indicator favours the AM system;
- The resource-related damage indicator favours the CC system because of the energy inherent in the asphalt used in the AM system;
- The indicator related to aquatic eutrophication poses significant uncertainty, which means there is a great likelihood that the system to be favoured for this impact category could be reversed.

As for the four damage categories, the **human health**, **global warming** and **ecosystem quality** indicators all favour the AM system, while the **resource consumption** indicator always favours the CC system, for each of the 16 functional classes.

The completed uncertainty and sensitivity analyses show a low likelihood for the findings to be changed, while the choice of the LCIA method could, on the contrary, influence some of the findings. More specifically, according to the individualist approach of the European Eco-indicator 99 method, the four damage indicators unanimously favour the AM system. It is important to note, however, that under the individualist approach, only proven effects are taken into consideration, and the use of non-renewable resources is not included (which makes it a value choice to be considered in a transparent manner).

In addition, as indicated by the literature review (Chapter 2) on the life cycle of pavement, road traffic is responsible for most of the total impacts, for all categories. Thus, any fuel savings, even marginal ones, could clearly favour one type of pavement over another (assuming the type of pavement significantly influences fuel consumption, which remains to be validated).

Considering these results, it is difficult to favour one option without being able to validate the influence of the type of pavement on fuel consumption or without making a value choice so as to weigh the different impact indicators.

According to the ISO standard (2006), when the results obtained based on natural sciences do not clearly favour one option of the LCA, a decision can be made by making a value choice. By using weighting factors, several indicators can be aggregated into a single score in order to be able to decide between the options. These value choices are up to the entity that commissioned the study (the MTQ) and should be presented in a transparent way. For information purposes, a simulation showed that the favourable option can be targeted through different combinations of possible weightings for the four damage indicators. This data will be taken into consideration in the context of the Policy.

Again, since any decrease in fuel consumption represents a significant decrease in the life cycle impacts of any type of pavement, the focus should be on reducing fuel consumption by encouraging the use of greener vehicles or carpooling, for instance.

It is also of note that the results obtained through this study were a function of a technological system that remains static over the 50-year period being considered. No one is currently in a position to accurately characterize the evolution of techniques for producing construction materials, pavement design and construction technologies or environmental regulations, although the market's competitiveness will most likely change the analyzed system and, therefore, the results of this study. As such, several new pavement technologies are emerging, such as cold mix, improved recycling techniques, polymer-modified asphalt which extends the pavement's useful life, etc. It would therefore be advisable for the MTQ to look at the environmental relevance of those pavement innovations.

Finally, as mentioned by Pears (2004), several road construction elements can reduce the environmental and social impacts of pavement: the choice of materials, road design, site design and intrinsic impacts of construction. PCRs (Product Category Rules) for making environmental product declarations (EPDs) on materials used in the different pavement types are required so as to make this study easier to update. From a sustainable development perspective, these considerations are factors that could possibly be integrated into MTQ transportation-related policies (without the MTQ having to favour one type of pavement over another).

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Appendix A:
Life cycle Analysis (LCA) Methodology

APPENDIX A:
LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

Life cycle assessment (LCA) methodology is regulated by the International Organisation for Standardisation (ISO), and, more specifically, by the ISO 14 040 standard. An introduction to the LCA methodology has been provided in the report. The following sections present certain LCA terms and their definitions and the main methodological aspects of the method's four phases.

A.1 Terms and definitions

Attribute-driven life cycle assessment (LCA-A): Assessment that aims to attribute to a product system the fair share of the impacts for which it is responsible.

Characterization factor: Factor based on a characterization model that is used to convert the life cycle inventory results into a common indicator category unit.

Consequence-driven life cycle assessment (LCA-C): Assessment that aims to analyze the consequences of a product system (or of a decision that impacts this system) on other systems.

Consistency check: Process begun before the conclusions are drawn and which makes it possible to verify that the hypotheses, methods and data are applied consistently throughout the study and remain in keeping with the objectives and scope of the study.

Completeness check: Process to verify whether the information in the previous phases of the life cycle is sufficient enough to draw conclusion that are in keeping with the objectives and scope of the study.

Critical review: Process to ensure the consistency between a life cycle assessment and the principles and requirements of the international standards that regulate life cycle assessment.

Elementary flow: Material or energy that enters the studied system and which was taken from the environment without previous transformation by man or the material or energy that exits the studied system and which is emitted into the environment without any subsequent transformation by man.

Elementary process: Smallest part of the life cycle inventory that is taken into account and for which input and output data is quantified.

Emissions: Emissions released into the air, water and soil.

Energy flow: Input or output of an elementary process of a product system expressed in energy units.

Functional unit: Quantified performance of a product system meant to be used as a reference unit in a life cycle assessment.

Impact category: Category that represents the environmental points to which the result of the life cycle inventory are assigned**.**

Impact category indicator: Quantifiable representation of an impact category (note: it is also sometimes referred to as *indicator category*).

Input: Product, material or energy flow entering an elementary process (note: the products and materials include raw materials, intermediate products and co-products).

Intermediary flow: Product, material or energy flow that impacts the elementary processes of the product system studied.

Life cycle assessment (LCA): Compilation and assessment of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.

Life cycle impact assessment (LCIA): Phase of the life cycle assessment that aims to understand and assess the extent and significance of the potential environmental impacts of the product system throughout its life cycle.

Life cycle interpretation: Life cycle assessment phase during which the results of the inventory or impact assessment (or both) are assessed in light of the objectives and scope of the study so as to establish conclusions and recommendations.

Life cycle inventory (LCI): Life cycle assessment phase that involves input and output compilation and quantification for a given product system throughout its life cycle.

Output: Outgoing product, material or energy of an elementary process (note: the products and materials include the raw materials, intermediate products, co-products and emissions).

Process: All of the correlated or interactive activities that transform the inputs into outputs.

Product flows: Input or output of one product system into another.

Product system: All of the elementary processes, including the elementary and product flows, that fulfill one or several of the defined functions and which serve as a model for a product's life cycle.

Raw material: Raw or secondary material used to manufacture a product.

Reference flow: Measure of the outputs of the processes of a given system that are necessary to carry out the function as it is expressed in the functional unit**.**

Results audit: Part of the interpretation phase of the life cycle that establishes the level of certainty of the life cycle assessment results (note: the audit includes the completeness, sensitivity and consistency checks and all other forms of validation that may be required, in keeping with the objectives and scope of the study).

Sensitivity analysis: Systematic procedure to estimate the effects of the method and data choices on the results of the study.

Sensitivity check: Process to verify if the information obtained from a sensitivity analysis is reliable enough to establish conclusions and formulate recommendations.

System boundary: Set of criteria that specify which elementary processes are included in the product system.

Uncertainty analysis: Systematic procedure that makes it possible to research and quantify the uncertainty that the cumulated effects of the imprecision of the model, uncertainty of the inputs and variability of the data introduce into the life cycle inventory results.

A.2 LCA Phase I: Defining the objectives and scope of the study

The first phase of the LCA consists in defining the objectives and scope of the study to determine its rationale and the methods that will be used to reach these objectives (i.e., the study model that defines the methodological framework that the subsequent phases of the LCA must conform to).

The application and target audience must also be clearly determined, since these factors will set the depth and breadth of the study.

As stipulated by ISO, LCA are carried out by honing the models that describe the key elements of the physical systems. The product system[1] represents all of the human activities considered in the study. The impact assessment is based on the models (environmental mechanisms) that link the environmental interventions of these activities and their potential environmental effects.

ISO defines a **product system** as all of the elementary processes linked by the matter and energy flows that fulfill one or several functions. The focus of the LCA is characterized by its functions and not only in terms of its final products. This makes it possible to compare products that do not have the same functional performance per product unit (e.g.: a one-time use Styrofoam cup and a ceramic cup used more than once) because the quantification of the functional performance by the **functional unit** creates a reference based on which the compared inputs and outputs are mathematically standardized (e.g.: drinking two cups of coffee per day during one year). The specificity of the functional unit is the starting point at which the boundaries of the product system are defined because they determine the elementary processes that must be included in order to fulfill the function. The more precise the functional unit, the more restrictive the system boundaries will be.

An **elementary process** (or unit process) is defined by ISO as the smallest part of the product system for which data is collected (i.e., it can represent a specific chemical process or an entire factory that includes many sub-processes). An elementary process is characterized by its inputs and outputs. If the elementary process represents more than one sub-process, then its inputs and outputs are aggregated.

ISO stipulates that the elementary processes are linked to natural ecosystems (or ecospheres) by **elementary flows** and to economic systems (or technospheres – the part of the ecosphere that was transformed through human activities) by **product flows** (Figure A-1). There are also **intermediate product flows** between the processes of the studied system. The elementary flows are therefore taken directly from the environment or emitted directly into the environment and contribute to the impact categories, while the product flows (matter, energy or service including the co-products, sub-products and waste) are used to determine the intensity of the modeled processes.

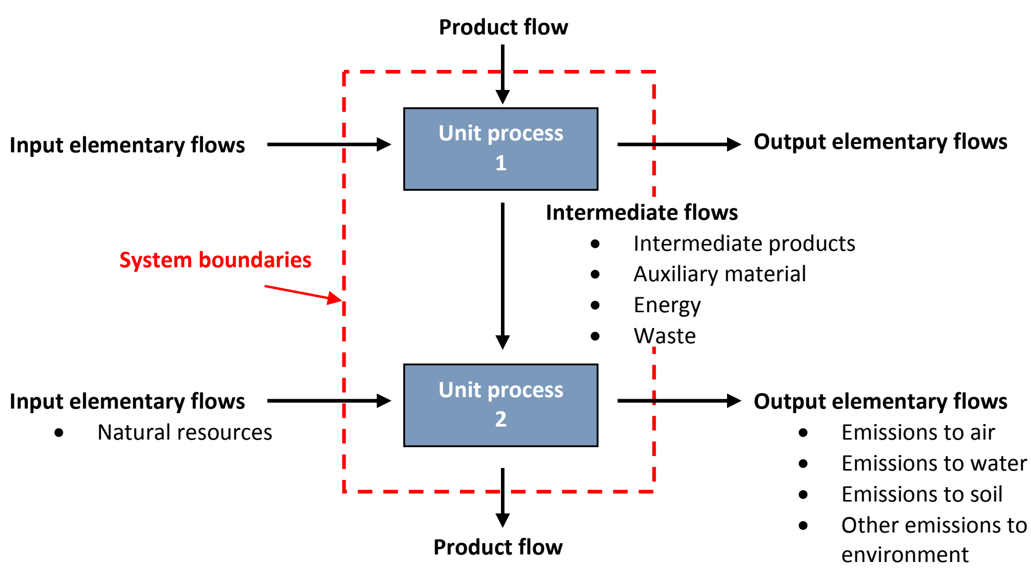

Figure A-1: Boundaries and elementary processes of a product system.

[1] The term *product*, when used alone, includes product systems and service systems.

Using a flow chart that illustrates the elementary processes and their interrelations (materials and energy flows) makes it possible to follow up on the product system boundaries.

According to ISO, it is best to model the product system so that the inputs and outputs at the boundaries are elementary flows. In many cases, however, time, resources and data are insufficient to conduct a complete study. Decisions must then be made on the elementary processes and flows[2] that should be initially included in the study. ISO also stipulates that it is not necessary to quantify the inputs and outputs that will have little impact on the broad conclusions of the study and suggests flow inclusion criteria (e.g.: contributions over a given threshold to the mass or energy balances or environmental relevance).

The list of all of the elementary flows and processes to be modeled can be adjusted when new information is acquired and the decisions that lead to these system boundary modifications must be clearly presented.

Once the list of the elementary processes included in the product system is complete and in order to build the system inventory and continue the assessment of the potential impacts, the relevant process data (i.e., the inputs and outputs) must be collected. However, prior to this collection, criteria pertaining to the data's quality (time, geographic and technological boundaries, precision and completeness), source (specific or generic), type (measured, calculated or estimated), nature (deterministic or probabilistic) and level of aggregation must be determined so as to remain focussed on the objectives of the study.

A.3 LCA Phase II: Inventory assessment

The second phase of the LCA, life cycle inventory assessment (LCIA), consists in quantifying the elementary flows that cross the product system boundaries.

The calculation process used to complete the inventory is presented in Figure A-2.

[2] Because the quantified elementary flows are the inputs of the impact assessment, the choice of impacts will affect the choice of elementary flows to follow.

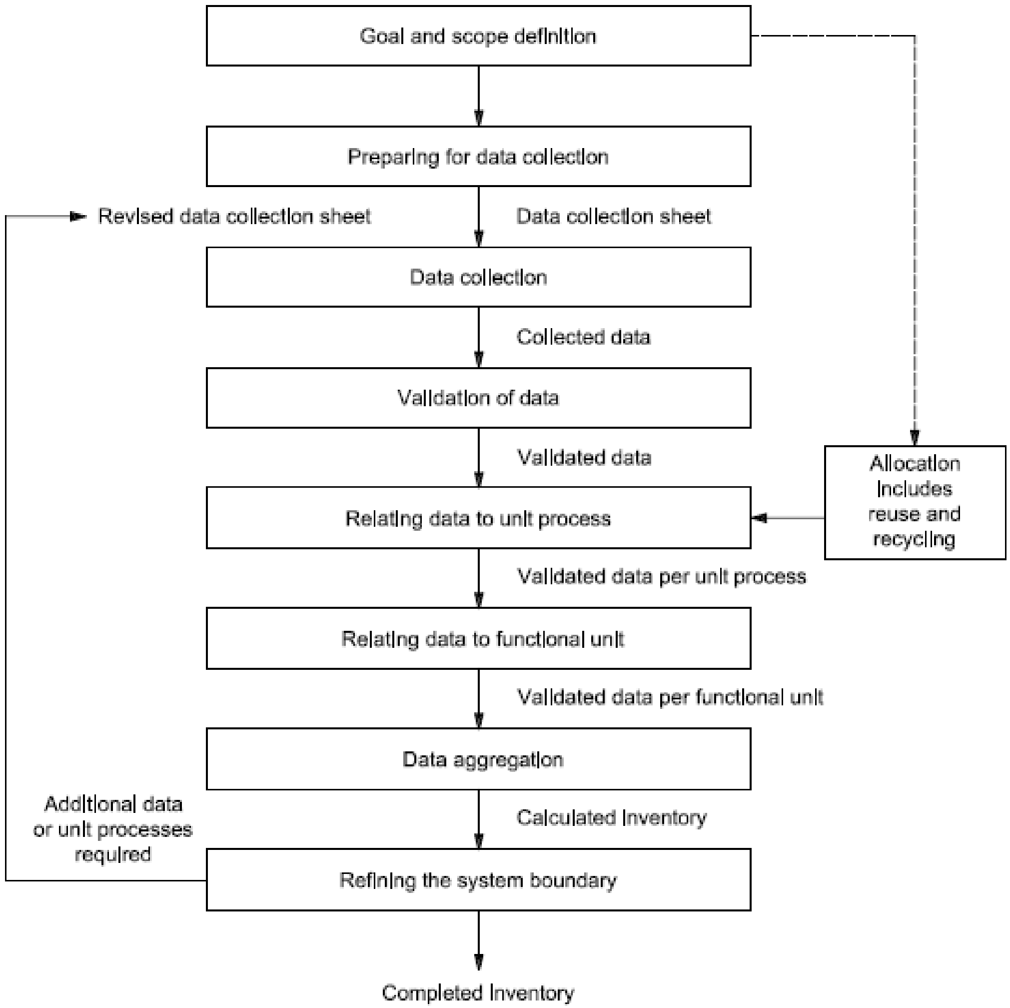

Figure A-2: Inventory calculation.
(from ISO 14 044, 2006)

A.3.1 Data category descriptions

The data used in the LCIA can be classified according to its source (specific or generic), type (measured, calculated or estimated), nature (deterministic or probabilistic) or level of aggregation.

A.3.1.1 Classification based on source

Specific or primary data

Specific data is collected from the installations that are linked to the elementary processes included within the boundaries of the system. The analyst overseeing data collection has direct access to the data during collection or a direct control over the collection process (i.e., the method used). Unless it is to characterize the installations included in the study, this type of data is not recommended because it lacks representativeness. It should be used only if 1) no other data source is available or 2) a sufficient number of installations in the same industrial sector provide data with which it is then possible to calculate representative industrial averages (which can then be used as generic data in other studies).

Generic or secondary data

Generic data is obtained from published sources (i.e., commercial databases, specialized literature). The analyst does not have access to the data during collection. Sufficient metadata[3] to provide information on the collection method or data variability is not usually available.

A.3.1.2 Classification based on type

Measured data

The measured data is from real installations and gathered through a monitoring program or random sampling. It could therefore be possible to obtain information on the variability and distribution of the data.

Calculated data

The calculated data is taken from the models in order to represent the processes or phenomena. Its quality therefore depends on the validity of the models. The data can be validated by or supplemented with measured data.

Estimated data

The estimated data includes information based on professional judgement or rules of thumb. It is only used when no other type of data is available.

A.3.1.3 Classification based on nature

Deterministic data

The deterministic data is represented by discrete values (i.e., measures, calculation results or estimates) for each of the characterized parameters (flows). It is therefore impossible to know the precision and variability of the reported data. .

Probabilistic data

The probabilistic data is represented by value ranges or probability distribution functions (e.g.: triangular, normal, lognormal) for each of the characterized parameters (flows). They therefore account for the imprecision and variability of a parameter and make it possible, in the interpretation phase, to eventually assess the uncertainty of the results obtained during the inventory and impact assessment phases.

A.3.1.4 Classification based on the level of aggregation

The level of aggregation of the data refers to the number of elementary processes that are represented by a same datum. When completely disaggregated, the data for a specific life cycle phase or product system is available for each individual process included in the phase or system. This same data can also be completely aggregated into a single datum that describes the phase of the system considered (all of the elementary flows of a same substances are summed up in a single flow). There is therefore information loss when the level of aggregation is increased because it is then no longer possible to know the individual contribution of each of the aggregated elementary flows. It is sometimes difficult to establish the level of aggregation (and the list of the aggregated processes) of the generic data in commercial databases.

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[3] Information with the inventory data and which provides facts on the data itself (e.g.: its origin, the collection method used and the boundaries of the elementary process being described).

A.3.2 Data collection

Depending on the complexity of the products studied (i.e., the number and nature of the elementary processes included within the boundaries), the amount of data to be collected is often quite large. Using commercial inventory databases eases the process by providing data on several elementary processes (e.g.: materials and energy production, transport). These databases are mainly European and are therefore not representative of the Canadian context. They can, however, be adapted to the Canadian context if the data is sufficient disaggregated and if the information needed to do so is available[4]. The methodology used for data collection must be clearly presented.

A.3.3 Data validation

The data collected for each of the elementary flows can be validated by 1) assessing the data based on the quality criteria established when defining the objectives and scope of the study and 2) carrying out mass or energy balances or comparative assessments of the emission factors. If obvious irregularities are determined, alternative data that meets with the previously established criteria is required.

The availability and quality of the relevant data (e.g.: data deficiencies, generic rather than specific averages) will limit the exactitude of the LCA. Specific North American inventory data is currently missing and this will affect the results of studies carried out in Canada.

The lack of a uniform documentation format[5], which can sometimes result in only a small amount of documentation for commercial inventory data, can also hinder data collection and validation, making it difficult to assess the data's quality and ability to meet the set criteria.

ISO stipulates that treating missing and forgotten data usually brings about a justified *non-zero* data value, a *zero* data value if it is justified or a value calculated based on the communicated values from the elementary processes that rely on a similar technology.

A.3.4 Linking the data and the elementary process

Once the inputs and outputs of each elementary process have been determined, they are quantified based on a reference flow established for each of the processes (e.g.: 1 kg or material or 1 MJ of energy). ISO states that if an elementary process has more than one product (e.g.: an oil refinery produces a mix of commercial petroleum hydrocarbons) or input (e.g.: a landfill site receives municipal waste made up of different products) or if it recycles the intermediate products or raw materials waste, the materials and energy flows and their environmental emissions must then be allocated to different co-products or co-inputs according to the rules set out when the objectives and scope were defined. ISO also suggests a series of principles and processes to follow when making these allocations.

The ISO allocation rules are listed below in order of importance.

1. It is best to avoid allocation whenever possible by:
   - Subdividing the multifunctional processes into two or more sub-processes (when certain sub-processes are specific to only one of the co-products);

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[4] Production data on certain materials in Europe may refer to other transport, energy or materials production processes (e.g.: for intermediate or auxiliary products). The data that describes these other elementary processes can be replaced with data that described these same processes, if available, from a source that is more specific to the Canadian or North American contexts, thus increasing the geographic representativeness of the European data.

[5] This type of format would create a level of documentation that is sufficient and uniform enough for the generic data from commercial inventory databases. ISO 14 048 (2002) is a step in the right direction.

- Broadening the boundaries so as to include the functions of the other systems (potentially) substituted by the co-products (and by allocating an environmental credit that is equal to the avoided impact of the substituted functions to the system being studied).

2. When it is impossible to avoid allocation, it is best to divide the input and output flows of the multifunctional processes between the various co-products so as to reflect the underlying physical relationships (e.g.: mass or energy).

3. When a physical relationship cannot be established, it is best to distribute the inputs and outputs so as to reflect their other relationships (e.g.: the economic value of the co-products).

A.3.5 Linking the data and the functional unit

The inputs and outputs of all of the elementary processes included in the product system are then standardized according to the functional unit and aggregated. ISO states that the level of aggregation must be sufficient enough to meet the objectives of the study and that the data categories (i.e.: individual or grouped substances of natural resources or environmental emissions) should only be aggregated of they refer to equivalent substances or similar environmental impacts.

A.4 LCA Phase III: Impact assessment

The third phase of the LCA, the life cycle impact assessment (LCIA) consists in interpreting the results of the life cycle inventory assessment of the product system so as to understand their environmental significance.

Inventory assessment makes it possible to quantify the exchanges between the product system and the environment. Depending on the study, the information will be of greater or lesser importance (i.e., certain natural resource and emissions flows into the environment can be quantified) and its practical use can become unclear. During the LCIA phase, certain environmental issues, called impact categories, are modeled and category indicators are used to condense and explain the results.

ISO stipulates that the methodological framework of the LCIA contains mandatory and optional elements (Figure A-3).

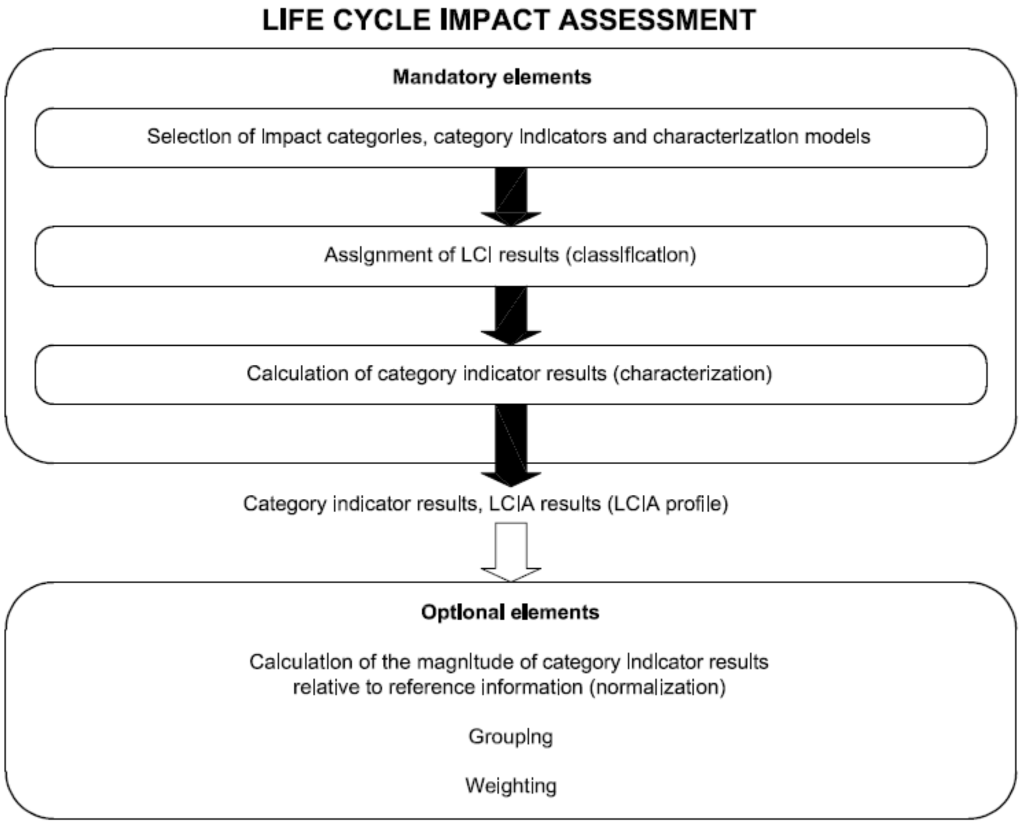

Figure A-3: Elements of the LCIA phase.
(From ISO 14 040, 2006)

A.4.1 Impact category and characterization model selection

The first step is selecting the **impact categories** that represent the problematic environmental issues considered in the study. Each category is identified by a final impact (i.e., an attribute or aspect of the natural environment, human health or natural resources). An **environmental mechanism** (i.e., a causality chain) is then established to link the inventory results to the final impact and a **category indicator** is chosen at a specific place in the mechanism to act as a quantifiable representation of the category. For example, Figure A-4 illustrates the environmental mechanism for the global warming category.

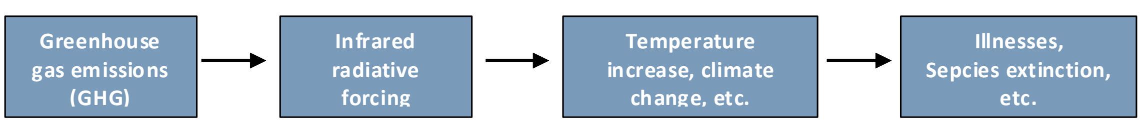

Figure A-4: Environmental mechanism for the global warming impact category.

A **characterization model** is then developed to determine the **characterization factors** that will then be used to convert the relevant inventory results into category indicator results according to their relative contributions to the impact category. For example, for the global warming category, the characterization factors represent the global warming potential of each of the greenhouse gases (in kg of CO_2-equivalent/kg of gas) and can be calculated based on the IPPC model. The inventory results that have been converted into a common unit can then be aggregated into a single **category indicator result** for each impact category. An example of the terms to describe the global warming category of the LCIA is presented in Table A-1.

Table A-1: Example of the terms used in LCIA

Term	Example	Unit
Impact category	Global warming	--
Inventory results	Amount of greenhouse gases (GHG) per functional unit	kg of gas
Characterization model	Basic 100-year model established by the Intergovernmental Panel on Climate Change (IPCC)	--
Category indicator	Infrared radiative forcing	W/m^2
Characterization factors	Global warming potential for (GWP_{100}) for each GHG	kg of equivalent CO_2 / kg of gas
Category indicator results	Sum of the characterized inventory results (i.e., multiplied by their respective characterization factors)	kg of equivalent CO_2 / functional unit
Final impacts per category	Illnesses, species extinctions, etc.	--
Environmental relevance	Infrared radiative forcing is indirect data on potential climate effects that depends on the absorption of the integrated atmospheric heat generated by the emissions and the distribution of this absorption over time.	--

(Adapted from ISO 14 044, 2006)

ISO stipulates that:

- The impact categories, indicator categories and characterization models should be accepted at the international level (i.e., they should be based on an international accord or approved by a knowledgeable international organization;
- The choice of impact categories must reflect a complete group of environmental points and how they pertain to the product system studied, taking into account the objectives and scope of the study;
- The characterization model for each indicator category should be scientifically and technically valid and based on a distinct environmental mechanism that is identifiable and/or a reproducible empirical observation;
- The choice of values and hypotheses made when selecting the impact categories, category indicators and the characterization models be minimized.

The impact categories often considered in LCA are:

- Global warming
- Acidification
- Photochemical smog
- Ozone layer depletion
- Eutrophication
- Human toxicity

- Ecotoxicity
- Land use
- Abiotic resource use
- Water use

Because no single widely-accepted LCIA method exists, there is no single list of impact categories that is generally recognized and used (Udo de Haes *et al.*, 2002). A compromise must therefore be reached between the foreseen applications of the results and the applicability and practicability of the choice of categories and models.

As for the inventory databanks, most of the LCIA methods are European and introduce a bias when considering the Canadian context. This is particularly important for the regional (photochemical smog, eutrophication, acidification) and local (human toxicity, ecotoxicity, land use) impact categories. Because these categories are influenced by the environmental conditions of the receptor area, the characterization models should normally take these characteristics into account[6]. For these impact categories, the CIRAIG has developed a Canadian LCIA method, LUCAS (Toffoletto *et al.*, 2005), based on the American model, TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) (Bare *et al.*, 2003). This method has the advantage of relying on characterization models that have been adapted to the North American context.

Also, the IMPACT 2002+ (Jolliet *et al.*, 2003) method proposes human toxicity factors for each continent. And, as presented by Rochat *et al.* (2006), though the substances emitted on different continents are linked to impacts that can be deferred by up to two orders of magnitude, the relative impact (ranking) of these substances remains the same overall. The authors therefore conclude that:

- Generic characterization factors calculated for a continent like those in most LCIA methods are normally valid for other continents on a comparative basis;
- Characterization factors that are specific to the receptor areas must be used when the study is focussed on absolute results or when a comparison is made between scenarios that involve emissions in very different receptor areas.

A.4.2 Classification and characterization of the inventory results

Once the impact categories have been selected, the inventoried elementary flows (those that are classified) are put into categories according to their predicted effects. Some can be exclusive to one category and others can be in several categories when serial or parallel effect mechanisms are being considered.

The categorized inventory results are then converted using characterization factors and the common units of the indicator categories. The converted results for each category are aggregated to obtain a numerical indicator result. All of the indicator results make up the LCIA profile.

Two elements should be noted regarding the LCIA profile:

1. The calculated range of the impacts considered only represents a potentiality since it is based on models that describe the environmental mechanisms and which therefore simplify reality[7].

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[6] The characterization models used for the impacts with global repercussions (global warming, ozone depletion, abiotic resource use and water use) are the same no matter where the emissions or resource extraction occurs.

[7] The divergence between the models' predictions and reality are increased mostly because they are based on the European context. This is particularly significant for regional and local impacts such as acidification and ecotoxicity.

2. The undefined substances (i.e., those that do not have a characterization factor because of a lack of data – (eco)toxicological data, for example) that are not included in the calculations increase the uncertainty of the results.

A.4.3 Optional elements

ISO stipulates that calculating the range of the category indicator results in relation to reference information (normalization) leads to a better understanding of the relative range of each indicator result of the product system. The reference information can consist in:

1. The total emissions or resource uses for a given geographic zone (global, regional or local);
2. The total emissions or resource uses for a given zone (global, regional or local) per inhabitant or a similar measurement;
3. A reference scenario such as another product system.

This optional step can be useful during the consistency check, for example. It also has the advantage of converting all of the category indicator results into the same unit (person-equivalent, for example), which is a pre-requisite for the optional elements below.

According to ISO:

1. **Grouping** consists in classifying the impact categories into one or several series, as predefined in the definition of the objectives and scope. This can involve sorting on a nominal basis (e.g.: per characteristic, such as emissions and resources or global, regional or local spatial scales) and/or an order based on a given hierarchy (e.g.: high, medium, low priority);
2. **Weighting** is the process of converting the indicator results of the various impact categories by using numerical factors. It can include the aggregation of the weighted indicator results into a single score.

These optional elements involve choosing values and different individuals, organizations or societies may therefore have preferences and thus obtain different grouping and weighting results from the same characterized indicator results.

The methodology (i.e., the selection of the impact categories, category indicators, characterisation models and optional elements) used to carry out the assessment of the potential impacts must be clearly presented when defining the objectives and scope of the study.

A.5 LCA Phase IV: Results interpretation

The objectives of the fourth phase of the LCA, the interpretation phase, are to assess the results, establish conclusions, explain the limitations and provide recommendations based on the results of the preceding phases of the study and to then report these results in a transparent way that is in keeping with the criteria set out with the objectives and scope.

Ideally, the interpretation is carried out in a way that considers the three other LCA phases. Defining the objectives and scope and interpreting the life cycle should constitute the framework of the study and the inventory and impact assessments should provide information on the product system.

According to ISO, interpreting the life cycle includes three elements:

1. Identifying the significant points based on the results of the inventory and impact assessment phases in view of the objectives and scope of the study;

2. Carrying out a verification that takes the completeness, sensitivity and consistency checks into account;
3. Determining the conclusions and recommendations and writing up a report.

The goal of the verification process is to establish and strengthen the credibility and reliability of the results. The **completeness check** aims to guarantee that all of the relevant information and data necessary to the interpretation of the results are available and complete. The **sensitivity check** is conducted to verify the reliability of the results and conclusions by determining whether or not they are affected by the uncertainty of the data and methodological choices (e.g.: inclusion criteria, allocation methods or category indicators). The **consistency check** determines whether or not the hypotheses, methods and data are consistent with the objectives and scope of the study and if they have been applied consistently throughout the study or to the compared product systems (when comparing various alternatives).

Results interpretation is hindered by the deterministic nature of the inventory and impact assessment data generally available, since it impedes the statistical and quantitative analysis of the uncertainty of the results that is associated with the use of this type of data. This affects the certainty of these deterministic results. The conclusions and recommendations could lack precision or even be erroneous because it is impossible to quantify the variability of these results or determine if there is a significant impact difference between the two alternatives. The methodology (i.e., types of controls) that will be used to guide the interpretation phase must be clearly detailed when defining the objective and scope.

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Appendix B:
Literature Review

ANNEXE B :
REVUE BIBLIOGRAPHIQUE

TABLE DES MATIÈRES

B.1 ÉTUDE SUÈDOISE (1995, 2001)

Une première étude publiée portant sur l'ACV des routes a été réalisée en 1995 par l'Institut de recherche environnementale de Suède (IVL), en collaboration avec la Swedish National Road Administration. Cette étude, qui a été révisée en 2001, constitue une analyse de l'inventaire du cycle de vie (AICV) des routes en béton de ciment et en enrobé bitumineux (Stripple, 2001).

Dans son rapport, l'auteur note que l'analyse des routes est différente de celle de tout autre produit, puisque chaque cas est unique et comporte des variantes importantes dues aux conditions géotechniques, à la localisation géographique, aux conditions météorologiques, à l'intensité de la circulation automobile, etc. Il note aussi qu'étant donné ces conditions variables, il est difficile de développer et d'employer un modèle statique s'appliquant au cycle de vie des routes en général. L'étude a donc été faite en morcelant les diverses étapes du cycle de vie (construction, entretien, etc.) en procédés unitaires pouvant être modifiés en fonction des différentes conditions rencontrées.

B.1.1 Objectifs et champ de l'étude

L'objectif principal de l'étude était de déterminer la consommation énergétique reliée au cycle de vie d'une route. Pour cette raison, tous les processus, même ceux étant communs aux deux types de chaussées analysés, ont été considérés dans l'analyse de l'inventaire.

Ainsi, cette analyse comprenait le cycle de vie complet des routes en béton de ciment et en enrobé bitumineux, incluant l'extraction des matières premières, la production des matériaux et composantes, le processus de construction lui-même, l'entretien et la réparation des routes et l'élimination ou la réutilisation (valorisation) des matériaux et composantes de la route en fin de vie. Étaient aussi inclus dans les limites de l'étude, le cycle de vie des systèmes d'éclairage et de signalisation, l'entretien des bordures de routes (fossés, coupe des herbes, etc.), l'épandage de sel, etc. La circulation automobile a toutefois été exclue de l'étude.

L'unité fonctionnelle employée était :

« Permettre le déplacement de véhicules routiers sur un segment de route de 1 km de long et de 13 m de large, évalué sur une période de quarante ans ».

L'équipe de Stripple a développé un « modèle » dynamique considérant tous les aspects déjà mentionnés liés à la construction de routes. Réalisé avec le logiciel Excel (MicroSoft®), ce modèle permet de calculer l'utilisation d'énergie et de ressources ainsi que les quantités d'émissions impliquées sur le cycle de vie d'une route avec des paramètres donnés. Rappelons que l'analyse de Stripple se limite à l'inventaire et n'inclut pas l'évaluation des impacts.

Notons de plus que cette étude comptabilise l'énergie inhérente liée au bitume (en tant que combustible non brûlé) contenue dans la chaussée pavée en enrobé bitumineux. Le choix de considérer ou non l'énergie inhérente au bitume est souvent discuté en ACV. Un rapport publié par les groupes Eurobitume et EAPA (European Asphalt Pavement Association) donne d'ailleurs plusieurs raisons pourquoi selon elles cette énergie ne devrait pas être prise en compte (Beuving et al., 2004) :

- Le bitume inclus dans l'enrobé n'est pas brûlé à la fin de son cycle de vie et ne mène donc à aucune émission de CO2 ;
- Le bitume peut être réutilisé avec de bons niveaux de performance (étendu une première fois comme enrobé neuf, puis recyclé à quelques reprises) ;
- Dans plusieurs pays, les mélanges chauds (en anglais : hot mix) contiennent d'ailleurs de 30 à 50 % de granulats d'enrobé bitumineux recyclés.

Toutefois, il pourrait être soulevé que le bitume étant une ressource non-renouvelable, l'énergie qui lui est inhérente devrait être considérée.

B.1.2 Conclusions de l'étude

Les données compilées ont permis d'établir la consommation énergétique reliée à chaque type de chaussée, de même que l'utilisation de matières premières et les émissions gazeuses produites (principalement le CO_2, le SO_2 et les NOx).

Puisque tous les éléments ont été considérés (plutôt que d'éliminer les procédés communs aux deux types de pavages étudiés), Stripple a pu estimer une quantité d'énergie totale associée à la construction, l'exploitation et l'entretien de 1 km de route pendant quarante ans. Les valeurs sont de 23 TJ pour l'enrobé bitumineux (la différence étant minime entre l'enrobé bitumineux froid et chaud) et de 27 TJ pour le béton de ciment. Il ressort aussi de l'étude que l'exploitation des routes compte pour une grande part dans la consommation énergétique totale. Principalement, l'énergie nécessaire à l'éclairage des routes et aux feux de circulation représenterait approximativement 12 TJ.

Dans le cadre de cette étude suédoise, il semble que les émissions de NOx, SO_2 et CO_2 soient principalement liées à la construction de la route, plus particulièrement pour le CO_2. L'entretien compte aussi pour une part importante des émissions, notamment pour les NOx. L'exploitation des routes ne compte que pour une faible part des émissions, dû au fait que l'électricité suédoise est majoritairement d'origine hydroélectrique et nucléaire.

B.2 ÉTUDE CANADIENNE (1999, 2006)

Une étude canadienne a été réalisée en 1999 par Athena Sustainable Materials Institute pour le compte de l'Association canadienne du ciment Portland (maintenant l'Association canadienne du ciment – ACC) (Trusty, 1999) et a été mise à jour en 2006 (Athena Sustainable Materials Institute, 2006).

Cette étude avait pour objectif de comparer les impacts environnementaux de la construction et de l'entretien des chaussées en béton de ciment et en enrobé bitumineux, mais en se limitant à l'énergie primaire utilisée et aux gaz à effet de serre (GES) émis.

B.2.1 Objectifs et champ de l'étude

Le champ de l'étude était restreint à l'analyse de l'inventaire du cycle de vie (AICV) en lien avec la consommation d'énergie primaire et la production de GES (mesurées en termes d'équivalent CO_2 afin de montrer le potentiel de réchauffement planétaire). Les GES pris en compte sont le CO_2, les NOx et le CH_4 et les facteurs de conversion sont ceux issus du troisième rapport du GIÉC (2001).

L'unité fonctionnelle choisie était :

« Permettre le déplacement de véhicules routiers sur 1 km d'une voie routière de 3,75 m de large sur une période de quarante ans (cinquante ans dans la version de 2006) ».

L'étude couvrait douze designs de routes, soit trois types de routes, avec deux variantes chacune pour les deux types de chaussées comparés.

Dans cette étude, les limites physiques du système sont situées entre le sol de fondation (couche inférieure) et la surface de roulement de la route. L'étude prend donc en considération l'utilisation de matériaux et les opérations reliées à la construction de la couche granulaire de fondation, de la couche de base et de la surface finie. Elle exclut la construction et la restauration de l'emprise routière, le marquage de la chaussée et la construction de barrières.

Sont aussi exclues toutes les activités communes aux deux types de chaussées, telles que le transport du béton et de l'enrobé du lieu de production au chantier routier (jugé équivalent pour les deux types de chaussée) et l'opération de la machinerie lors de la construction initiale et de l'entretien de la chaussée (jugée négligeable ou équivalente). Également exclus sont le déboisement initial et les aspects opérationnels de la chaussée, soit la consommation d'énergie associée au trafic routier et à l'éclairage de la chaussée, ainsi que la consommation de sels fondants.

Pour que l'étude soit applicable à l'ensemble du Canada, deux cas de base ont été étudiés pour chaque type de chaussée en béton de ciment et en enrobé bitumineux (douze cas en tout), les cas différant principalement en termes de quantité de matériaux requise.

Une période de quarante ans est considérée, afin d'inclure les activités allant de la construction initiale aux réparations majeures pour les deux types de chaussées. L'énergie primaire comptabilisée inclut toute l'énergie fossile utilisée dans la production et le transport des matériaux considérés, mais aussi l'énergie inhérente de ces derniers, celle-ci étant non nulle dans le cas du bitume. L'énergie de précombustion des combustibles et de l'électricité utilisés est également incluse. L'étude n'inclut pas les considérations opératoires qui peuvent différer d'un type de route à l'autre, tel que la consommation de carburant des camions et voitures et l'énergie requise pour l'éclairage des zones urbaines.

Dans le cas de la chaussée en enrobé bitumineux pour les routes canadiennes, deux pourcentages de chaussée recyclée sont considérés, soit 0 % et 20 % de la couche de base de la surface de roulement. Pour les douze cas considérés, des ajustements ont aussi été faits afin de tenir compte des spécificités régionales quant à la production d'électricité, aux processus de production (par ex. pour le ciment) et à la composition du béton de ciment et de l'enrobé bitumineux. À partir de cette définition des limites du système, l'étude se concentre sur les aspects affectant les résultats comparatifs ou relatifs des deux types de chaussées à l'étude, et ce, plutôt que d'estimer les effets environnementaux absolus de chaque type de chaussée.

Les données utilisées pour les deux études proviennent de divers rapports publiés par Athena Sustainable Materials Institute, de la base de données de Franklin Assoicates Ltd et d'autres sources tirées de la littérature.

L'étude a été reprise en 2006 et le champ de l'étude a été modifié : les cas types ont été modifiés et la période considérée est de cinquante ans au lieu de quarante. L'étude a donc comme objectif de comparer la consommation d'énergie primaire et les émissions de GES liés à la construction initiale et à l'entretien sur une période de cinquante ans d'un tronçon de un kilomètre de chaussée, en béton de ciment et en enrobé bitumineux, pour six différents types de chaussée. Les types considérés sont : deux types de route (artère importante et autoroute à deux voies) représentatifs du contexte canadien, chacun tenant compte de deux options pour la fondation de la chaussée (en fonction de l'importance du trafic routier), deux autoroutes urbaines spécifiques au contexte québécois (deux voies dans un sens) et ontarien (trois voies dans un sens).

Dans le cas des chaussées en béton de ciment, aucune opération d'entretien n'est considérée pour l'artère importante canadienne durant la période de cinquante ans, tandis que les autoroutes canadienne et ontarienne sont recouvertes d'une couche d'enrobé bitumineux de différentes épaisseurs et à différents intervalles. Dans le cas de l'autoroute québécoise, la surface de roulement est complètement reconstruite après 49 ans. Dans le cas des chaussées en enrobé bitumineux, l'entretien consiste au planage et au resurfaçage de la surface de roulement sur différentes épaisseurs et à différents intervalles. Dans tous les cas, la quantité de matériaux utilisés lors de la dernière intervention est ajustée au prorata des années avant la fin de la période de cinquante ans sur la durée de vie de l'intervention.

B.2.2 Conclusions de l’étude

Pour les structures de chaussées étudiées, l’étude de Trusty (1999) conclut que la consommation énergétique est « clairement » supérieure pour les chaussées en enrobé bitumineux par rapport aux chaussées en béton de ciment (de l’ordre de 200 à 300 % de plus). Cependant, cette conclusion est faite en considérant l’énergie inhérente au bitume. Si on exclut cette quantité d’énergie liée au matériau et qui ne sera probablement jamais libérée, la différence est moins importante. En effet, l’augmentation de la consommation énergétique pour les chaussées en enrobé bitumineux par rapport aux chaussées en béton de ciment varie alors entre 2,6 % et 30,2 % selon le type de route considéré.

En ce qui a trait au potentiel de réchauffement planétaire, ce sont les chaussées en enrobé bitumineux qui ont le meilleur profil, présentant une diminution des émissions de GES potentiels de l’ordre de 41 % à 82 % (en tonnes de CO_2 équivalent) par rapport aux chaussées de béton de ciment

Une analyse de sensibilité a été faite sur la distance de transport des matériaux granulaires de la fondation vers le chantier routier. Étant considérée identique pour les deux types de chaussée, une augmentation de celle-ci ne fait que rendre plus apparente la plus importante quantité de matériaux utilisée dans le cas des chaussées en enrobé bitumineux, même si ce transport ne représente qu’une faible portion de l’énergie primaire et des émissions de GES totales.

Les résultats de l’étude de 2006 permettent de tirer les mêmes conclusions : la consommation énergétique de la chaussée en enrobé bitumineux est supérieure à celle de la chaussée en béton de ciment (de l’ordre de 130 % à 425 % d’augmentation). Les résultats sont présentés à la Figure B-1.

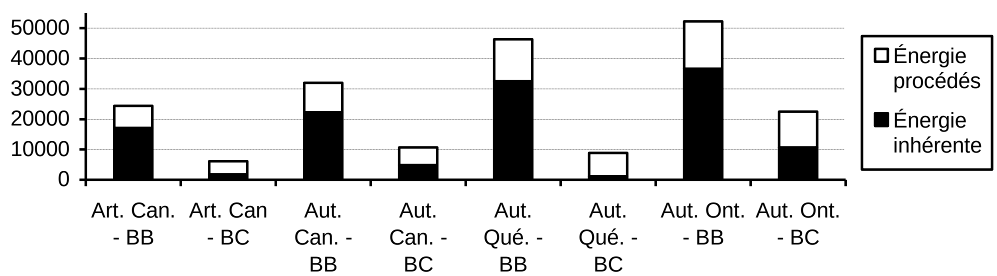

Figure B-1 : Résultats de l’étude canadienne par Athena Sustainable Materials Institute pour le compte de l’Association canadienne du ciment.
(Trusty, 1999)

Pour l’étude de 2006, une seconde analyse de sensibilité a été faite dans le cas de l’autoroute canadienne, sur le remplacement de l’enrobé bitumineux par du béton de ciment pour la surface de roulement, ainsi que sur le recouvrement de toute la surface de roulement avec de l’enrobé bitumineux par un meilleur entretien de celle-ci (jusqu’à inclure une reconstruction complète sur 10 % de la surface). Ceci amène une réduction de la quantité d’énergie primaire utilisée par le système (près de 50 % de réduction) par rapport au cas de base, mais une augmentation des émissions de GES (environ 15 %).

B.3 AUTRES ÉTUDES

D'autres études moins complètes ont été répertoriées. Deux sont résumées ici.

B.3.1 Étude américaine (1998)

Un rapport du *Transportation Research Board* du Conseil national de recherche américain publié en 1998 présentait une comparaison environnementale des chaussées en béton de ciment armé et en enrobé bitumineux basé sur l'ACV (Horvath et Hendrickson, 1998). Il s'agit d'une analyse de l'inventaire du cycle de vie extrêmement simplifiée, réalisée uniquement à partir de données génériques publiquement disponibles (*economic input-output- based LCA* ou EIO-LCA). Ce modèle utilise une matrice d'entrants et sortants économiques permettant de remonter la chaîne de production des principaux produits faisant partie de l'économie américaine.

Dans cette étude, seul le revêtement lui-même a été pris en compte, tout le reste ayant été considéré identique pour les deux types de chaussées (ceci comprend entre autres la fondation et la sous-fondation, les transports associés à l'étape de production des matériaux et à l'étape de construction des deux types de chaussées et l'énergie consommée lors de la construction des deux types de chaussées). Ainsi, pour recouvrir une section de route de 1 km de long et de 7,2 m de large, les auteurs ont estimé qu'il fallait 5 018 tonnes d'enrobé bitumineux ou 3 680 tonnes de béton de ciment avec tiges d'acier. C'est uniquement à partir de cette information que l'inventaire des matières premières a été élaboré.

À l'issue de leur étude, les auteurs notent qu'en tenant compte des incertitudes liées aux données employées, la quantité de matières premières requises pour la construction des deux types de chaussées est sensiblement la même.

B.3.2 Étude européenne (1999)

Un rapport d'Eurobitume datant de 1999 présente un inventaire du cycle de vie « partiel » du bitume (Blomberg et al., 1999). À l'issue de cette étude, un « éco-profil » de l'enrobé bitumineux typique est présenté : énergie totale nécessaire, principales émissions atmosphériques, rejets liquides et solides, ainsi que la quantité de matières premières requises. Cette étude est citée ici à titre informatif seulement, puisqu'elle comprend des données d'inventaire permettant la validation liée à la production de bitume.

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Appendix C:
Diagrams of Analyzed Systems

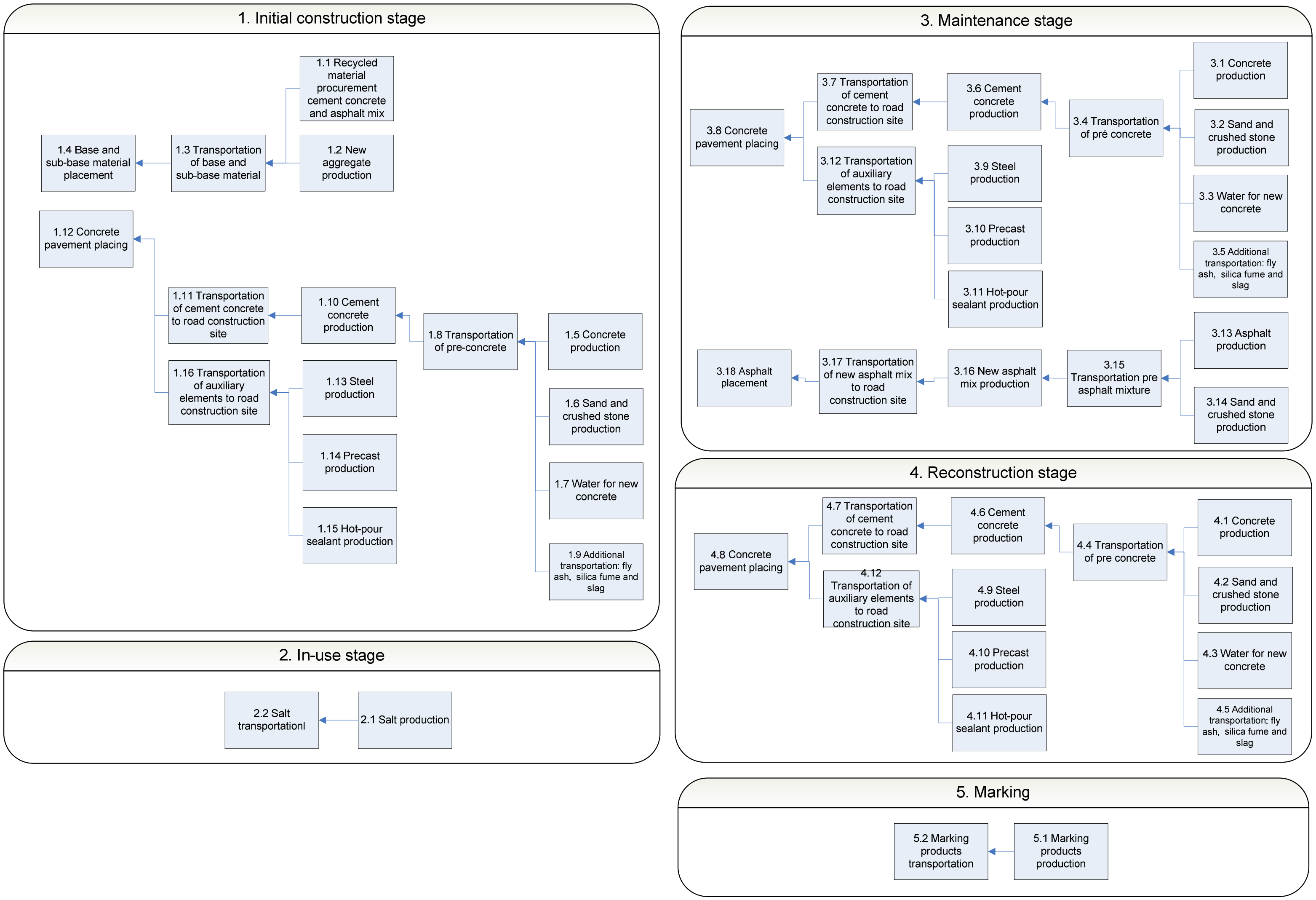

Figure C-1: Product system for the life cycle of a cement concrete pavement (CC).

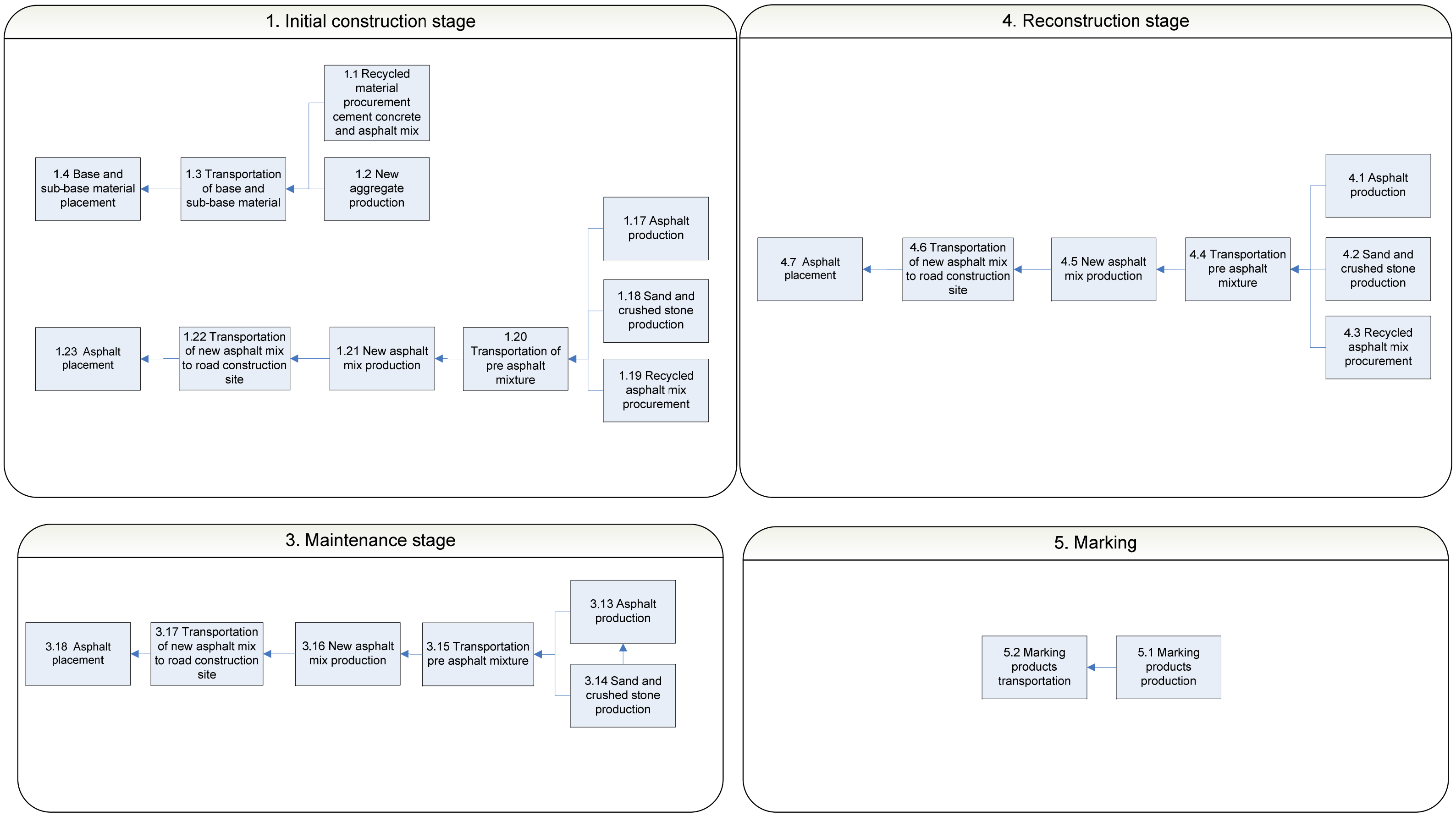

Figure C-2: Product system for the life cycle of a asphalt mixture pavement (AM).

Appendix D:

Method for Assessing Life cycle Impacts

IMPACT 2002+

The LCIA methodology IMPACT 2002+ (Jolliet et al. 2003) proposes a combined midpoint/damage-oriented approach. Figure A shows the overall scheme of the IMPACT 2002+ framework, linking all types of LCI results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) to four damage categories (human health, ecosystem quality, climate change, resources). An arrow symbolizes that a relevant impact pathway is known and quantitatively modelled based on natural science. Impact pathways between midpoint and damage levels that are assumed to exist, but that are not modeled quantitatively due to missing knowledge are represented by dotted arrows.

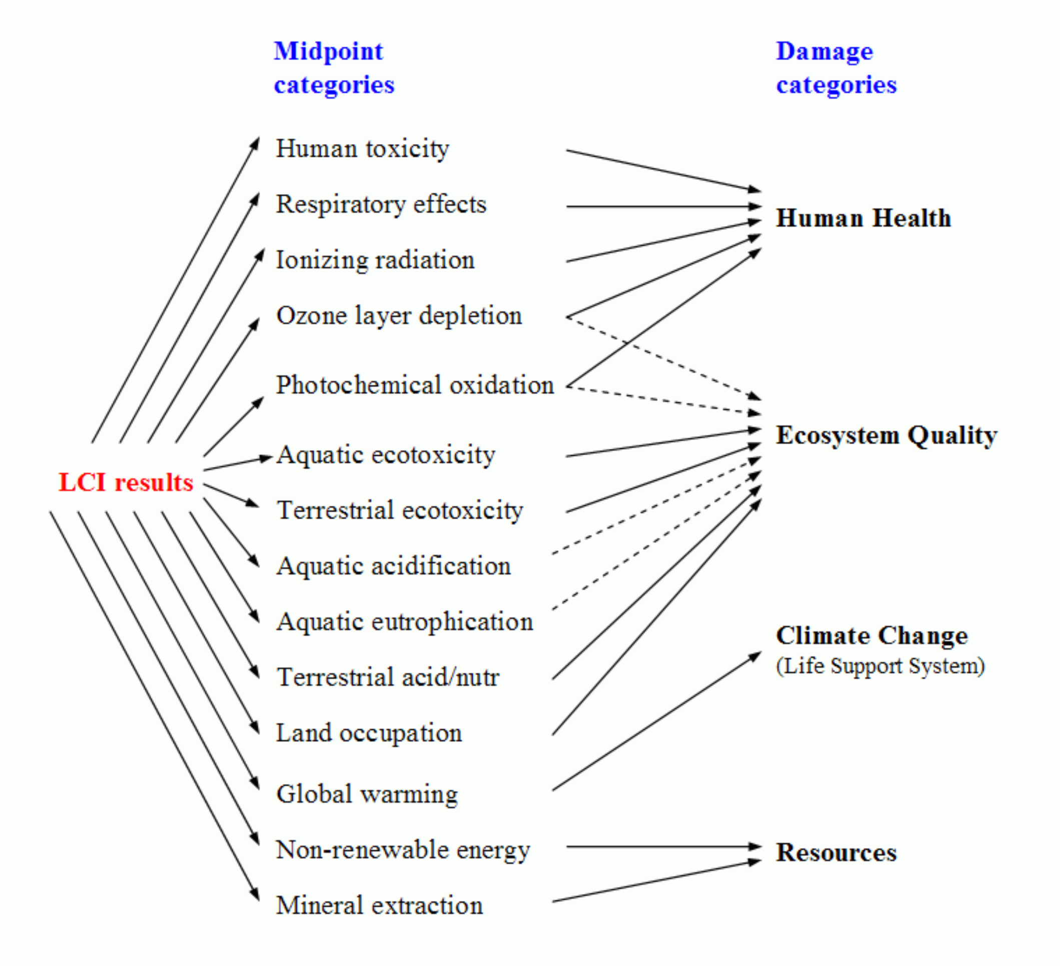

Figure A: Overall scheme of IMPACT 2002+, linking the life cycle inventory results (LCI) and the damage categories, via the midpoint categories.

New concepts and methods for the comparative assessment of human toxicity and ecotoxicity were developed for the IMPACT 2002+ methodology. For other categories, methods have been transferred or adapted mainly from the Eco-indicator 99 (Goedkoop et al. 2000) and the CML 2002 (Guinée et al. 2002) methods, from the

IPCC list (IPCC 2001), the USEPA ODP list (EPA) and ecoinvent database (ecoinvent Centre, 2005).

By the following we shortly describe the main assessment characteristics for midpoint and damage categories, as well as related normalization factors.
Midpoint categories are:

1. Human Toxicity measures the impact on human life related to carcinogen and non-carcinogens toxic effects caused by pollutants emitted into the environment and eventually reaching the humans through air inhalation, drinking water and food ingestion. Carcinogen and non-carcinogens are separated in two indicators in the analysis realised in the present study.
2. Respiratory Inorganics are air pollutants such as fine particles that affect human lungs. These pollutants are massively released by heavy industries and road traffic.
3. Ionizing Radiation measures the impact on human life caused by substances emitting ionizing radiations. These substances are mainly released by the nuclear energy sector.
4. Ozone Layer Depletion measures the potential in reducing the stratospheric ozone layer and thus the increase in UV light reaching the earth. It can therefore generate impact on human life such as skin cancer and cataract, and damage terrestrial life and aquatic ecosystems. The pollutants destroying the ozone layer, such as CFCs are emitted by some specific industrial processes, in need, for example, for strong cooling systems.
5. Photochemical Oxidation measures the effects on human health (and eventually on crop growth) associated with tropospheric ozone formation (also called summer smog formation). Pollutants responsible for trophosperic ozone such as NOx and Volatiles Organic Carbons (VOCs) are mainly emitted by road traffic and industrial activities.
6. Aquatic Ecotoxicity measures the effects on fresh water ecosystems in term of loss in biodiversity caused by toxic emissions emitted into the environment.
7. Terrestrial Ecotoxicity measures the effects on terrestrial ecosystems in term of loss in biodiversity caused by toxic emissions emitted into the environment.
8. Aquatic Acidification literally refers to processes increasing the acidity in aquatic systems that may lead to declines in fish populations and disappearances of species. These substances such as airborne nitrogen (NOx and NH_3) and sulfur oxides (SOx) are mainly emitted by heavy oil and coal combustion for electricity production, and by road traffic.
9. Aquatic Eutrophication measures the potential of nutrient enrichment of the aquatic environment, which generates a growth of biomass that pushes this ecosystem population out of balance: decrease of oxygen leads to further fish kills and disappearance of bottom fauna. These nutrients are mainly associated with phosphorus and nitrogen compounds in detergents and fertilizers.
10. Terrestrial Acidification and Nutrification measure the potential change in nutrient level and acidity in the soil leading to a change of the natural condition for plant growth and competition. A reduction of species are observed with an excess of nutrients and a decrease in forest health by soil acidification (effect on biodiversity). Acidifying and nutrifying substances

such as NOx, SOx and NH_3 are massively released by heavy industries and road traffic.

11. Land Occupation measures the reduction of biodiversity caused by the use of land. Agriculture (farming) is the main contributor to this category.
12. Global Warming covers a range of potential impacts resulting from a change in the global climate. It is the measured heat-trapping effect of a greenhouse gas (GHG) released in the atmosphere. CO_2 emitted by fossil fuel combustion is the main GHG.
13. Primary Non-Renewable Energy measures the amount of energy extracted from the earth contained in the fossil energy carrier (coal, oil and natural gas) or uranium ore. These resources are subject to depletion. Electricity, heat and fuel production and consumption are the main consumer of fossil fuels and uranium ore.
14. Mineral Extraction measures the surplus of energy associated with the additional effort required to extract minerals from lower concentration ore mines.

The indicators of each midpoint impact category have units expressed in kg of substance equivalent that are linked to the following 4 damage indicators (Table A2 and A3):

- human health (DALY). Human toxicity (carcinogenic and non-carcinogenic effects), respiratory effects (inorganics and organics), ionizing radiation, and ozone layer depletion all contribute to human health damages.
- ecosystems quality (PDF·m^2·yr), measure how far the anthropogenic processes affect the natural development of the occurrence of species within their habitats. Their impact can directly be determined as a Potentially Disappeared Fraction over a certain area and during a certain time per kg of emitted substance, expressed in [PDF. m^2. year/kg emitted]. It includes the contribution of terrestrial acidification/nitrification, land occupation and terrestrial + aquatic ecotoxicity.
- resources depletion (MJ primary non-renewable energy) and. The two midpoint categories contributing to this endpoint are mineral extraction and non-renewable energy consumption. Damages due to mineral resource extraction are specified according to Eco-indicator 99, with the concept of surplus energy (in [MJ]). This is based on the assumption that a certain extraction leads to an additional energy requirement for further mining of this resource in the future, caused by lower resource concentrations or other unfavorable characteristics of the remaining reserves (Goedkoop et al. 2000).
- climate change (kg CO_2 equivalent into air). From the authors' point of view, the modeling up to the damage of the impact of climate change on ecosystem quality and human health is not accurate enough to derive reliable damage characterization factors. The interpretation, therefore, directly takes place at midpoint level, which can be interpreted as damage on life support systems that deserve protection for their own sake. The global warming is considered as a stand-alone endpoint category with units of [kg-eq CO_2], which is normalized in the next step. The assumed time horizon is also 500 years to account for both short-term and long-term effects as there is little evidence that global warming effects will decrease in the future

Table A2: Number of substances covered, source and units of IMPACT 2002+ (v2.1).

LCI coverage	Midpoint category	Reference	Midpoint reference substance	Damage unit	Damage unit	Normalized damage unit
769	Human toxicity (carcinogens + non-carcinogens)	IMPACT 2002	kg chloroethylene$_{-eq}$	Human Health	DALY	point
12	Respiratory (inorganics)	Ecoindicator 99	kg chloroethylene$_{-eq}$			
25	Ionizing radiations	Ecoindicator 99	kg PM2.5$_{-eq}$			
95	Ozone layer depletion	USEPA and Ecoindicator 99	Bq Carbon-14$_{-eq}$			
130	Photochemical oxidation	Ecoindicator 99	kg CFC-11$_{-eq}$			
393	Aquatic ecotoxicity	IMPACT 2002	kg ethylene$_{-eq}$	Ecosystem Quality	PDF·m^2·yr	
393	Terrestrial ecotoxicity	IMPACT 2002	kg triethylene glycol$_{eq}$ into water			
5	Terrestrial acidification/ nutrification	Ecoindicator 99	kg triethylene glycol$_{eq}$ into soil			
15	Land occupation	Ecoindicator 99	m^2 organic arable land			point
10	Aquatic acidification	CML 2002	kg $SO_{2\text{-}eq}$	*n/a*	*n/a*	*n/a*
10	Aquatic eutrophication	CML 2002	kg $SO_{2\text{-}eq}$	*n/a*	*n/a*	*n/a*
77	Global warming	IPCC 2001 (500 yr)	kg $CO_{2\text{-}eq}$	Climate Change (life supporting functions)	kg $CO_{2\text{-}eq}$ into air	
9	Non-renewable energy	Ecoinvent	MJ/kg crude oil$_{-eq}$	Ressource depletion	MJ primary non-renewable energy	
20	Mineral extraction	Ecoindicator 99	MJ/kg iron$_{-eq}$			

Table A3: Units of midpoint impact categories and conversion factors between the midpoint categories and the damage categories of IMPACT 2002+ (v2.1).

Midpoint category	Damage factor	Unit
Carcinogens	2.80^{E}-6	DALY/kg chloroethylene$_{-eq}$
Non-carcinogens	2.80^{E}-6	DALY/kg chloroethylene$_{-eq}$
Respiratory (inorganics)	7.00E-4	DALY/kg PM2.5$_{-eq}$
Ionizing radiations	2.10E-10	DALY/Bq Carbon-14$_{-eq}$
Ozone layer depletion	1.05E-3	DALY/kg CFC-11$_{-eq}$
Photochemical oxidation	2.13E-6	DALY/kg ethylene$_{-eq}$
Aquatic ecotoxicity	5.02E-5	PDF·m^2·yr/kg triethylene glycol$_{-eq}$ into water
Terrestrial ecotoxicity	7.91E-3	PDF·m^2·yr/kg triethylene glycol$_{-eq}$ into soil
Terrestrial acidification/nutrification	1.04	PDF·m^2·yr/kg $SO_{2\text{-}eq}$
Aquatic acidification	1	kg $SO_{2\text{-}eq}$/kg $SO_{2\text{-}eq}$
Aquatic eutrophication	1	kg $PO_4^{---}{}_{-eq}$/kg $PO_4^{---}{}_{-eq}$
Land occupation	1.09	PDF·m^2·yr/m^2 organic arable land
Global warming	1	kg $CO_{2\text{-}eq}$/kg $CO_{2\text{-}eq}$
Non-renewable energy	45.8	MJ/kg crude oil$_{-eq}$
Mineral extraction	5.10E-2	MJ/kg iron$_{-eq}$

The normalization is performed by dividing the impact scores by the respective normalization factors (cf. Table A4). A normalization factor represents the total impact of the specific category divided by the total European population. The total impact of the specific category is the sum of the products between all European emissions and the respective damage factors.

The normalized characterization factor is therefore determined by the ratio of the impact per unit of emission divided by the total impact of all substances of the specific category, per person per year. The unit of all normalized characterization factors is therefore [point/unit$_{emission}$] = [pers·yr/unit$_{emission}$], i.e. it is the impact caused by a unitarian emission, which is equivalent to the impact generated by the given number of persons during 1 year. Additional details are provided by Humbert et al. (2005).

Table A4: Normalization factors relative to the four damage categories for Western Europe

Damage categories	Normalization factors	Units
Human Health	0.0071[48]	DALY/point
Ecosystem Quality	13’700	PDF.m^2.yr/point
Climate Change	9’950	kg CO_2 into air/point
Resources	152’000	MJ/point

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ANNEX D:
LUCAS LIFE CYCLE IMPACT ASSESSMENT (LCIA) METHOD

TABLE OF CONTENTS

The LUCAS (life cycle impact assessment method used for a Canadian-specific context) life cycle impact assessment (LCIA) method was developed by the Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG) at École Polytechnique de Montréal (Toffoletto *et al.*, 2005). This method is strongly based on the SETAC recommendations on the best practices in LCIA and on the various characterization models of the three internationally-recognized LCIA methods: EDIP2003, IMPACT2002+ and TRACI. The choice of these models rests on their levels of representativeness and scientific refinement and on the possibility of integrating region-specific values.

Table D-1 presents the 10 impact categories of the LUCAS method. The following paragraphs detail the type of approach that was chosen for this method and its spatial differentiation of the regional and local impacts as well as each of the impact categories.

Table D-1: Impact categories, category indicator results, type of approach and level of geographic specificity available in LUCAS

Impact category (Abbreviation)	Indicator result	Type of approach	Level of geographic specificity
Categories linked to pollutant emissions			
Global warming (RG_{100})	g CO_2 equivalent	Problem	Global
Ozone layer depletion (OLD)	g CFC-11 equivalent	Problem	Global
Acidification (AC)	Mole H^+ equivalent	Problem	Ecozones
Terrestrial eutrophication (EUT)	g N or P equivalent	Problem	Ecozones
Aquatic eutrophication (EUA)	g N or P equivalent	Problem	Canada
Photochemical smog (PS)	g NO_X equivalent	Problem	Ecozones
Human toxicity – carcinogenic (ToxC)	g chloroethene equivalent or DALY*	Problem or Damage	Ecozones
Human toxicity – non-carcinogenic (ToxNC)	g chloroethene equivalent or DALY*	Problem or Damage	Ecozones
Ecotoxicity (Ecotox)	g triethylene glycol equivalent or PAF m^2 year*	Problem or Damage	Ecozones
Categories linked to natural resource use			
Abiotic resource use (ARU)	Energy surplus	Problem	Global
Land use (LU) Ecosystem productivity Biodiversity	g C weighted biodiversity	Problem	Ecozones
Water use (WU)	m^3	Problem	Global

* DALY: Disability-adjusted life-years;
PAF: Potentially affected fraction.

D.1 Type of approach

The LUCAS method essentially adopts a midpoint approach since its category indicators are relatively close to the beginning of the chain of causality, as opposed to an endpoint approach in which the indicators are closer to the final impact of each category. For example, in the problem-driven approach, the gasses released into the air are characterized by their potential effect on ozone layer depletion based on their chemical reactivity and atmospheric half-lives. Using the damage-driven approach, they are characterized by their incidence on the number of cases of skin cancers, cataracts or species extinctions. In LUCAS, the choice of the midpoint approach was made in order to minimize uncertainty when modeling the impacts and simplify results communication. However, as recommend by the SETAC (Haes, 2002) and Bare *et al.* (2000), LUCAS will eventually include problem- and damage-driven characterization factors. First, only problem-driven characterization models were chosen (except in the assessment of the toxic and ecotoxic impacts for which the method allows for a damage-driven approach), keeping in mind that damage factors should be developed within a framework that is compatible with the future developments of the method.

D.2 Spatial differentiation of regional and local impacts

All of the regional and local impact categories of the LUCAS method can be *regionalized*, meaning that their models were developed to take the spatial differentiation of the impacts into account. The spatial resolution selected (how the Canadian territory was divided) is the *ecozone*. The 15 Canadian terrestrial ecozones are therefore the spatial resolution units of the LUCAS method. For aquatic eutrophication, (eco)toxicity and land use, models that took regionalization, fate and effect into account were available and their parameters were adapted to the Canadian context. For acidification, photochemical smog formation and terrestrial eutrophication, the existing models were regionalized for fate and the regionalization of the effect factor was included by incorporating the level of vulnerability of each ecozone.

D.3 Description of the impact categories

Two types of impact categories were considered: 1) the pollutant emissions categories (global warming, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity and ecotoxicity) and 2) the reductions in natural resources categories (use of fossil fuels, water and land).

The LUCAS method does not cover all of the environmental impacts of human activities (e.g.: noise, odours, radiation) but does include the impact categories recommended by the SETAC (Udo de Haes, 2003).

Most of the characterization models that are used were developed by taking the fate and effect of the substances into account. Though this general substance characterization model was suggested by the first SETAC LCIA working group (Jolliet, 1996) for (eco)toxic impacts, it can still be applied to other impact categories. It is therefore recommended that an effect (E) and fate (F) factor be integrated when characterizing the substances:

$$S_i^{mn} = E_i^m F_i^{mn} M_i^n \qquad \text{(C-1)}$$

In equation C-1, the score (S) for a substance *i* initially emitted into the compartment/zone *n* and in the compartment/zone *m* is the product of the effect factor (E), the fate factor (F) and of the masse (M) of emitted contaminants *i*.

D.1.1 Global warming (RG_{100})

Global warming has a worldwide impact on the environment (i.e., the zones where global warming impacts occur are not directly linked to the zones in which greenhouse gases are released) The potential of each GHG is calculated based on the International Panel on Climate Change model (IPCC, 1996) in grams of carbon dioxide (g CO_2) equivalent and based on infrared radiative climate forcing data. The potential effects of the emissions are quantified over a 500-year period, in keeping with IPCC recommendations.

D.1.2 Ozone layer depletion (OLD)

The depletion of the protective ozone layer in the stratosphere caused by the reactions between the ozone and the substances that destroy it is also a global environmental impact. The substances that deplete the ozone layer (SDOL) are converted into g CFC-11 equivalent, as suggested by the World Meteorological Organization (WMO). The data published in the *Handbook for the International Treaties for the Protection of the Ozone Layer* (UNEP, 2000) is used. The effects of the inventoried substances are usually quantified for an infinite period of time.

D.1.3 Acidification (AC)

Acidification considers substances that release protons into the environment and lead to an increase in soil and surface water acidity. The characterization model includes an atmospheric transport model (fate factor) that takes into account the chemical processes, topography, climate and temperature and is calibrated to the various levels of geographic specificity (ASTRAP model). Deposits on soil and water surfaces occur in various ways: 1) through humidity (rain, snow, etc.), 2) through dryness (deposits of particles or gasses), and 3) through clouds (cloud drops or fog). The fate of the emissions is then multiplied by an effect factor in order to express the characterisation factors in moles H+ equivalent (i.e., proton moles deposited per kilogram of emitted substances).

D.1.4 Aquatic eutrophication (EUA)

Eutrophication occurs when limiting nutrients are added to an aquatic or a terrestrial ecosystem and lead to a proliferation of photosynthetic plants. The characterization factors for each of the contributing substances are the product of: 1) a transport factor and 2) a nutriment factor. The transport factor accounts for the sources of nitrogen and phosphorus from agriculture (manure, fertilizer), waste water and atmospheric deposits. The calculation method to determine this factor is based on the EDIP2003 model (Hauschild *et al.*, 2003), which regionalizes the data by modeling groundwater flows. For the moment, there is no Canadian flow model and therefore regionalization in this impact category is not yet possible. The nutrient factor is based on the relative effect of the addition of 1 kg of substance to the environment. The characterization factor is expressed in grams of nitrogen (g N) or grams of phosphorus (g P) equivalent.

D.1.5 Terrestrial eutrophication (EUT)

Terrestrial eutrophication is caused by excess nitrogen in the soil, which leads to excessive plant growth. The LUCAS method considers the nitrogen source to be the fraction of atmospheric nitrogen that does not contribute to aquatic eutrophication (which therefore deposits itself in wooded areas and remains in the soil). This means that the atmospheric nitrogen that does not contribute to aquatic eutrophication causes terrestrial eutrophication. Deposits are calculated with ASTRAP deposit matrices and the fraction that contributes to terrestrial eutrophication is determined through a balance. This amount of nitrogen is then weighted using a vulnerability factor that regionalizes the effect of the nitrogen deposits in the soils of various ecozones.

D.1.6 Photochemical smog (PS)

Photochemical ozone is a reactive and oxidant gas that is formed in the troposphere and affects humans and ecosystems. Ozone formation depends on the concentration of precursor gases (nitrogen oxides – NO_X – and volatile organic compounds – VOC) and the environmental conditions (temperature and sunlight, in essence). The potential for photochemical smog formation characterized by the LUCAS method is based on the TRACI method, which itself is based on 1) the relative effect of the individual VOC on smog formation, 2) the relative effect of the concentration of NO_X on smog formation as compared to an average or typical mix of VOC, 3) the effect of the emissions on the ozone concentrations per release zone, and 4) the regional aggregation of the effects on the receptor zones (Bare *et al.*, 2003). The calculation of the relative effects of the individual VOC is based on a model by Carter (2000) and relies on the maximum incremental reactivity (MIR) parameter, which represents the variation in ozone concentration induced by the variation in VOC concentration. A factor of 2 is used to quantify the relative influence of the concentration of NO_X on smog formation in relation to a typical VOC mix, in keeping with experimental studies (Cardelino & Chameides, 1995). A sub-receptor matrix is used to characterize the influence of the location of the emissions sources. It links the seasonal NO_X emissions of a given region (sources) to the variations in the ambient concentrations of NO_X for each region (receptors). The characterization factors are expressed in grams of NO_X equivalent.

D.1.7 Human toxicity – carcinogenic (ToxC) and non-carcinogenic (ToxNC)

The potential to impact human health is based on 1) a toxicity factor that takes the carcinogenic and non-carcinogenic effects into account and 2) fate and exposure factors.

Human health characterization factors are determined based on the IMPACT 2002 model (Jolliet *et al.*, 2003). They consider the chemical fate of the contaminant, human exposure through food production, the water supply and inhalation based on an exposure factor[1] and the potential human health risks (carcinogenic and non-carcinogenic effects). In order to assess the damage factor, the gravity of the illnesses expressed in DALY (disability-adjusted life-years – a unit that reflects human health damages) is added to the list.

The basic hypothesis of the IMPACT 2002 fate model is that all of the reactions in the environment (biodegradation, sedimentation, deposits, advection, etc.) are of the first order. When calculating human toxicity, the spatial model makes it possible to account for food imports and exports in the exposure of the population to toxic substances.

The model also accounts for:

- Run-off on ground surfaces (imperviousness);
- Two horizontal layers of ocean (top, bottom);
- A correction factor for the dry and rainy periods;
- A "plant" compartment for flora exposure (only basic);
- Colloids in surface water.

D.1.8 Ecotoxicity (EC)

The characterization factors are estimated from fate and effect factors in a way that is analogous to human toxicity and based on the IMPACT 2002 method. Human toxicity assessment considers the ingested doses while ecotoxicity assessment examines water and soil concentrations to assess the effects on the aquatic and terrestrial ecosystems.

A substance's fate includes its transport in space and between the various areas and is assessed using a multi-compartment model (see human toxicity). The hazard potential is expressed in terms of the fraction of species affected (PAF – potentially affected fraction) for a unitary increase in the concentration of a given water and soil pollutant. The AMI (assessment of mean impact, Payet et Jolliet (2003)) is used to carry out these calculations. It relies on the concentration with 50% effect as compared to the control point (EC50: effect concentration 50 %). This approach is based on (EC50) data, which is usually more widely available in the literature than the NOEC (no observed effect concentration) and LOEC (lowest observed effect concentration) data. The assessment of the ecotoxicological impact, just like the human toxicity impact, is carried out by determining the most probable values and not the safest.

D.1.9 Abiotic resource use (ARU)

The model chosen for the Canadian method is the one provided in Eco-Indicator 99. It is applied to both types of abiotic resources: mineral resources and fossil fuels. This global impact category does not follow the general fate and effect model rules. The energy surplus method is used to calculate this impact category (Muller-Wenk, 1998). An energy surplus is defined as the difference between the energy necessary to extract the resource

[1] This exposure factor is the equivalent fraction of the environment (air, water, soil or food) ingested daily by the general population.

today and at a certain point in the future. This type of indicator assesses the environmental consequences of the hypothetical extraction processes taking the increased difficulties of future extraction into account. This method also calculated future energy needs y QN where Q represents total extraction before 1990 and N represents the number of times that the amount was extracted (Goedkoop et Spriensma, 2001). The energy surpluses required for future extraction for each mineral resource and each fossil fuel represent the characterization factors for this impact category.

D.1.10 Land use (LU) and water use (WU)

These impact categories are not characterized.

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Appendix E:
Description of the LCA Model's Product Systems and Assumptions

This appendix was removed due to the confidential nature of the industrial information that it contains. Its content is found in the following file (not publicly available):
« Pi08_Rpt_final_Annexe_E »

Appendix F: Results

This appendix was partially removed due to the confidential nature of the industrial information that it contains. Its content is found in the following file (not publicly available):
« Pi08_Rpt_final_Annexe_F »

It should be noted that the comparative results are presented and discussed in the Summary and in Chapter 5.

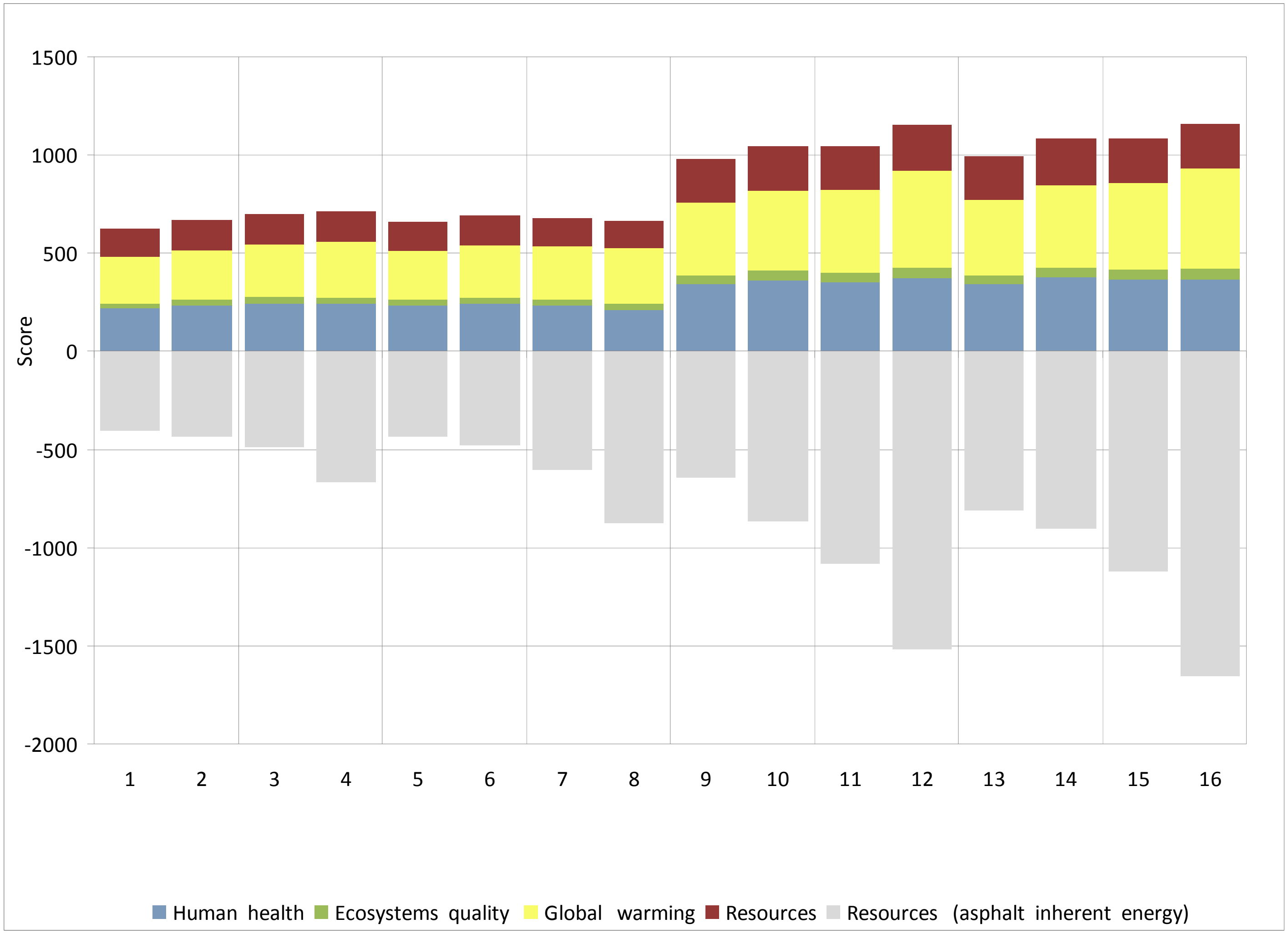


Figure 11.1: Weighted Damage Indicators for the Comparative Profile (CC System – AM System) for the 16 Functional Classes.

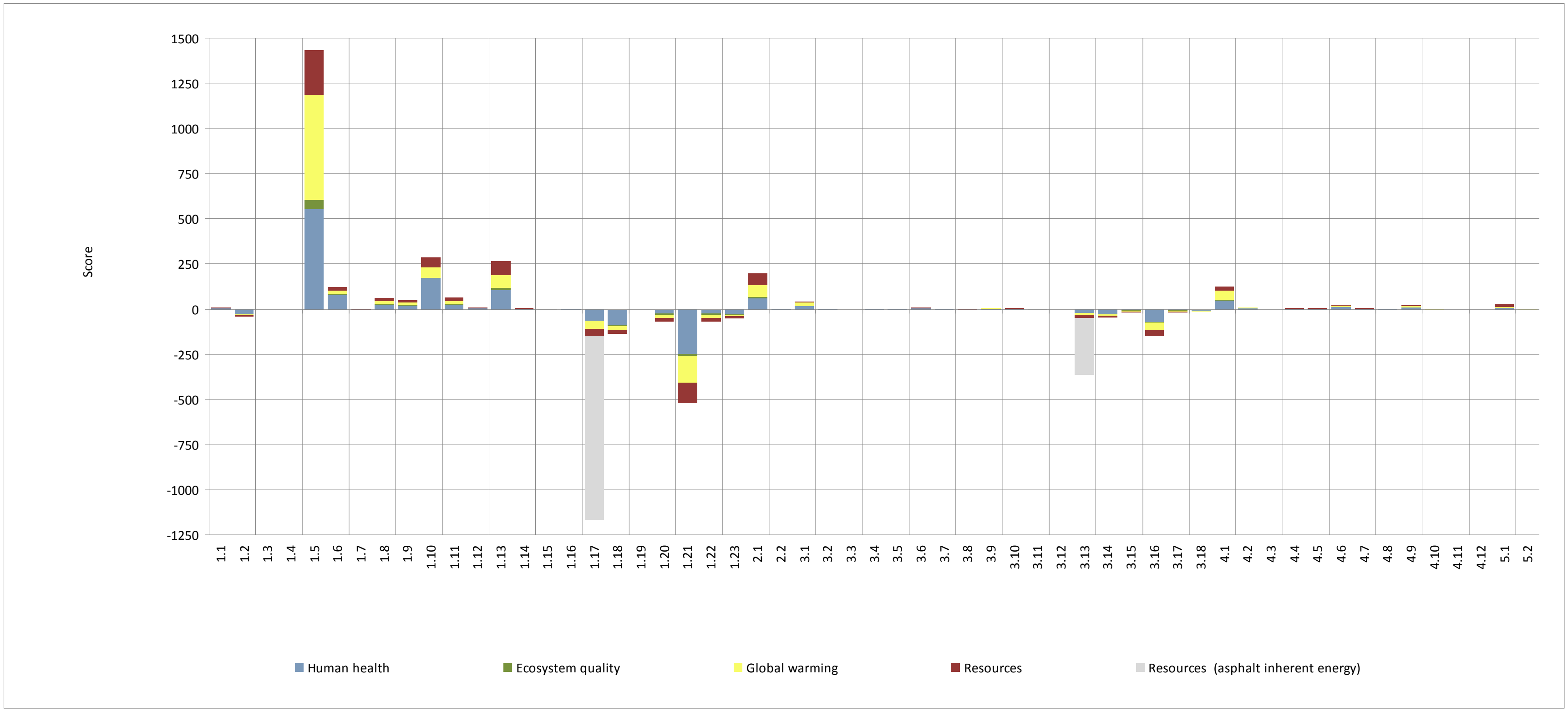


Figure 12.1: Weighted Damage Indicators Broken Down by Life Cycle Processes for Functional Class 16 (CC System – AM System).

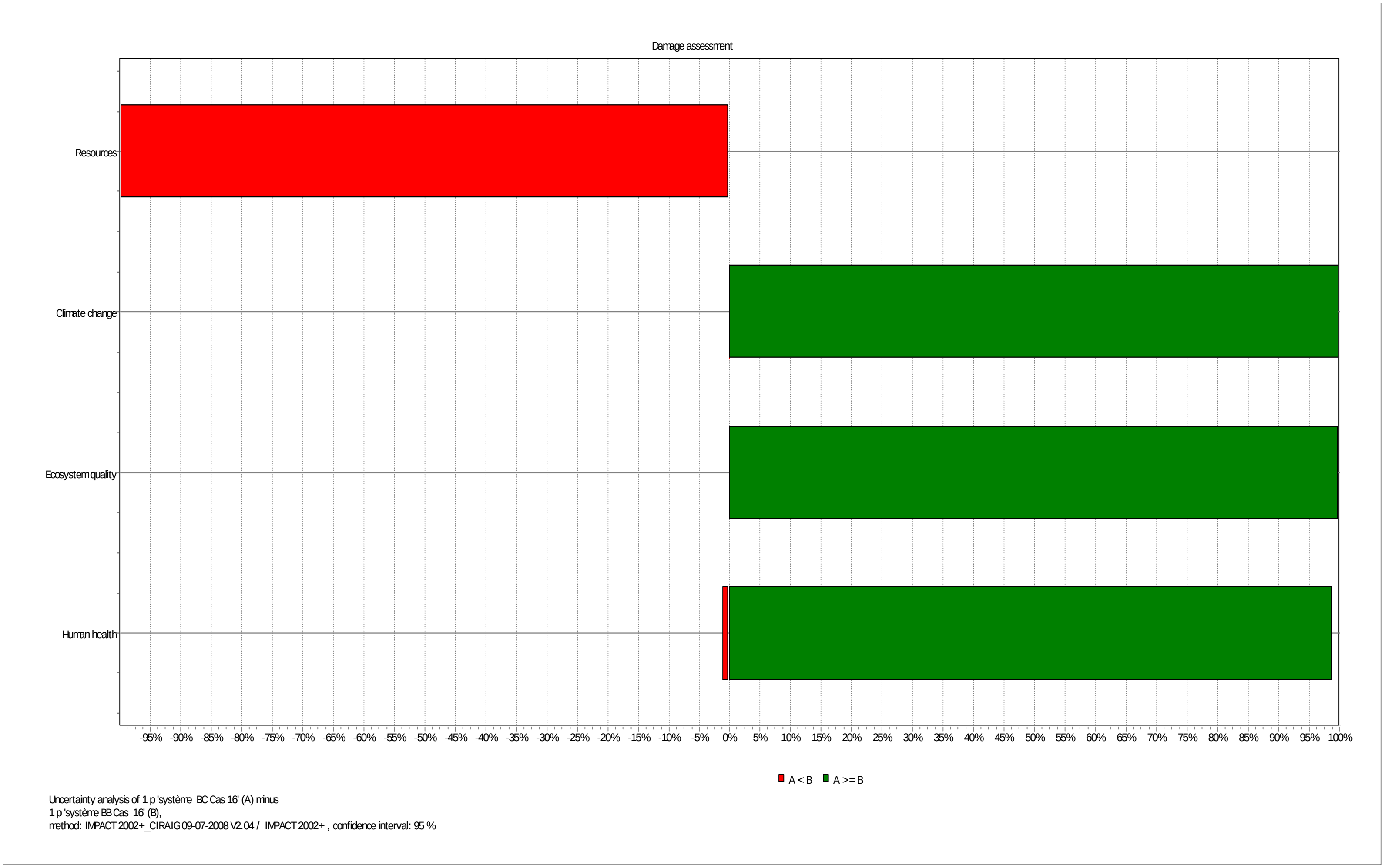


Figure 20.3.3: Probability of Occurrence of Results for Damage Indicators for Functional Class 16 (CC System – AM System).

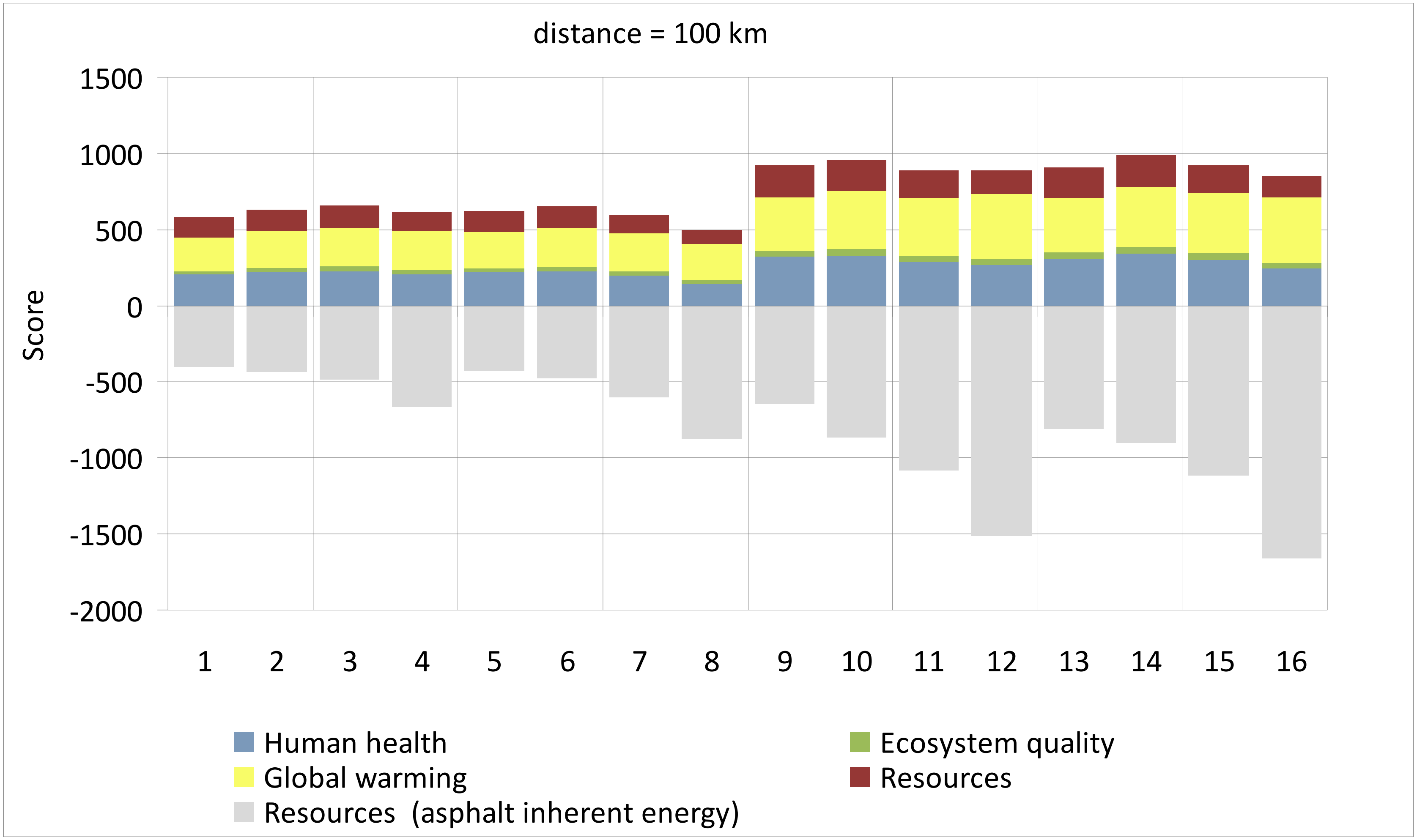


Figure 14.2.1: Weighted Damage Indicators in Reference to Different Transport Distances to Road Construction Site, for the Comparative Profile (CC System – AM System) for the 16 Functional Classes. a) 100 km

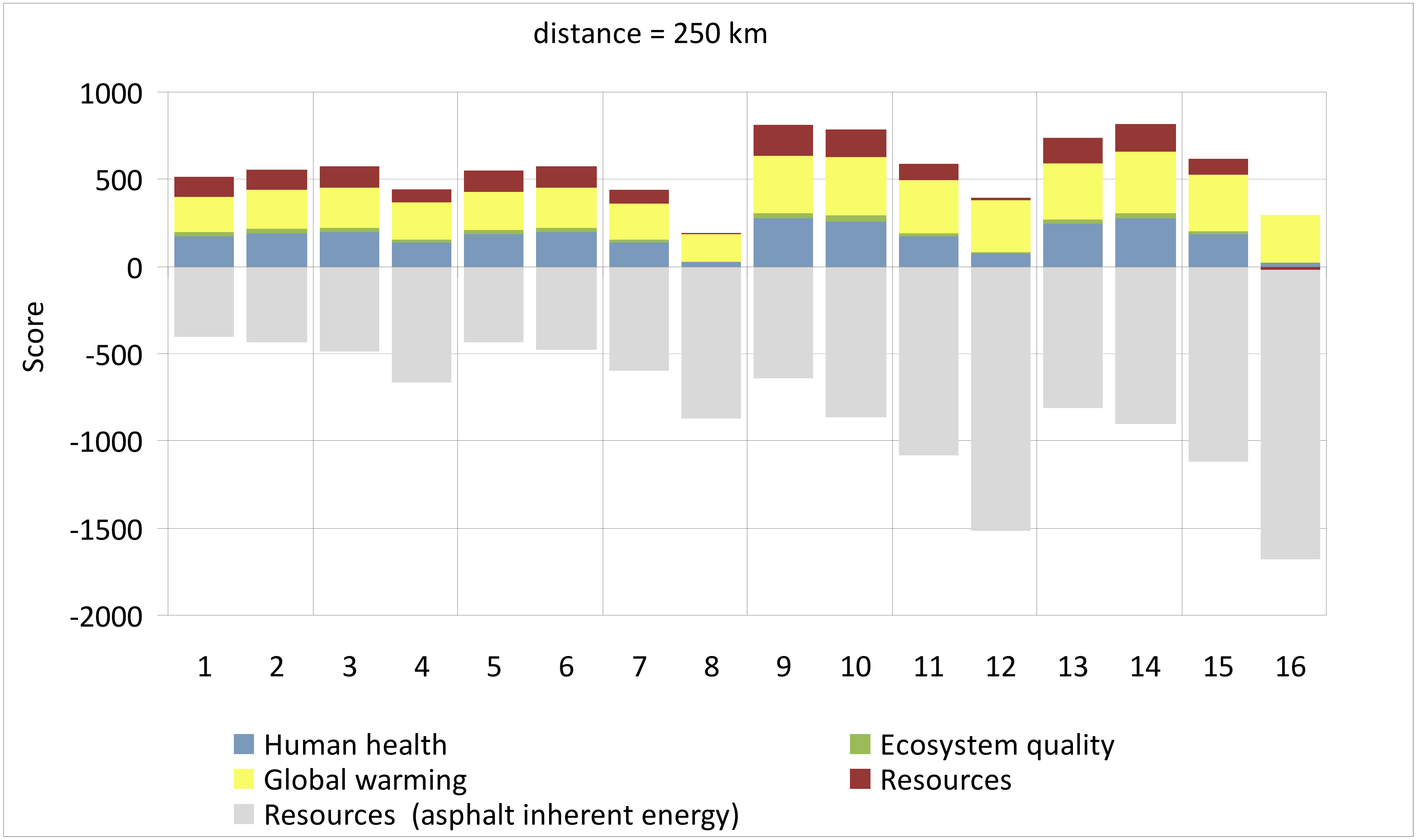


Figure 14.2.1: Weighted Damage Indicators in Reference to Different Transport Distances to Road Construction Site, for the Comparative Profile (CC System – AM System) for the 16 Functional Classes. b) 250 km

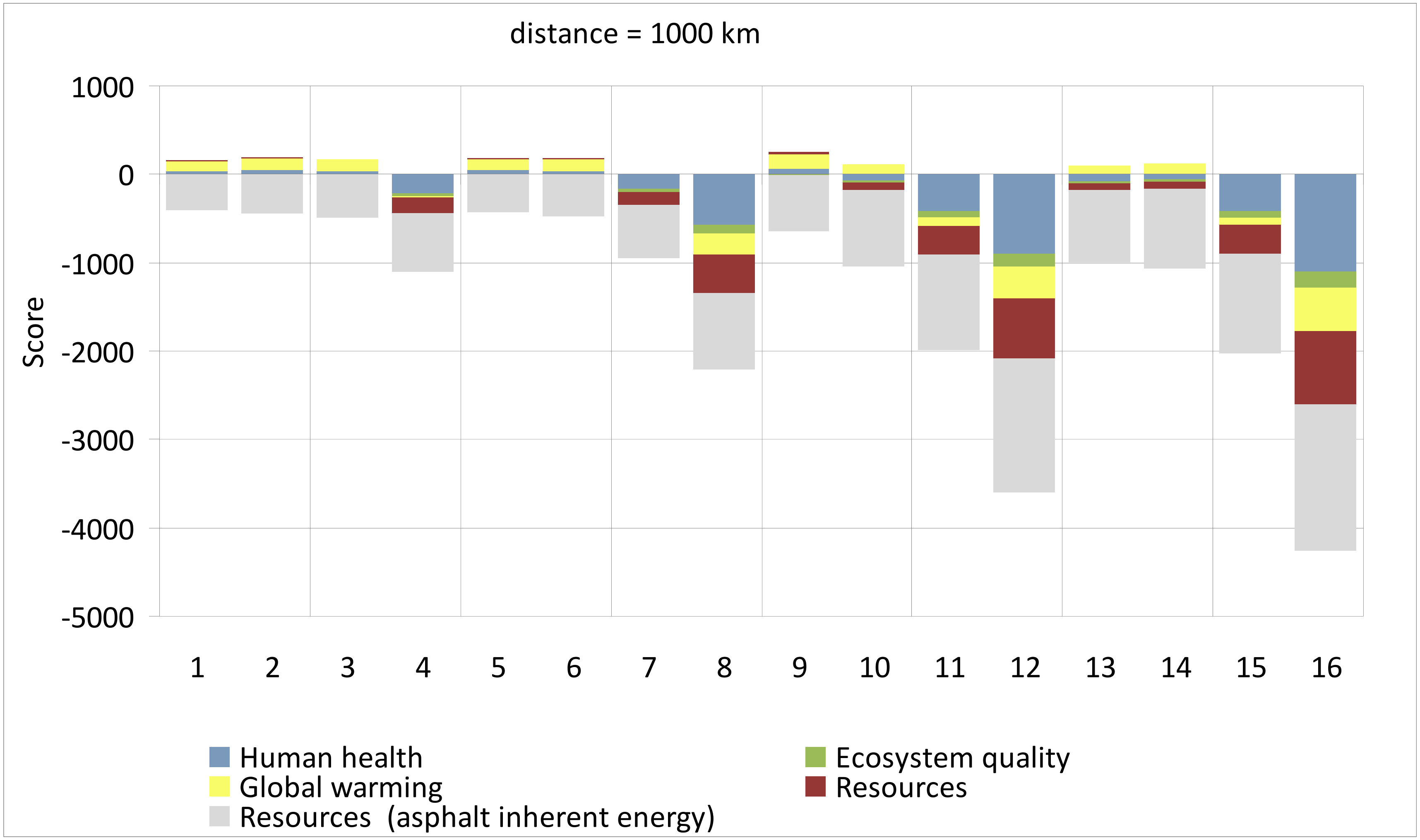


Figure 14.2.1: Weighted Damage Indicators in Reference to Different Transport Distances to Road Construction Site, for the Comparative Profile (CC System – AM System) for the 16 Functional Classes. c) 1000 km

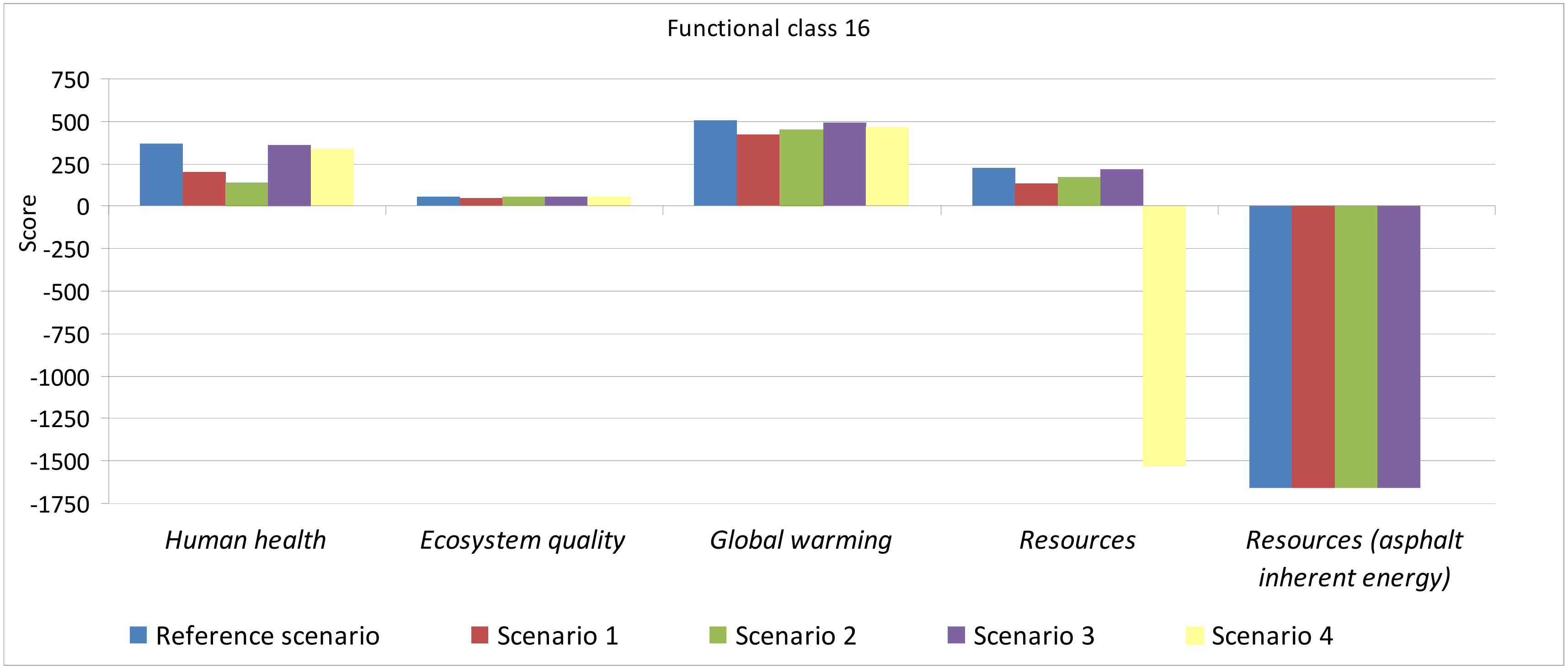


Figure 15.2.1: Weighted Damage Indicators in Reference to Different Asphalt Production Data for the Comparative Profile (CC System – AM System) for Functional Class 16.

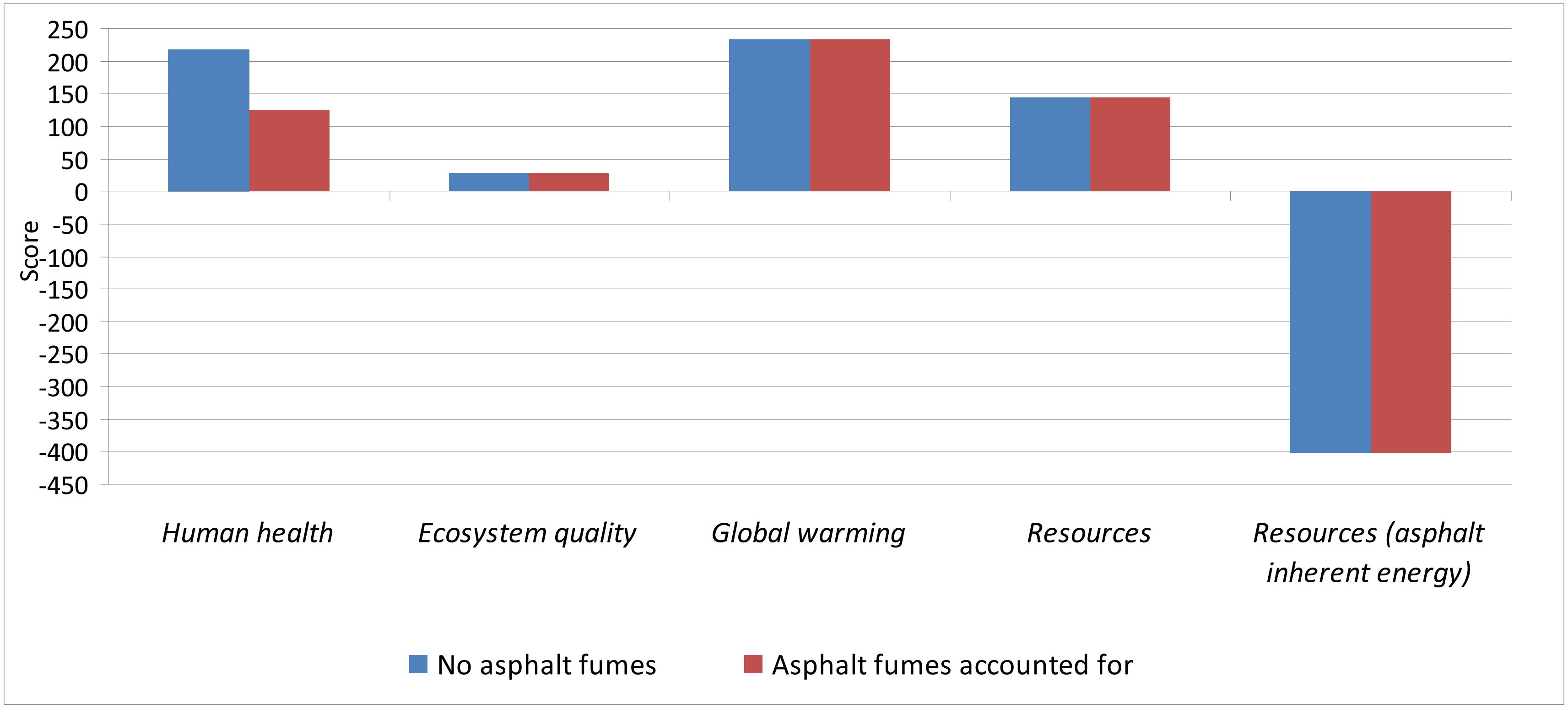


Figure 16.2.1: Weighted Damage Indicators in Reference to Asphalt Fume for the Comparative Profile (CC System – AM System) for the 16 Functional Classes.

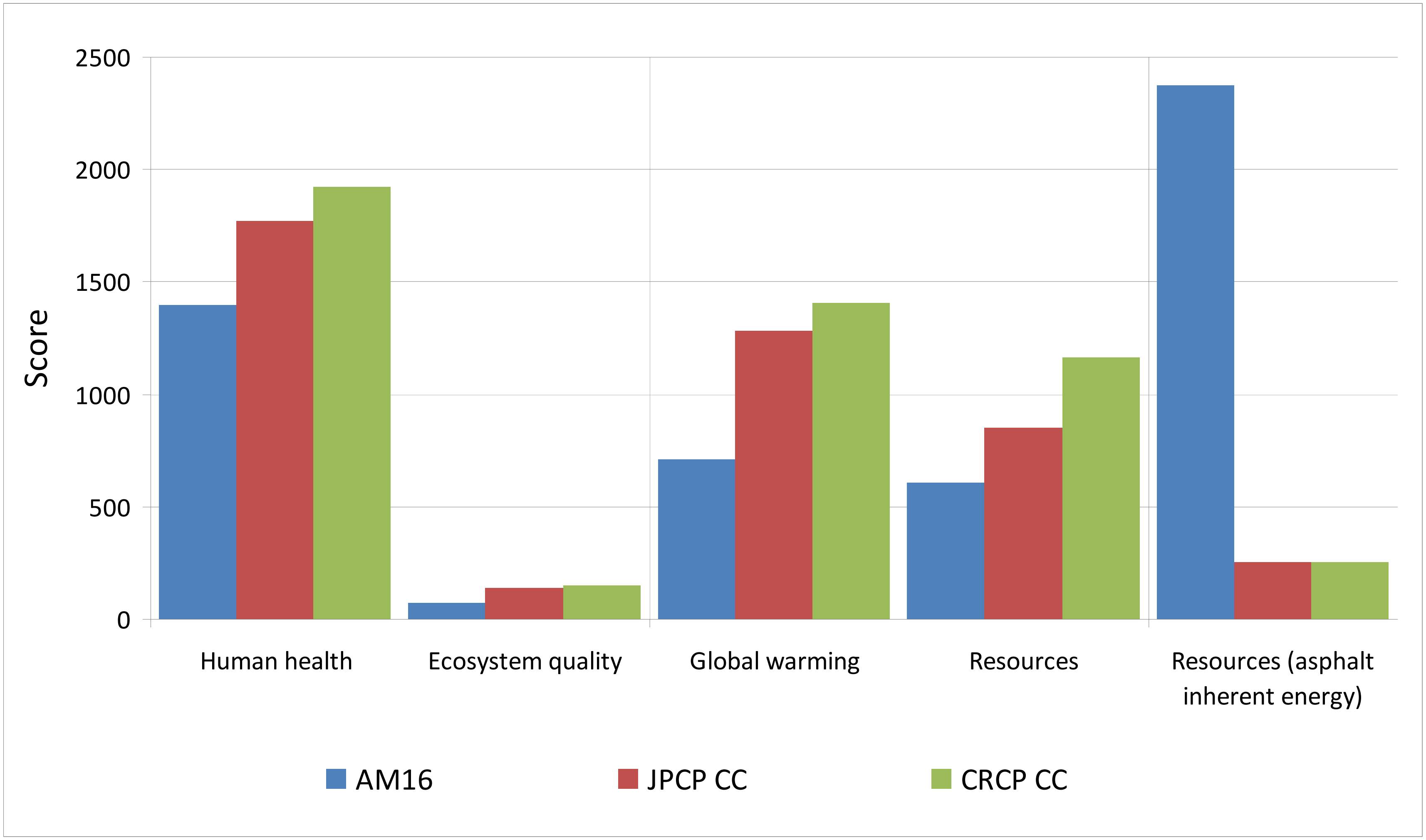


Figure 17.2.1: Compar Weighted Damage Indicators for AM (Asphalt Mixture) and two Cement Concrete Systems: JPCP (Jointed Plain Concrete Pavement) and CRCP (Continuously Reinforced Concrete Pavement) for Functional Class 16.

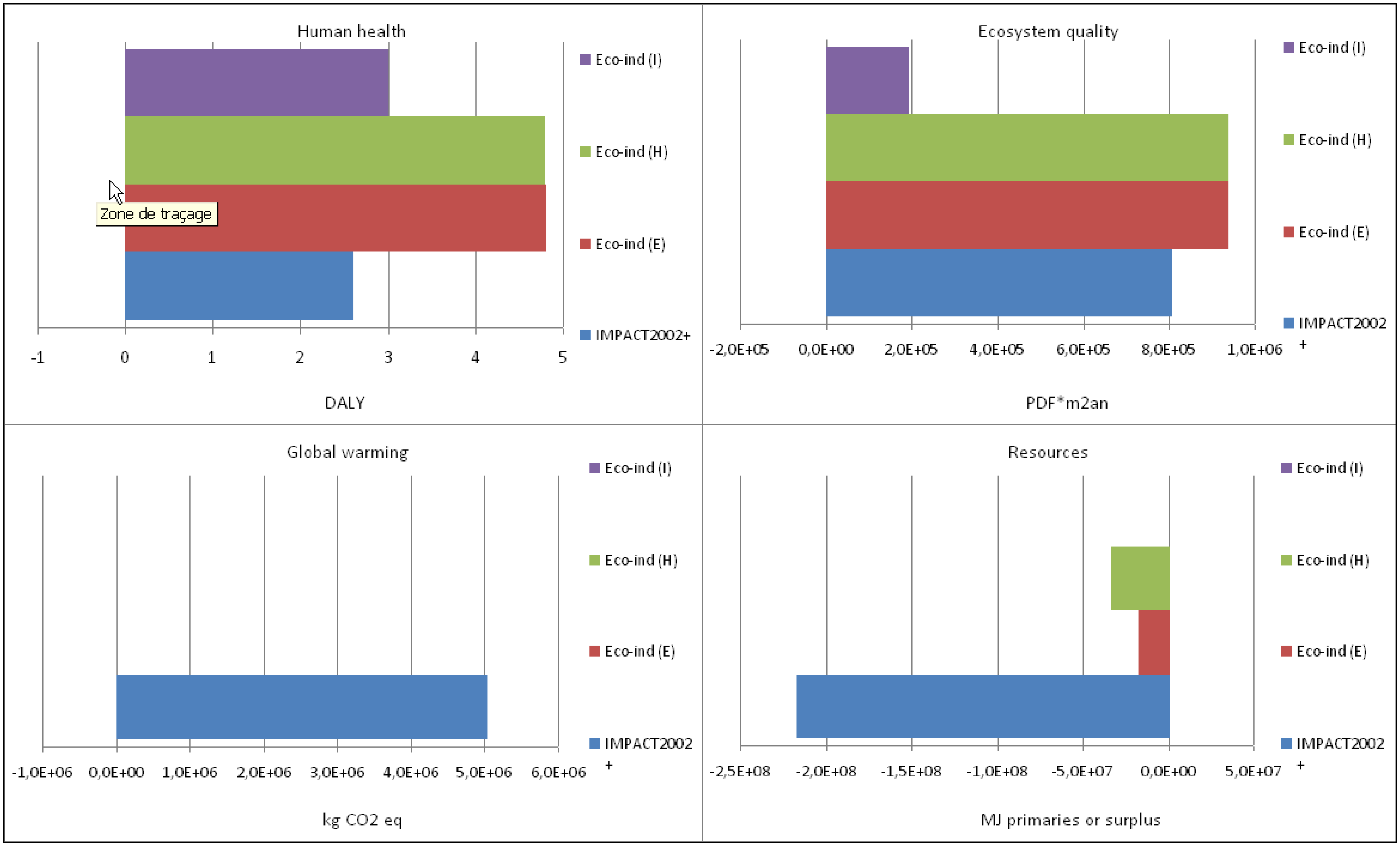
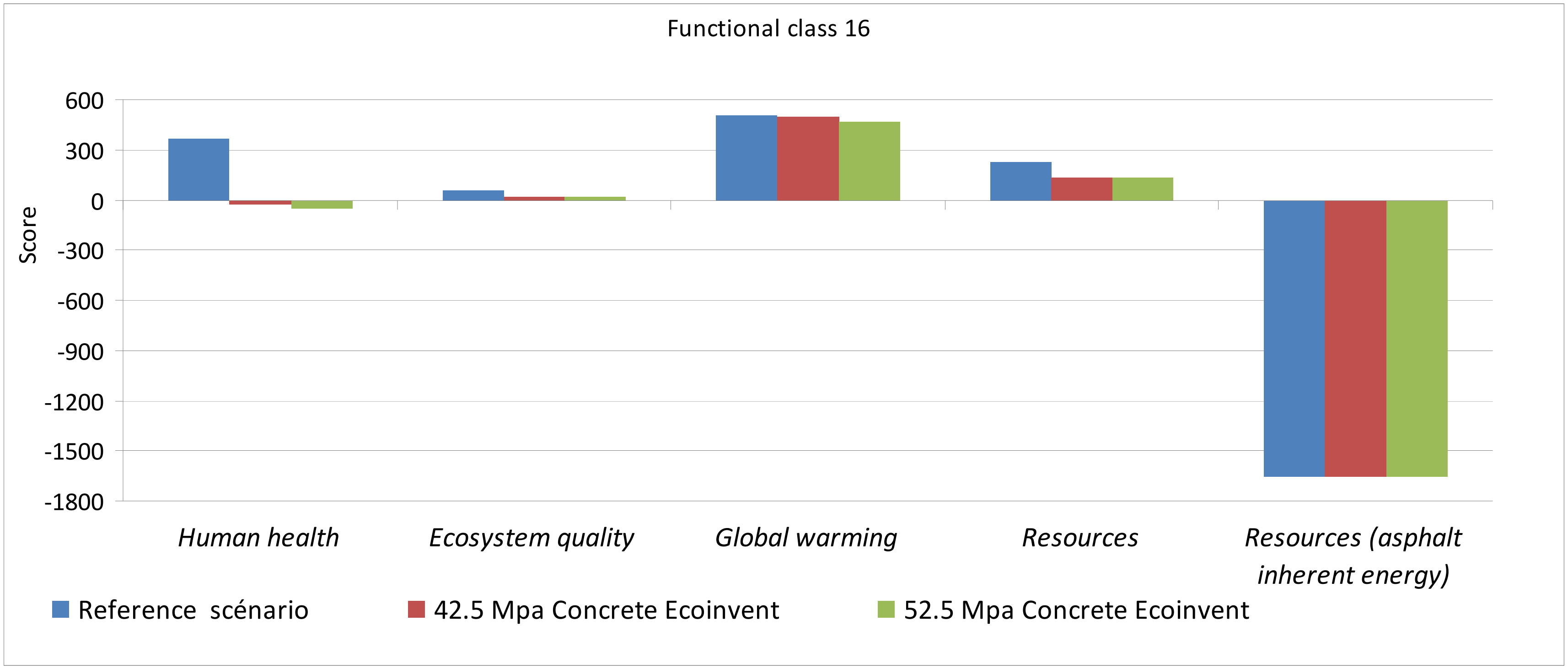


Figure 18.2 : Weighted Damage Indicators for the Comparative Profile (CC System – AM System) According to Different LCIA Methods, for Functional Class 16.



19.2.1 : Weighted Damage Indicators for the Comparative Profile (CC System – AM System) According to Specific Cement Production Data, for Functional Class 16.

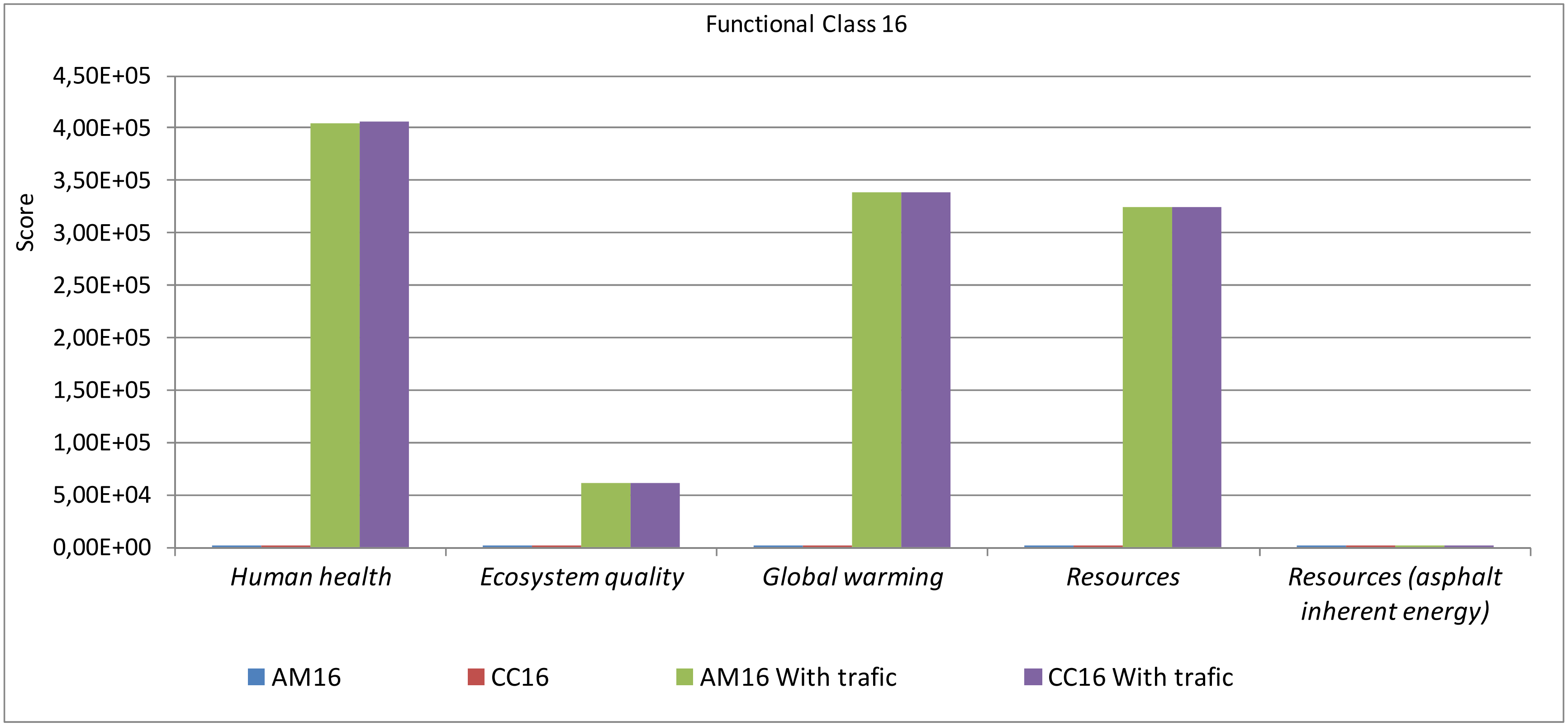


Figure 22.2.1 : Compared Weighted Damage Indicators Considering the Impact of 100 % of Road Traffic Fuel Consumption, for Functional Class 16.

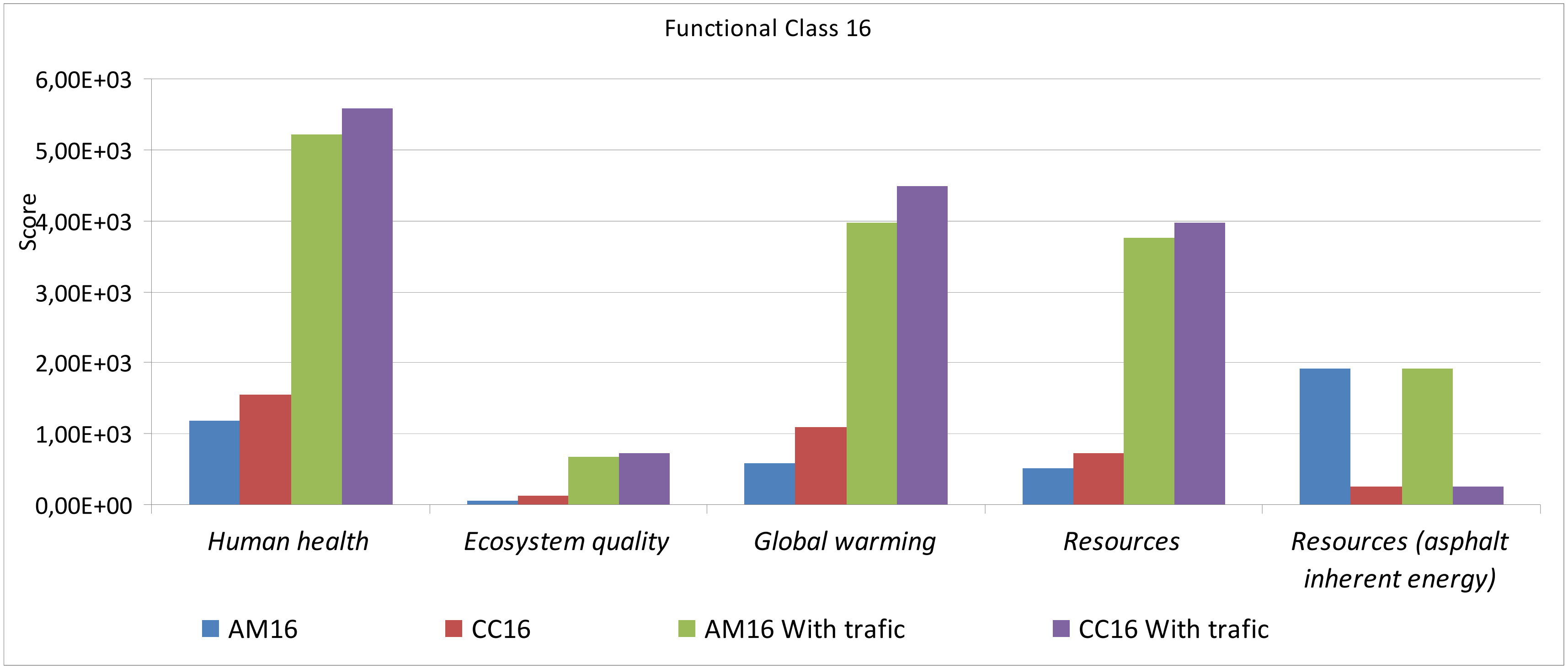


Figure 22.2.1b : Compared Weighted Damage Indicators Considering the Impact of 1 % of Road Traffic Fuel Consumption, for Functional Class 16.

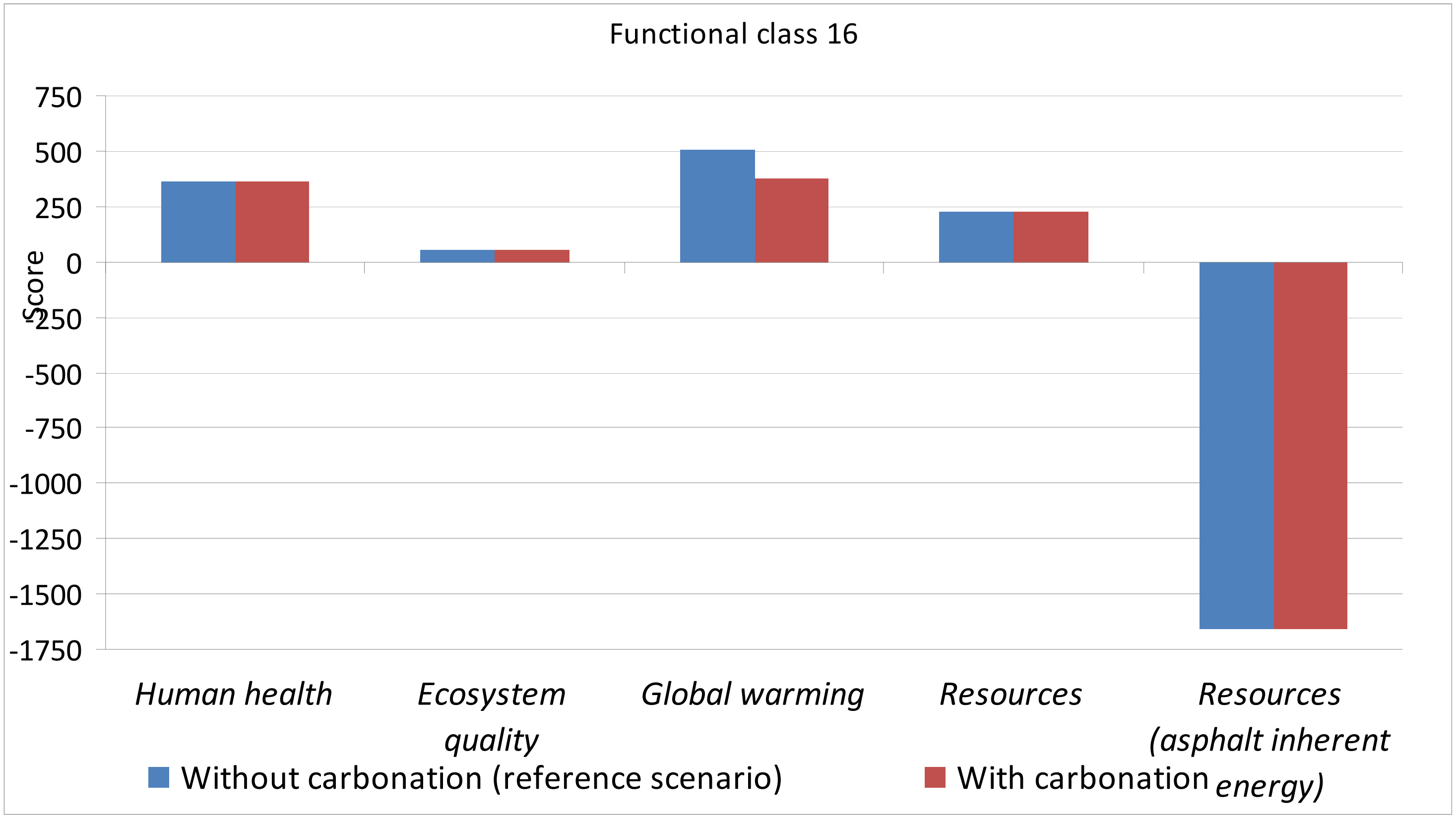


Figure 23.2.1 : Weighted Damage Indicators for the Comparative Profile (CC System – AM System) Considering Carbonation Process, for Functional Class 16.

Appendix G:

Report of the Critical Review Committee and CIRAIG's Responses to the Committee

Ministère des Transports du Québec

Note de revue critique de l'Analyse du Cycle de Vie comparative des chaussées en béton de ciment et en béton bitumineux à des fins d'intégration de paramètres énergétiques et environnementaux au choix des types de chaussées

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Bio Intelligence Service - La mesure du facteur santé
Écologie industrielle - Santé nutritionnelle
Bio Intelligence Service S.A.S. - bio@biois.com
1 rue Berthelot - 94200 Ivry-sur-Seine - France
Tél. +33 (0)1 56 20 28 98 - Fax. +33 (0)1 58 46 09 95

Contacts Bio Intelligence Service S.A.S.
Eric LABOUZE – Yannick LE GUERN
☏ +33 (0)1 53 90 11 80
eric.labouze@biois.com
yannick.leguern@biois.com

1. Préambule

Le Ministère des Transports du Québec (MTQ) a mandaté le Centre interuniversitaire de recherche sur le cycle de vie des produits, procédés et services (CIRAIG) afin qu'il réalise l'Analyse du Cycle de Vie (ACV) comparative de chaussées en béton de ciment et de chaussées en enrobé bitumineux.

Les bilans environnementaux établis dans cette étude seront utilisés pour établir des critères décisionnels quant au choix des futurs types de chaussées du réseau autoroutier québécois.

Bien que les résultats de l'étude ne soient pas destinés à être divulgués publiquement, ceux-ci appuieront une affirmation comparative utilisée dans un processus décisionnel de L'Orientation. Le MTQ souhaite désormais qu'une revue critique de l'étude soit donc conduite.

La norme ISO 14 044 relative aux Analyses de Cycle de Vie indique que le recours à une revue critique doit garantir que

- les méthodes utilisées pour réaliser l'ACV sont cohérentes avec la Norme internationale ISO 14 044,
- les méthodes utilisées pour réaliser l'ACV sont valables d'un point de vue scientifique et technique,
- les données utilisées sont appropriées et raisonnables par rapport aux objectifs de l'étude,
- les interprétations reflètent les limitations identifiées et les objectifs de l'étude,
- le rapport d'étude est transparent et cohérent.

Afin de réaliser la revue critique de l'étude ACV de différents types de chaussées, le MTQ a mandaté BIO Intelligence Service en tant que tierce partie indépendante pour mener la revue critique de l'étude menée le CIRIAIG, centre interuniversitaire de recherche spécialisé lui-même dans les analyses de cycle de vie. La mission de revue critique de l'étude est placée sous la responsabilité de Yannick Le Guern, Manager du pôle ACV et éco-conception chez de BIO Intelligence Service.

Trois parties prenantes ont été consultées afin d'obtenir leur avis sur l'étude conduite pour le MTQ. Les interlocuteurs sont :

- Pour la filière ciment :
  - Monsieur Pierre-Louis Maillard de l'Association canadienne du ciment (ACC):

- Pour la filière bitume
  - Madame Catherine Lavoie de l'association Bitume Québec (BQ)
  - Monsieur René Dufresne de Pétro-Canada

- Pour la filière relative à la construction de routes :
  - Messieurs Charles Abesque et Olivier Bouchard de l'Association des constructeurs de routes et grands travaux du Québec (ACRGTQ).

2. Déroulement de la revue critique

Dans un premier temps, le CIRAIG a transmis à BIO Intelligence Service un rapport préliminaire de l'étude daté du 8 janvier 2009. Suite à une première lecture de ce rapport, une réunion téléphonique a été organisée entre le CIRAIG et BIO Intelligence Service le 28 janvier 2009 afin que nous apportions un premier avis général sur l'objectif et le champ de l'étude.

Le rapport final pré-revue critique, daté du 6 mars 2009, a ensuite été transmis par le CIRAIG à BIO Intelligence Service.

BIO Intelligence Service est entré en contact avec l'ensemble des parties prenantes de l'étude (cf. précédemment) afin de recueillir leurs avis sur l'étude.

Une seconde réunion téléphonique a ensuite été conduite entre BIO Intelligence Service, les auteurs de l'étude au sein du CIRAIG et le MTQ (en la personne de Ronald Collette, ingénieur au Service de l'environnement et des études d'intégration au milieu – Direction de la recherche et de l'environnement du MTQ) afin de présenter l'avis recueillis auprès des parties intéressées, d'informer le MTQ sur le déroulement de la mission.

Le CIRAIG a ensuite modifié le rapport et l'a transmis à BIO Intelligence Service (rapport final post revue critique daté du 4 juin 2009) pour dernière relecture. Des ultimes modifications ont été intégrées dans le rapport final daté du 28 septembre 2009.

3. Présentation de la structure de cette note de revue critique

Pour chacune des exigences des normes ISO 14 040 et ISO 14 044 relatives à la revue critique d'une étude d'analyse de cycle de vie, nous avons restitué, dans la mesure du possible :

- Les remarques générales formulées par l'expert du comité de revue ainsi que celles formulées par les parties prenantes de l'étude.
- Les questions posées au CIRAIG.
- Les autres éléments proposés par l'expert pour renforcer la crédibilité de l'étude et faciliter sa compréhension

De manière générale, l'étude ACV conduite par le CIRAIG est complète et répond bien aux exigences de la norme ISO 14 044. Néanmoins, les réponses aux questions posées dans ce document ainsi qu'une version modifiée du rapport qui devra tenir compte de l'ensemble des questions, remarques ou commentaires présentés dans ce document sont attendus afin de procéder à la validation finale de l'étude.

3.1. AVIS SUR LE RAPPORT FINAL PRE-REVUE CRITIQUE DU 6 MARS 2009.

3.1.1. PREAMBULE

Ces avis émis par BIO sont également complétés par les avis émis par les parties prenantes sur la base des résultats qui leur ont été présentés en 2008 et ne se basent donc pas sur le rapport du 6 mars 2009.
Par ailleurs, le CIRAIG souhaitait également que BIO se positionne sur un aspect du rapport préliminaire.

3.1.2. SUR LA DEFINITION DES OBJECTIFS ET DU CHAMP DE L'ETUDE.

- **Objectifs de l'étude :**

[1] Proposition (BIO) : il est nécessaire de préciser dans le but de l'étude que cette étude a pour objectif de comparer les impacts environnementaux potentiels liés à la mise en œuvre d'une nouvelle chaussée en béton de ciment à ceux d'une nouvelle chaussée en béton bitumineux. En effet, cette étude ne couvre pas le renouvellement des chaussées existantes.

Réponse apportée par le CIRAIG :

En accord avec la proposition du réviseur, le CIRAIG a effectué la modification à l'application envisagée à la section 3.1.2 en précisant que l'ACV visait ultimement à comparer les impacts environnementaux potentiels liés à la mise en œuvre d'une nouvelle chaussée en béton de ciment à ceux d'une nouvelle chaussée en béton bitumineux afin de fournir un indicateur environnemental à l'analyse multicritère de l'Orientation.

Avis sur la réponse apportée (BIO) : nous approuvons cette réponse.

- <u>**Systèmes étudiés et fonction des systèmes**</u>

[2] avis des parties prenantes (BQ) : dans les résultats qui ont été présentés en 2008, les auteurs n'avaient considéré pour les chaussées en béton de ciment que la technique des dalles courtes goujonnées. Or, la technique en béton armé continu est visiblement déjà employée au Québec. En outre, cette technique aurait été considérée dans le cadre d'une analyse des coûts des différents types de chaussées conduite pour le MTQ (Life Cycle Cost Assessment). Il est donc nécessaire que l'analyse de cycle de vie prenne en compte cette alternative.
Modification apportée par le CIRAIG : Tel que demandé par les parties prenantes, le CIRAIG a traité de la technique du béton armé continu dans le rapport final. Les résultats de cette analyse sont présentés à la section 5.3.4 du rapport final.
Avis sur la réponse apportée (BIO) : nous approuvons cette réponse.

- <u>**Frontières des systèmes**</u>

[3] Remarque (BIO) : pour la phase d'exploitation, les auteurs n'ont pris en compte que la production des sels fondants. Les effets des émissions dans l'eau et les sols de ces sels ne sont pas considérés. Il est nécessaire d'évaluer l'influence de ces sels. Si les méthodes d'évaluation des impacts ne considèrent pas les effets de ces sels, ces émissions doivent néanmoins apparaitre dans l'inventaire de cycle de vie (cf. remarque sur l'analyse de l'inventaire de cycle de vie plus bas).
Réponse du CIRAIG :
Les émissions à l'eau et au sol dues à l'épandage des sels n'ont effectivement pas été considérées. Bien que ces données devraient figurer à l'inventaire, il a tout de même été convenu de ne pas modifier la modélisation puisque :
1) Les émissions à l'eau et au sol des sels ne sont caractérisées par aucune des méthodes d'évaluation des impacts employées. En raison de cette limite de l'ACVI, les effets de ces émissions ne peuvent donc pas être évalués.

2) Même si cette limite aurait été corrigée pour inclure les émissions des sels, les conclusions de l'étude n'auraient pas été affectées. Plus précisément, l'utilisation des sels fondants est plus importante dans le cas du système BC, ce qui le défavoriserait davantage en ce qui a trait aux émissions à l'air, à l'eau et au sol, ainsi qu'à la qualité des écosystèmes.

Pour ces raisons, la modification de l'inventaire n'est pas requise, bien qu'une note ait été ajoutée à cet effet au Tableau 4-4.

Avis sur la réponse apportée (BIO) : si cette réponse est compréhensible, il relève néanmoins que le bilan massique de l'inventaire est de ce fait non équilibré. Nous acceptons néanmoins que ceci soit maintenu dans la mesure où le CIRAIG a bien indiqué cette limite dans le rapport.

Réponse du CIRAIG :
Il est vrai que la norme ISO indique que le bilan massique d'un inventaire du cycle de vie doit être équilibré. Par contre, en pratique, il est rare qu'un inventaire puisse être parfaitement équilibré, puisqu'il existe toujours un niveau de précision de la collecte de données qui ne peut être accompli (limites de l'ICV). Dans notre cas, nous n'avons pu obtenir les données d'émissions dues aux sels

fondants. Toutefois, comme l'indique Bio Intelligence Service, nous avons bel et bien indiqué cette limite de l'inventaire dans le rapport.

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[4] Avis (BIO) : nous approuvons l'approche retenue dans l'analyse de sensibilité liée à la prise en compte des effets sur la consommation de carburant. Celle-ci met bien en évidence que des travaux complémentaires seraient nécessaires pour évaluer l'influence du type de chaussées sur la consommation de carburant des véhicules.

Réponse du CIRAIG :
Pas de commentaire à ajouter sur cet aspect.

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[5] remarque (BIO et ACC) : lorsque les premiers résultats de l'étude ont été présentés aux parties prenantes, les auteurs n'avaient pas considéré les émissions de composés organiques volatils (COV) et d'hydrocarbures lors de la mise en œuvre du bitume sur le chantier. Or, si les données issues d'enquêtes épidémiologiques et d'expérimentation animale n'ont pas permis de tirer de conclusions définitives quant à la toxicité de ces fumées, les émanations de COV et d'hydrocarbures lors de l'épandage du bitume sont bien reconnues.
Réponse du CIRAIG :
En réponse à cette demande, le CIRAIG a traité de cet aspect dans le rapport final au moyen d'une analyse de sensibilité, ce qui a été approuvé par BIO. Les résultats de cette analyse sont présentés à la section 5.3.3 du rapport final.
Avis sur la réponse apportée (BIO) : nous approuvons la prise en compte de cette étape dans les analyses de sensibilité.

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[6] avis des parties prenantes (ACC) : les chaussées en béton nécessitent moins de fondation granulaire en 0-20 mm qui exige un concassage plus important (plus de consommation d'énergie et d'émission de poussières). Il faut justifier ce choix.
Réponse apportée par le CIRAIG :
Il s'agit d'une spécification du MTQ. Le Tableau 3-2 du rapport final indique bien que les chaussées en béton de ciment requièrent moins de matières granulaires que les chaussées en enrobé (basé sur les épaisseurs des couches indiquées). Les quantités totales de granulats en tonnes sont disponibles à l'Annexe E, aux Tableau 1-1 et Tableau 1-2 pour les systèmes BC et BB respectivement. Tel qu'indiqué à l'Annexe E (sections E-2.1 et E-2.2), les granulats sont constitués de gravier et leur production a été modélisée avec le processus correspondant de la base de données ecoinvent, adapté au contexte québécois en ce qui à trait à l'origine de l'électricité utilisée, la consommation d'énergie (0,027 MJ/kg d'énergie mécanique et 0,0108 MJ/kg d'électricité) et les émissions de particules (50 mg/kg) sont tirées des rapports sur la production de ciment et de béton de ciment (Athena Sustainable Materials Institute et CANMET et Radian Canada Inc.). Puisque l'extraction des matières granulaires (comprenant le broyage et les émissions de poussières) n'a pas été ciblée comme un processus clé lors de l'analyse comparative ces informations sont jugées suffisantes à la description des systèmes et processus.
Avis sur la réponse apportée (BIO) : nous approuvons cette justification.

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[7] Question (BIO) : les auteurs indiquent que la quantité de sels fondants est plus importante pour les chaussées en béton de ciment que pour les chaussées en béton bitumineux (page 15 de l'annexe E du rapport final). Or, il est également indiqué que les activités de déneigement sont équivalentes pour les deux types de chaussées. Cette étape est donc exclue de l'étude (page 14 de l'annexe E du rapport final). Si la chaussée en béton de bitume nécessite moins de sels fondants, cela n'entraine-t-il pas un déneigement plus important ? Une explication devrait être ajoutée dans le rapport.

Réponse apportée par le CIRAIG :

La quantité en surplus de sel ne permet pas de faire fondre une couche suffisamment épaisse pour que les opérations de déneigement (c.-à-d. le type de machinerie et la fréquence des interventions) diffèrent entre les deux types de chaussées.

Néanmoins, il a été précisé à l'Annexe E (à la section E.3.5) que l'utilisation d'un surplus de sels dans le cas des chaussées en béton de ciment ne modifie aucunement les opérations de déneigement.

Avis sur la réponse apportée (BIO) : nous approuvons cette justification.

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[8] Remarque (BIO) : les auteurs indiquent, au chapitre 3.2.2.1 du rapport, que l'étape de fin de vie comprend la démolition complète des voies de roulement et d'accotement ainsi que la mise en place et le marquage d'une nouvelle dalle de béton de ciment ou d'une nouvelle couche d'enrobé. Le tableau 3-3 indique que dans le cas des chaussées en béton de ciment, cette reconstruction intervient au bout de la 46ème, 47ème, 49ème et 50ème année en fonction des types de voiries. Dans le cas des chaussées en enrobés bitumineux, l'enlèvement complet du revêtement et la pose d'un nouvel enrobé intervient au bout de la 38ème, 40ème, 42ème et 49ème en fonction des types de voiries.

Les auteurs n'indiquent pas dans le rapport d'étude comment ont été affectées l'étape de reconstruction de la dalle de béton de ciment et la pose du nouvel enrobé entre le cycle amont de la chaussée et le cycle aval (cad entre les 50 années considérées dans l'unité fonctionnelle et les 50 années à venir de la nouvelle chaussée).

Question (BIO) : les impacts environnementaux de cette dernière étape sont-ils totalement affectés aux 50 années considérées dans l'unité fonctionnelle de l'étude ou bien un prorata en fonction du nombre d'années permettant d'arriver à la 50ème année a-t-il été considéré ? (par exemple, dans le cas 16 des chaussées en béton de ciment, 4/50ème des impacts environnementaux ont-ils été affectés à la durée de vie considérée dans l'unité fonctionnelle de l'étude ?).

Réponse du CIRAIG :

Comme la reconstruction peut intervenir à différents moments pour les seize cas-types, les impacts environnementaux pour cette dernière ont été imputés aux systèmes de produits au prorata des années incluses dans la période de cinquante ans considérée dans la présente étude sur la durée de vie de la reconstruction. Par exemple, pour le cas-type 16 pour la chaussée en béton de ciment, la reconstruction est multipliée par un facteur 4/46, soit le nombre d'année permettant d'atteindre le cycle de 50 ans considéré divisé par la durée de vie de la dalle de béton.

Puisque le calcul lié à la reconstruction ne semble pas clair, dans le rapport un paragraphe a été ajouté à la sous-section 3.2.2.1 afin de mieux expliquer l'affectation des impacts à cette étape du cycle de vie.

Avis sur la réponse apportée (BIO) : nous approuvons le complément ajouté dans le rapport en vue de clarifier cette hypothèse.

Recommandation (BIO) : nous ne recommandons pas d'affecter l'ensemble des impacts environnementaux liés au remplacement des chaussées au cycle aval, si cette hypothèse a été retenue dans l'étude. En effet, cette hypothèse ne serait pas cohérente avec l'unité fonctionnelle puisque dans ce cas, la chaussée permet le déplacement de véhicules pendant plus de 50 ans.

Réponse du CIRAIG :
Le premier cycle de 50 ans de la chaussée est considéré. Les impacts de la reconstruction sont imputés au prorata pour les premières 50 années, ce qui est en accord avec l'unité fonctionnelle.
Avis sur la réponse apportée (BIO) : nous approuvons cette approche.

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[9] Remarque (BIO) : les auteurs indiquent que l'analyse de sensibilité tenant compte de l'influence de la technique en béton armé continu a été réalisée en tenant compte d'une durée de vie de 60 ans (page 44 du rapport final). Pour être cohérent avec la définition de l'unité fonctionnelle, qui précise qu'elle couvre les 50 premières années de la chaussée, il est nécessaire que les auteurs considèrent la même durée de vie que dans le scénario de référence, soit 50 ans.
Réponse du CIRAIG :
Le principal avantage de la chaussée en béton armé continu (BAC) est une durée de vie plus élevée. Puisque la reconstruction de la chaussée en BAC a lieu à l'année 56 (pour le cas-type 16 à l'étude), il est nécessaire de considérer un cycle de vie permettant d'inclure les effets de cette dernière séquence d'intervention. Vu la durabilité plus élevée de ce type de chaussée et afin d'assurer la comparaison des trois types de chaussée, l'unité fonctionnelle a été modifiée spécifiquement pour cette analyse de sensibilité. Elle s'exprime de la manière suivante : *« Permettre le déplacement de véhicules routiers sur une distance de cinq kilomètres durant les* ***soixante*** *premières années de vie d'une chaussée en béton de ciment comparativement à une chaussée en enrobé bitumineux et à une chaussée en béton armé continu, construites au Québec en 2009 ».* La spécification de l'unité fonctionnelle modifiée et le raisonnement derrière cette dernière ont été ajoutés à la section 5.3.4.
Avis sur la réponse apportée (BIO) : nous n'approuvons pas cette réponse. Il est tout à fait possible de ramener les impacts potentiels sur l'environnement par annuité puis de les calculer sur une période de 50 ans. C'est l'approche qui est considérée dans le cadre de l'élaboration de Fiches de Déclaration Environnementale et Sanitaire sur les produits et matériaux de construction en France (cf. AFNOR NF P 01 010).

Proposition (BIO) : si les auteurs souhaitent prendre en compte l'étape de fin de vie, nous proposons que les impacts environnementaux de la chaussée en béton armé continu soient évalués sur 60 ans et ramené au prorata des 50 ans. Dans ce cas, il serait nécessaire de modifier la définition de l'unité fonctionnelle en ôtant la notion de 50 premières années et en indiquant « pendant 50 ans ».
Réponse du CIRAIG :
Si cette méthode est employée, seul le cycle partiel de la chaussée en béton armé continu sera pris en compte : les impacts liés à la l'étape de reconstruction ne seront pas considérés, et les trois systèmes ne seront pas équivalents, et donc non comparables.
Note : cette méthode proposée est en désaccord avec la recommandation [8] du réviseur
Avis sur la réponse apportée (BIO) : comme indiqué précédemment, il est tout à fait possible de ramener les impacts potentiels sur l'environnement par annuité puis de les calculer sur une période de 50 ans. Cette approche est parfaitement cohérente avec la recommandation [8].

Réponse du CIRAIG :

Il est effectivement possible de ramener les impacts du cycle de vie d'une chaussée par année. Toutefois, compte tenu des séquences dans la vie d'une chaussée, le modèle de calcul se complexifie. Plus précisément, la fondation et la sous-fondation de la chaussée sont construites à la première année, mais ne sont pas remplacées lors des étapes de reconstruction. Par conséquent, il ne convient pas d'additionner les impacts associés à la construction de la fondation et de la sous-fondation aux impacts de la construction et de simplement les ramener par année en fonction de la période de 50 ans considérée, afin d'obtenir un cycle de 50 ans moyen :

$$\text{Im}\,pacts\_sur\_50\_ans = \frac{(\text{Im}\,pactsA + \text{Im}\,pactsB)}{D_{chaussée}} \times 50$$

Où A est la construction de la fondation et de la sous-fondation, B est la construction de la chaussée et $D_{chaussée}$ est la durée de vie de la chaussée.
Il faut plutôt considérer :

$$\text{Im}\,pacts\_sur\_50\_ans = \frac{(\text{Im}\,pactsA + \text{Im}\,pactsB + K \times \text{Im}\,pactsC)}{D_{fond}} \times 50$$

$$K = \frac{(D_{fond.} - D_{chaussée})}{D_{chaussée}}$$

Où C est la reconstruction de la chaussée, D_{fond} est la durée de vie de la fondation et sous-fondation, et K est le nombre de reconstructions ayant lieu à l'intérieur de la période couverte par la durée de vie de la fondation et sous-fondation.

Toutefois, la durée de vie de la fondation et de la sous-fondation comporte beaucoup d'incertitudes et n'a pu être déterminée par le MTQ. C'est pour cette raison qu'il a été décidé de ne considérer que le premier cycle de 50 ans de la chaussée pour cette étude, et de calculer les impacts de cette façon :

$$\text{Im}\,pacts\_sur\_1er\_50\_ans = \left(\text{Im}\,pactsA + \text{Im}\,pactsB + \left(\frac{50 - D_{chaussée}}{D_{chaussée}}\right) \times \text{Im}\,pactC\right)$$

Ce modèle de calcul correspond à ce qui a été expliqué à la remarque [8] et accepté par Bio Intelligence Service.
Afin d'effectuer l'analyse de sensibilité sur le BAC en utilisant ce même modèle de calcul, il est nécessaire de modifier l'unité fonctionnelle puisque Dchaussée>50. Les impacts des trois types de chaussées sont alors calculés comme suit :

$$\text{Im}\,pacts\_sur\_1er\_60\_ans = \left(\text{Im}\,pactsA + \text{Im}\,pactsB + \left(\frac{60 - D_{chaussée}}{D_{chaussée}}\right) \times \text{Im}\,pactC\right)$$

NOTE : Après réflexion de l'applicabilité de ce modèle de calcul, il sera nécessaire d'ajouter une hypothèse dans le rapport, spécifiant que les durées de vie des fondations et sous-fondations des trois différents types de chaussée sont jugées les mêmes. Ceci permettra d'appuyer que les trois systèmes sont fonctionnellement équivalents.

Avis sur la réponse apportée (BIO) : cette réponse expose bien la complexité de ramener les résultats de cette analyse de sensibilité à une période de 50 ans. La comparaison qui est faite entre la technique BAC et la chaussé de bitume se faisant pour les deux types de chaussées sur une période de 60 ans, elle permet de positionner les deux types de chaussées à service équivalent. Nous approuvons donc cette approche.

[10] Remarque (BIO) : le béton réabsorbe, tout au long de sa vie, du dioxyde de carbone atmosphérique lors du processus de carbonatation (phénomène de carbonatation de la chaux contenue dans le béton, suivant la réaction suivante : $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$. Ce processus n'a pas été pris en compte dans l'ACV. Il est nécessaire que les auteurs l'indiquent dans le rapport d'étude ou bien que la prise en compte de ce phénomène soit évaluée dans l'étude. Pour cela, nous proposons que les auteurs se basent sur le document « Guidelines – Uptake of carbon dioxide in the life cycle inventory of concrete, by Danish Technological Institute, Denmark. Kirsten Pommer, Claus Pade. October 2005 ISBN: 87-7756-757-9 ».

Réponse du CIRAIG :

Le CIRAIG est en accord avec la proposition du réviseur et à ajouter cette analyse de sensibilité à l'étude à la sous-section 5.3.8.

Afin de vérifier l'influence de la prise en compte de ce processus sur les résultats, cette analyse de sensibilité comptabilise la quantité totale de CO_2 pouvant être absorbé par la chaussée en béton de ciment du cas-type 16 durant la période de cinquante ans considérée. Pour se faire, quelques hypothèses simplificatrices ont été posées :

- Le béton recyclé (c.-à-d. de seconde génération) peut aussi absorber du CO_2 lorsqu'il est employé dans la sous-fondation des deux types de chaussées. Bien que les couches de sous-fondation soient plus épaisses pour les chaussées en béton, le taux de CO_2 absorbé est calculé à partir de la surface de béton de ciment, et donc n'est pas une fonction de l'épaisseur. Puisque les longueurs et largeurs des chaussées sont les mêmes pour les deux types, le taux d'absorption sera considéré équivalent. Ainsi, seule l'absorption par le béton employé dans le revêtement de béton de ciment du système BC sera considérée pour cette analyse.
- Les lignes directrices du document intitulé « *Guidelines – Uptake of Carbon Dioxide in the Life Cycle Inventory of Concrete* » (Pommer et Pade, 2005) ont été employées pour estimer la quantité de CO_2 absorbé par le cycle de vie du revêtement de béton de ciment.

La quantité totale de CO_2 absorbée sur le cycle de vie de la chaussée pour le cas-type 16 calculée est de **1 310 tonnes**. La quantité totale de CO_2 qui avait été inventoriée sur le cycle de vie total de la chaussée en béton de ciment pour le cas-type 16 était de **6 060 tonnes**. Il y a donc une diminution de 22 % de la quantité nette de CO_2 émise lors du cycle de vie de la chaussée en béton de ciment pour ce cas-type, ce qui se traduit par une diminution de 26 % de la quantité totale de CO_2 équivalent. Les résultats sont en accord avec cette diminution de CO_2 équivalent puisque l'indicateur de dommage pour le réchauffement climatique indique une diminution du dommage de la même proportion lorsque l'on considère le processus de carbonation. En revanche, bien qu'il y ait une diminution de l'impact, l'indicateur demeure plus élevé pour le système BC que le système BB. Les autres indicateurs de dommage ne sont pas modifiés. Afin d'obtenir un portrait représentatif de la réalité, et dans une perspective de cycle de vie, la considération du processus de carbonation du béton de ciment est importante. Par contre, pour cette ACV comparative, la prise en compte de la quantité de CO_2 absorbée par la chaussée tout au long de son cycle de vie ne semble pas être un paramètre sensible. Les conclusions de cette étude **ne sont donc pas modifiées** par la prise en compte du processus de carbonation par le béton de ciment

Avis sur la réponse apportée (BIO) : nous approuvons cette approche et son intégration dans l'étude en tant qu'analyse de sensibilité.

3.1.1. SUR LA METHODE D'EVALUATION DES IMPACTS ET DOMMAGES POTENTIELS SUR L'ENVIRONNEMENT.

[11] Remarque (BIO) : dans le rapport préliminaire, les auteurs indiquent la nécessité de solliciter l'avis du comité réviseur sur la méthode de caractérisation des impacts potentiels sur l'environnement.

Par ailleurs, dans le rapport préliminaire, les auteurs ont donc utilisé la méthode IMPACT 2002+ développée par l'Ecole Polytechnique Fédérale de Lausanne (EPFL) en justifiant par le fait que des facteurs de normalisation étaient disponibles dans cette méthode. Ces facteurs de normalisation permettent de traduire les indicateurs de dommage en équivalent habitants (c'est-à-dire en nombre d'habitants par an qui engendrent la même quantité de dommage à l'environnement et à la santé de l'homme). La traduction en équivalent habitants a ensuite été utilisée par les auteurs pour permettre le calcul d'un indicateur unique en utilisant un facteur de pondération de 1 entre les différents indicateurs de dommage. **Nous ne recommandons pas d'utiliser un système à score unique** pour différentes raisons :

- Il n'existe pas à l'heure actuelle de consensus par la communauté internationale des experts en ACV pour aboutir à un score unique.
- La description de la méthode IMPACT 2002+[1] ne recommande pas une pondération entre les différents indicateurs de dommage normalisés : « *The authors suggest considering the four damage oriented impact categories human health, ecosystem quality, climate change, and resources separately for the interpretation phase of LCA* »
- Les normes ISO relatives aux ACV indiquent qu'une pondération des résultats d'ACV n'est pas adéquate dans le cadre d'une communication des résultats d'ACV.
- Il est de notre point de vue nécessaire que l'étude réalisée par le CIRAIG apporte une vision exhaustive des enjeux environnementaux des deux types de chaussées. Seule une approche multi-critères garantira que l'Orientation ait connaissance des différentes conséquences écologiques liées aux choix qu'elle pourra faire.

Avis (BIO) :

Les auteurs ont retenu la méthode IMPACT 2002+. Nous approuvons l'utilisation de cette méthode qui répond aux exigences de la norme ISO 14 044 et principalement :

- Les catégories d'impact, les indicateurs et le modèle de caractérisation sont acceptés au niveau international (cette méthode a, par exemple, fait l'objet d'une publication dans l'International Journal Of LCA Int J LCA 8 (6) 324 – 330 (2003)).
- Les catégories d'impacts et de dommages représentent l'ensemble des impacts des entrants et des extrants des systèmes considérés.
- Le modèle de caractérisation de chaque indicateur est scientifiquement et techniquement valable.
- Les indicateurs de catégorie ont une pertinence environnementale.

Les auteurs indiquent dans le rapport préliminaire que d'autres méthodes d'évaluation des impacts potentiels, dont LUCAS, seront considérées dans le rapport final pour identifier si le choix d'une méthode peut modifier les tendances observées sur les résultats obtenus avec la méthode IMPACT 2002+.

[1] IMPACT 2002+: User Guide Draft for version 2.1 Industrial Ecology & Life Cycle Systems Group, Jolliet et al. GECOS, Swiss Federal Institute of Technology Lausanne (EPFL). October 2005

Dans le rapport de mars 2009, les auteurs de l'étude ont intégré d'autres méthodes d'évaluation des impacts potentiels, dont LUCAS dans le rapport final. Le choix d'une méthode ne change pas le positionnement des deux types de chaussées obtenu avec la méthode IMPACT 2002+.
Par ailleurs, les auteurs ont modifié leur approche pour ne plus présenter les résultats des deux types de chaussées sous la forme d'un score unique mais selon une analyse multicritère exprimée selon les quatre indicateurs de dommage de la méthode IMPACT 2002+.

Réponse du CIRAIG :
Les méthodes LUCAS et Eco-indicator 99 ont été employées pour cette étude et ont été présentées dans le rapport final. Le CIRAIG avait demandé au comité réviseur leur avis sur les méthodes à employer pour cette étude. Le CIRAIG avait opté pour ces deux méthodes, ainsi que la méthode LUCAS mais sollicitait tout de même l'avis du comité. Ces méthodes ont bien été employées dans le rapport final. Les résultats des deux types de chaussées n'ont pas été présentés sous la forme d'un score unique mais bien selon une analyse multicritère exprimée selon les quatre indicateurs de dommage de la méthode IMPACT 2002+.
Avis sur la réponse apportée (BIO) : nous approuvons cette approche.

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[12] avis des parties prenantes (BQ) : le bilan de consommation d'énergies non renouvelables pour les chaussées de béton bitumineux soulève la question de la prise en compte la prise en compte ou non de l'énergie matière (énergie inhérente ou énergie « feedstock »).
Avis (BIO) : l'énergie primaire non renouvelable exprime les quantités de ressources naturelles énergétiques non renouvelables (tel que le pétrole, le charbon, le gaz, l'uranium…) puisées dans l'environnement et qui sont mobilisées à chacune des étapes du cycle de vie du produit. Elle est exprimée dans une unité énergétique (en général en MJ) en tenant compte du contenu énergétique des différentes ressources (Pouvoir Calorifique Inférieur ou PCI). La quantité de pétrole entrant dans la composition « matérielle » du bitume contribue à diminuer la ressource pétrole. Celle-ci est exprimée au travers de l'énergie « feedstock ». Cette énergie « feedstock » n'est pas perdue dans la mesure où elle peut être récupérée en fin de vie par un processus de valorisation énergétique (c'est le cas par exemple pour les emballages en matière plastique). Il est donc nécessaire de considérer cette énergie « feedstock » dans le bilan énergie primaire. Nous approuvons donc le choix qui a été fait par les auteurs de l'étude d'intégrer cette énergie dans les bilans environnementaux des deux types de chaussées.

Réponse du CIRAIG :
Bien que la problématique de cette prise en compte ait été soulevée par les parties prenantes, il a été décidé de comptabiliser l'énergie totale liée à la production du bitume. L'énergie inhérente du bitume a été prise en compte dans les résultats du rapport final, ce qui est aussi en accord avec l'avis de BIO.
Proposition (BIO) : compte tenu de l'horizon temporel de l'étude (50 ans) une analyse de sensibilité sur la valorisation énergétique du bitume (procédé de fin de vie qui pourrait être envisagé en 2059 pour récupérer l'énergie « feedstock ») permettrait d'affirmer ou d'infirmer l'intérêt du développement d'une telle filière au Québec.

Réponse du CIRAIG :
La fonction du système est de permettre une circulation routière sur un tronçon donné de chaussée. La valorisation du bitume en fin de vie serait donc considérée comme une fonction secondaire et nécessiterait une extension des frontières. Or, il n'existe actuellement aucune technologie

permettant de revaloriser énergétiquement le bitume contenu dans les enrobés de construction. Il n'est donc pas possible pour le CIRAIG d'effectuer une telle analyse.

Avis sur la réponse apportée (BIO) : nous n'approuvons pas cette réponse en partie. La valorisation énergétique ne confère pas une seconde fonctionnalité au produit ou système étudié dans une analyse de cycle de vie. La valorisation énergétique d'un produit en fin de vie est en effet couramment prise en compte dans les ACV (cf. ACV études de la commission Européenne, pour l'ADEME, Eco-emballages etc.). L'hypothèse couramment admise est que l'énergie produite se substitue à la production d'énergie par des moyens conventionnels. Par ailleurs, si le process de valorisation énergétique n'existe pas à l'heure actuelle, un scénario prospectif aurait pu être considéré pour évaluer l'influence de cette hypothèse.

Néanmoins, cette proposition avait pour objectif de compléter l'étude et ne remet pas en cause les autres hypothèses considérées.

Réponse du CIRAIG :

Nous sommes d'accord que la valorisation énergétique en fin de vie et l'hypothèse de la substitution d'énergie sont couramment prises en compte en ACV. Toutefois, il est communément reconnue en ACV que cette prise en compte d'une énergie en fin de vie confère une seconde fonction au système, ce qui peut notamment être expliqué dans le récent document de référence publié par la Commission Européenne (International Reference Life Cycle Data System (ILCD) Handbook, document présentement en consultation, mais disponible au : http://lct.jrc.ec.europa.eu/lca-files/ILCD-Handbook-General-guidance-document-for-LCA-data-and-studies-Draft-for-public-consultation-clean.pdf). Les impacts évités par une substitution d'énergie peuvent alors être retranchés du système à l'étude.

Néanmoins, selon les recherches effectuées sur la valorisation énergétique du bitume, le CIRAIG n'a pas été en mesure d'identifier un scénario prospectif vraisemblable, et donc les impacts évités par une valorisation énergétique du bitume n'ont pas été considérés.

Avis sur la réponse apportée (BIO) : cette réponse n'appelle aucun commentaire supplémentaire.

3.1.1. SUR LES TYPES DE DONNEES, LEURS SOURCES ET LES EXIGENCES EN TERMES DE QUALITE.

[13] Remarque (BIO) et parties prenantes (ACC[2]): les auteurs de l'étude se sont approchés des différentes parties prenantes pour obtenir les données de production du bitume, du ciment, de mise en œuvre des chaussées… une attention particulière doit être considérée dans la mesure où ces données n'ont pas été validées par une tierce partie indépendante.

En outre, la description de la méthode utilisée pour la modélisation de la production du bitume n'est pas claire. Il est d'ailleurs étonnant que les émissions de CO_2 issues d'Eurobitume ou d'Ecoinvent soient entre 3,5 et près de 6 fois plus importantes que celles fournies par Petro-Canada.

Des analyses de sensibilité ont été conduites en prenant d'autres données d'inventaires de cycle de vie (données Ecoinvent adaptées au contexte Québécois par exemple) pour évaluer leur influence sur les résultats.

L'analyse de sensibilité sur les inventaires de cycle de vie de la production de ciment montre également que ceux-ci peuvent influencer les tendances observées sur le positionnement des deux filières.

Réponse du CIRAIG :

Puisque la méthode employée pour la modélisation de la production du bitume n'est pas claire, un paragraphe a été ajouté à la sous-section 3.2.3.1 du rapport, spécifiant que les données sur la consommation d'énergie et sur les émissions ont pu être fournies pour la production spécifique d'un

[2] L'avis de l'ACC ne concerne que les données sur la production du bitume.

kilogramme de bitume plutôt que pour la totalité des activités de la raffinerie, ce qui évite de recourir à une imputation massique sur l'ensemble des produits de la raffinerie.

Avis sur la réponse apportée (BIO) : nous approuvons le complément ajouté dans le rapport en vue de clarifier cette hypothèse.

Avis (BIO) : nous approuvons cette approche mais apportons une réserve sur les données utilisées. En effet, une étude comparative de ces deux filières ne peut se faire que sur la base d'inventaires de cycle de vie établis par les industriels. Les hypothèses méthodologiques retenues pour l'établissement de ces inventaires devraient être homogènes (frontières des systèmes à considérer, règles d'allocations entre les différents coproduits, modèles énergétiques, flux élémentaires à considérer…) de manière à permettre une analyse comparative robuste. Ces inventaires de cycle de vie doivent être établis conformément aux normes ISO 14 040 et ISO 14 044, voire selon la norme ISO 14 025 en établissant un PCR visant à l'établissement de déclarations environnementales produit (EPD). Ces inventaires de cycle de vie devraient ensuite être vérifiés par une tierce partie indépendante, voire un panel d'experts indépendants.

Réponse du CIRAIG :

Les hypothèses méthodologiques pour l'établissement de l'inventaire du système BB et du système BC sont les mêmes. Plus précisément, les frontières considérées sont équivalentes. En ce qui a trait à l'imputation, le système BC ne nécessitait pas de règle d'imputation pour la modélisation de la production du ciment, tandis que le système BB comportant une imputation au niveau de la raffinerie (étant un processus multifonctionnel). Aucun modèle énergétique n'a été employé pour la modélisation des deux systèmes et les flux élémentaires considérés dans les deux systèmes sont les mêmes ; aucun flux élémentaire n'a été exclu. La modélisation de la production du bitume a bien été faite sur la base d'inventaires du cycle de vie établis pas un expert industriel, soit par Petro-Canada, mais n'a pas été validée par une tierce partie indépendante. De plus, aucun PCR n'apparaît dans le domaine pétrochimique et dans l'industrie du ciment, et donc aucune procédure n'existe à ce jour pour le développement d'un EPD pour le bitume et le ciment. Le CIRAIG avait déjà communiqué au MTQ l'intérêt de valider les données obtenues des parties prenantes par un panel d'experts indépendants lors de la réalisation de la revue critique, dans le but d'augmenter le niveau de qualité des données employées (ou du moins d'en obtenir une meilleure estimation). Des analyses de sensibilité ont été réalisées sur les inventaires de cycle de vie de la production de ciment et de la production du bitume. Bien qu'il fût démontré que le choix de l'inventaire puisse influencer les tendances observées sur le positionnement des deux filières, ces modifications ne changent pas les conclusions obtenues : il n'est aucunement possible de conclure quant à la supériorité d'un type de chaussée relative à l'autre.

Avis sur la réponse apportée (BIO) : nous approuvons cette réponse. Néanmoins il nous semble pertinent que le développement d'un PCR sur les matériaux entrant dans la composition des types de chaussées soit établis afin de faciliter l'actualisation de cette étude et de renforcer sa crédibilité.

Réponse du CIRAIG :

Le développement d'un PCR ne faisait pas partie du mandat de cette étude. Toutefois, le CIRAIG est d'accord qu'il est important de développer des PCR sur les matériaux de construction. Une recommandation encourageant le développement de ces PCR a donc été intégrée au rapport final

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[14] Remarque (BIO) : l'horizon temporel souhaité pour cette étude est en désaccord avec la représentativité temporelle des données utilisées mais également des techniques retenues pour l'étude. En effet, cette étude vise à fournir un bilan comparatif des différentes techniques de chaussées jusqu'en 2059. Or, les bilans environnementaux sont basés sur des techniques actuelles et des données de production basées sur les années 2005 et 2006 pour la production du ciment, du béton de ciment et du bitume. De même, les données fournies par l'ACRGTQ sont visiblement représentatives des techniques de construction utilisées à l'heure actuelle. Or, ces données entrainent un biais s'il on veut que cette étude soit représentative des conséquences écologiques des différents types de chaussées jusqu'en 2059 pour les raisons suivantes :

- Les procédés industriels auront certainement évolués d'ici 2059 et l'on peut raisonnablement supposer que ceux-ci seront optimisés par rapport à aujourd'hui (augmentation des rendements des procédés, meilleure efficacité énergétique, amélioration des techniques de dépollution de l'air, de l'eau…, moindre quantité de déchets et meilleure valorisation, captage et séquestration du CO_2 …) Quelle filière évoluera le plus rapidement en termes de performance énergétique et environnementale ?
- Les modèles énergétiques (grid mix pour la production d'électricité notamment) auront certainement évolués d'ici 2059 entrainant ainsi une modification du profil environnemental du béton de ciment et du béton bitumineux.
- Les techniques de revêtements de route évolueront probablement d'ici 2059. On constate par exemple en Europe la mise en œuvre de nouvelles techniques comme par exemple :
    - Les enrobés basse température pour un "petit chantier".
    - Les enrobés à chaud dans lesquels les liants végétaux remplacent le bitume. Ce nouveau procédé permet de réduire les températures de fabrication et d'application de 40°C par rapport aux enrobés classiques.
    - Des produits végétaux, à base d'huiles de colza et de tournesol, utilisés pour la préparation des bitumes fluxés, utilisés comme enduits superficiels. Ils remplacent des produits fluxants qui étaient jusqu'alors fabriqués à partir de produits pétroliers.
    - Le recyclage à froid des enrobés (technique qui consiste à raboter l'ancien enrobé puis à le traiter à froid en y ajoutant des additifs et à le réutiliser pour la nouvelle couche de base de la chaussé).

Avis (BIO) : pour ces différentes raisons, il ne nous semble pas raisonnable de conclure sur le positionnement de l'un ou l'autre type de chaussée à horizon 50 ans dans la mesure ou les profils environnementaux de ces techniques évolueront probablement d'ici 2059. Si cette étude peut servir à alimenter la réflexion de l'Orientation sur les conséquences écologiques des types de chaussées qu'elle retiendra avec un horizon temporel, elle doit inciter les différentes filières à s'engager davantage dans une démarche de progrès d'un point de vue environnemental ; à la fois en incitant à s'engager dans la réduction des impacts environnementaux liés au cycle de vie des chaussées (qui concerne l'étape de production des matériaux, leur mise en œuvre, leur influence sur la consommation des véhicules et leur fin de vie) mais également en les incitant à innover davantage dans les techniques de revêtement routiers.

Réponse du CIRAIG :

Il est vrai que les technologies risquent de varier à l'intérieur des cinquante années considérées. Cependant, personne n'a actuellement le recul nécessaire pour caractériser avec précision l'évolution des techniques de production et le comportement des routes. L'étude effectuée n'est pas prospective et le système technologique à l'étude est considéré statique. Une note a alors été ajoutée aux limites de l'étude à la section 3.2.8 et en conclusion. La note ajoutée indique qu'il est important de noter que les résultats obtenus dans le cadre de cette étude sont fonction d'un système technologique statique sur la période de cinquante ans considérée. Nul n'a actuellement le recul nécessaire pour caractériser avec précision l'évolution dans le temps des techniques de production des matériaux de construction, des technologies de conception et de mise en place des chaussées, et des règlementations environnementales, bien que la compétitivité du marché risque fort probablement de modifier le système étudié, et conséquemment, les résultats de cette étude. Il en suit que plusieurs nouvelles technologies de revêtement émergent, telles que les enrobages à froids, à recyclage facilité, les bitumes modifiés au polymère augmentant la durée de vie du revêtement, etc. Il serait donc recommandable que le MTQ puisse investiguer sur la pertinence environnementale de développer ces innovations des chaussées, si elles sont applicables au contexte canadien.

Avis sur la réponse apportée (BIO) : nous approuvons cette réponse et le complément apporté dans le rapport final.

Recommandation (BIO) : une analyse de sensibilité en tenant compte d'un mix électrique marginal serait un premier élément d'appréciation de l'évolution possible du profil environnemental des différents types de chaussées. Pour cela, les producteurs d'électricité au Québec pourrait être consultés pour tenter d'évaluer quel pourrait être l'évolution probable du mix électrique Québécois (et des autres mix électriques utilisés dans l'étude) d'ici 50 ans.

Réponse du CIRAIG

La consommation d'électricité n'a pas été identifiée comme un élément clé lors de la réalisation de cette étude. Conséquemment, le mix électrique québécois (tout comme les autres mix électriques utilisés dans l'étude) n'est pas un paramètre sensible. En fait, selon les résultats de la modélisation, l'utilisation du *grid mix* québécois (processus *Electricity mix - Qc U*) ne contribue pas plus de 1 % à chacune des quatre catégories de dommages, et ce pour les deux systèmes. Or, comme c'est le système BC qui consomme davantage d'électricité québécoise, (8,44E6 MJ pour le système BC16 et 5,456E6 MJ pour le système BB16, attribuables à la consommation d'électricité québécoise), la prise en compte d'un *grid mix* marginal (qui serait probablement moins propre que le mix Québécois actuel constitué à plus de 90 % d'hydroélectricité) ne ferait qu'augmenter l'écart relatif des indicateurs d'impact en comparatif, ce qui désavantagerait supérieurement le système BC. Les conclusions de l'étude ne seraient aucunement modifiées par cette analyse de sensibilité. Pour ces raisons énumérées ci-dessus, aucune analyse de sensibilité ne sera effectuée sur le paramètre du mélange énergétique.

Avis sur la réponse apportée (BIO) : nous approuvons cette réponse.

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[15] Remarque (BIO) : le tableau 5-8 relatif à la qualification des données appel plusieurs commentaires :

- La note de 1 exprimant le meilleur niveau de qualité des données ne considère pas une validation par tierce partie indépendante.
- La note 2 (« quantité ») qui est donnée pour la production du ciment nous semble trop élevée (pour une échelle allant de 1 à 5) dans la mesure où la comparaison avec des données issues de base de données génériques d'inventaires de cycle de vie (Ecoinvent par exemple) montrent que l'on observe des facteurs d'émissions (CO_2, NOX, SO_2...) variables d'une source à l'autre et que cela influence sensiblement les résultats de l'étude.

Réponse du CIRAIG :

Les notes pour les qualités de données « quantité » pour la production du ciment et pour la production du bitume correspondent à la fiabilité (pour les flux primaires) des quantités de matière et d'énergie inventoriées, de même que des distances de transport et des quantités de rejets selon leur devenir. Ainsi, les quantités de bitume et de ciment requises pour les étapes de construction, d'entretien et de reconstruction ont été fournies par le MTQ, et sont des valeurs actuelles mesurées. La note « 1 » attribuée à la qualité « quantité »pour la production du ciment sera ainsi conservée.

En ce qui concerne les notes pour la qualité « processus » (c.-à-d. tous les flux secondaire liés aux processus d'arrière-plan), il est vrai que la note « 1 » indique un niveau de qualité de la donnée (relative aux aspects quantité, processus et contribution), et non un niveau de qualité relative à une validation par tierces parties. Comme indiqué précédemment, une validation permettrait en effet d'augmenter le niveau de qualité des données employées (ou du moins d'en obtenir une meilleure estimation) et le CIRAIG a clairement communiqué au MTQ l'importance d'impliquer un panel d'experts indépendants à cet effet lors de la réalisation de la revue critique. Les notes pour les qualités de données « processus » pour la production du ciment et pour la production du bitume ont ainsi été modifiées à « 2 » puisque ces processus n'ont pas été validés par une tierce partie indépendante. Par contre, ces notes pour la qualité « processus » (c.-à-d. tous les flux secondaire liés aux processus d'arrière-plan) sont jugées suffisamment conservatrices et ne seront pas incrémentées davantage. En fait, les données obtenues concernant les quantités de consommables liées au processus de la production du ciment on été tirées d'une étude effectuée par l'ACC sur différentes cimenteries canadiennes, et les données sur les trois cimenteries québécoises qui y figuraient ont été utilisées. En ce qui a trait aux émissions, les quantités d'émissions annuelles répertoriées par le gouvernement canadien pour ces trois mêmes cimenteries ont été obtenues. Dans un premier temps, la représentativité géographique et technologique de cette donnée est jugée adéquate puisque le ciment utilisé dans les chaussées au Québec est modélisé à l'aide des données de production au Québec. Dans un deuxième temps, la qualité de l'échantillonnage est jugé élevée puisque les données sont représentatives de 100 % de la population totale (puisque l'échantillon de données correspond aux trois cimenteries existantes au Québec). Dans un troisième temps, les données ont été fournies par l'ACC, et donc provienne d'une source fiable dont l'expertise dans le domaine est reconnue. En outre, les conclusions de l'analyse de sensibilité effectuée sur la donnée de production du ciment indiquaient cependant que, peu importe la donnée employée, les conclusions de l'étude n'étaient pas renversées, c'est-à-dire que bien qu'il en résultait d'une incidence sur les dommages à la santé humaine et à la qualité des écosystèmes, il n'en demeure pas moins que ces diminutions ne permettent pas de discriminer quel système est favorable globalement.

Avis sur la réponse apportée (BIO) : nous approuvons cette réponse sous réserve que les auteurs indiquent dans le rapport d'étude que la note 1 n'intègre pas une vérification par tierce partie.

Réponse du CIRAIG :

Le CIRAIG est d'accord avec cet avis et a ajouté cette précision au Tableau 5-7 du rapport.

3.1.2. Sur l'analyse de l'inventaire de cycle de vie.

[16] Recommandation (BIO) : si les flux de Na+ et Cl- liés à l'utilisation des sels fondants ne sont pas caractérisés dans les méthodes d'évaluation des impacts potentiels sur l'environnement ils doivent être présentés dans le tableau 4-4 du chapitre 4 du rapport final.

Réponse du CIRAIG :

Les conclusions de l'analyse de l'inventaire indiquaient que le système BC générait davantage d'émissions à l'air, à l'eau et au sol que le système BC. La prise en compte de ces sels ne ferait qu'augmenter l'ampleur des émissions totales du système BC en comparaison à celles du système BB. Puisque les conclusions de l'analyse de l'inventaire ne seraient pas modifiées, l'inventaire ne sera pas modifié pour inclure ces substances. Cet aspect est tout de même mentionné dans les limites de l'étude. Une note a cependant été ajoutée au Tableau 4-4 afin de préciser que les émissions dues à l'épandage des sels n'ont pas été considérées et donc, qu'elles ne figurent pas dans le tableau.

Avis sur la réponse apportée (BIO) : cf. réponse [3].

[17] Question (BIO) : quelle est la version d'Ecoinvent utilisée ? la préciser dans le rapport
Réponse du CIRAIG :
La version d'ecoinvent utilisée est la version 2.0. Le rapport a été modifié à la sous-section 3.2.4.1 et au sommaire exécutif afin de préciser la version employée.
Avis sur la réponse apportée (BIO) : nous approuvons cette réponse.

3.1.1. Sur la presentation des resultats des indicateurs d'impacts potentiels sur l'environnement

[18] Recommandation (BIO) : la normalisation des résultats en équivalent habitants des catégories de dommages évaluées par la méthode IMPACT 2002+ permet d'identifier les enjeux environnementaux significatifs. La norme ISO 14 044 requiert que les enjeux environnementaux significatifs soient identifiés.
Par ailleurs, si l'on souhaite apporter une information aux filières considérées sur l'origine des impacts environnementaux, une analyse doit être conduite pour chacun des types de chaussées de manière à identifier les processus élémentaires et les étapes les plus contributrices (y compris les flux élémentaires) aux impacts potentiels sur l'environnement.

Réponse du CIRAIG :
La consigne de la norme ISO 14 044 sur l'identification des enjeux significatifs a été respectée. Une analyse de contribution a été effectuée à la section 5.1.2 et présente les indicateurs de dommage pondérés du profil comparatif (système BC - système BB), désagrégés par étape (processus) du cycle de vie. Cet exercice permet d'identifier les processus élémentaires et les étapes étant les plus grands contributeurs aux impacts du cycle de vie d'une chaussée en béton de ciment comparativement à ceux d'une chaussée en enrobé bitumineux. Il n'est nullement indiqué dans la norme ISO 14 044 que les profils spécifiques de chacun des systèmes doivent être obtenus dans le cadre d'une ACV comparative. Le choix de présenter les profils spécifiques de chacun des systèmes ou bien simplement le profil comparatif découle des objectifs du projet et non de la consigne de la norme ISO 14 044. Le but de cette présente étude est : *de comparer les impacts environnementaux potentiels du cycle de vie des chaussées en béton de ciment de type dalles courtes goujonnées (DCG) à ceux d'une chaussée en enrobé bitumineux.* Le MTQ n'a pas demandé à obtenir les enjeux environnementaux (ou « points chauds ») des deux types de chaussées individuellement, mais bien de la comparaison des deux dernières. Par conséquent, le CIRAIG n'ajoutera pas d'analyses conduites pour chacun des types de chaussées de manière à identifier les processus élémentaires et les étapes les plus contributrices (y compris les flux élémentaires) aux impacts potentiels sur l'environnement.
Avis sur la réponse apportée (BIO) : nous comprenons que la réalisation d'une telle analyse ne rentre pas dans le cadre du mandat entre le CIRAIG et le MTQ.

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[19] Recommandation (BIO) : les résultats obtenus par la méthode de Monte Carlo doivent être utilisés pour encadrer les résultats des scénarios de références avec des valeurs minimum et maximum (ceci permettra d'identifier d'éventuels chevauchements entre les différents indicateurs et ainsi identifier les indicateurs sur lesquels il n'y a pas de positionnement clair des deux types de chaussées).
Réponse du CIRAIG :
Le CIRAIG est en accord avec cette recommandation. Les barres d'erreurs ont été ajoutées à la Figure I du sommaire exécutif. Par contre, il n'était pas possible d'ajouter des barres d'erreurs lorsque la catégorie de dommage de la consommation des ressources distinguait la part d'énergie inhérente du

bitume. La Figure I a donc été modifiée pour illustrer l'impact total de la catégorie ressources (en ne distinguant pas la part d'énergie inhérente du bitume), et la Figure II a été ajoutée afin de bien illustrer la part d'énergie inhérente du bitume, sans toutefois présenter les barres d'erreur.
Avis sur la réponse apportée (BIO) : nous approuvons cette réponse.

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[20] Remarque (BIO) : les résultats chiffrés des analyses de sensibilité ne doivent pas être fournis uniquement dans les annexes.
Proposition (BIO) : pour les analyses de sensibilité relatives à l'origine des inventaires de cycles de vie, nous proposons aux auteurs que les résultats d'un cas type du scénario de référence (le 16 par exemple) soit présentés comme référence (en base 100) et que les résultats des analyses de sensibilité soient calculés en conséquence et présentés dans le même graphique. Cette proposition de restitution vaut également pour les analyses de sensibilité, sauf celles ayant trait aux méthodes d'évaluation des impacts.
Réponse du CIRAIG :
Cette proposition de présentation des résultats ne permettrait pas de mieux comprendre les analyses de sensibilité et ne changerait pas la façon dont sont présentées les conclusions de chacune des analyses de sensibilité individuelles. Pour cette raison, et fautes de ressources supplémentaires disponibles à la réalisation du projet, le CIRAIG ne procédera pas à une restitution de la présentation des résultats des analyses de sensibilité.
Avis sur la réponse apportée (BIO) : cette modalité de présentation largement employée dans de nombreuses études ACV a comme intérêt de faciliter la compréhension des résultats. Nous comprenons que les ressources allouées au CIRAIG ne permettent pas de prendre en compte cette proposition.
Réponse du CIRAIG :
À noter que les résultats des analyses de sensibilité sont tout de même disponibles à l'annexe F du rapport.

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[21] Proposition (BIO) : pour les analyses de sensibilité relatives aux différentes méthodes d'évaluation des impacts potentiels sur l'environnement, nous proposons qu'elles soient présentées, dans le rapport, selon le même mode de présentation du tableau 5-2 page 34 du rapport, ce qui permettrait de mieux visualiser si les tendances sont modifiées en fonction de la méthode retenue.
Réponse du CIRAIG :
Puisque les tendances ont été expliquées clairement pour chacune des analyses de sensibilité, le CIRAIG ne croit pas qu'il est nécessaire de présenter un tableau sommaire additionnel au rapport. Ainsi, afin de minimiser le nombre de tableaux et figures inclus dans le rapport, et fautes de ressources supplémentaires disponibles à la réalisation du projet, le CIRAIG ne présentera pas le tableau proposé.
Avis sur la réponse apportée (BIO) : nous comprenons que les ressources allouées au CIRAIG ne permettent pas de prendre en compte cette proposition.

3.1.1. Sur les conclusions de l'etude

Avis (BIO) : nous souhaitons disposer des modifications et des réponses apportées aux questions avant d'émettre un avis sur les conclusions du rapport.
Réponse du CIRAIG :
Le CIRAIG modifiera la conclusion lorsque le réviseur émettra l'avis.

Avis de BIO sur la conclusion du rapport final de septembre 2009.

La conclusion et les résultats sont cohérents avec l'objectif de l'étude. La conclusion de l'étude reflète bien les résultats obtenus au regard des hypothèses et données utilisées. Les limites de l'étude et les limites inhérentes à la méthode des ACV sont clairement évoquées ce qui répond bien aux exigences des normes ISO.

Une seule réserve porte sur la proposition de reboisement des bords de route : si la plantation d'arbres ou d'arbustes sur le bord de route permet une séquestration de CO_2, une telle proposition ne peut se faire qu'en regard d'une analyse sur la conséquence en termes de risques pour la sécurité routière. Il serait par ailleurs utile de préciser une source confirmant les effets d'une telle mesure sur la consommation de carburant des véhicules.

COMPARATIVE LIFE-CYCLE ASSESSMENT OF CEMENT CONCRETE PAVEMENT AND ASPHALT PAVEMENT FOR THE PURPOSES OF INTEGRATING ENERGY AND ENVIRONMENTAL PARAMETERS INTO THE SELECTION OF PAVEMENT TYPES

Sponsor: Ministère des Transports du Québec
Study author: CIRAIG
Final report, September 28, 2009. Final version integrating the comments of the critical review.

CRITICAL REVIEW REPORT

As part of the critical review mission that was entrusted to us by the ministère des Transports du Québec, we provide you with our report on the information and knowledge acquired as part of the study on the comparative life-cycle assessment of cement concrete pavement and asphalt pavement for the purposes of integrating energy and environmental parameters into the selection of pavement types.

The environmental impacts of both types of pavement—asphalt concrete and cement concrete—were obtained by CIRAIG, which completed the life-cycle assessments between 2008 and September 2009. Life-cycle assessment is an accounting method for determining the environmental impacts of systems that are clearly defined and designed so as to facilitate their comparison. It consists in performing a complete assessment of the amount of materials and energy extracted and discharged along the entire system, from raw materials production to waste treatment.

The results are presented in the study's final report, which was submitted by CIRAIG in March 2009 and then amended in September 2009 following the first critical review note. The review committee is tasked with expressing an opinion on this latest version of the report, based on:

- The verification of conditions under which the life-cycle assessments were performed, as transcribed in the final report submitted by CIRAIG;
- The specific verifications and general requirements provided for by international standards related to life-cycle assessment.

SPECIFIC VERIFICATIONS AND INFORMATION

We carried out our critical review based on international standards related to life-cycle assessment (ISO 14040 to 14044). These standards require the adoption of due diligence measures to obtain reasonable assurance that the environmental accounts obtained through the life-cycle assessments are free from any significant anomalies. A critical review consists in systematically examining the accuracy and coherence of evidence used to support the data contained in those accounts. It also includes assessing the accounting principles followed and the main assumptions made to establish environmental impacts, as well as assessing their overall presentation.

We carried out our mission from January 2009 to September 2009, with our role consisting in verifying that:

- The methods used to perform the life-cycle assessment are consistent with ISO 14040 series standards;
- The assumptions, methodological principles and models used to carry out the life-cycle assessment are technically and scientifically sound;
- The data used is appropriate and reasonable considering the study's objective;
- The interpretations provided reflect the study's identified limitations and objective;
- The overall presentation of the study's final documents (final report and summary report) is transparent and coherent.

The verifications we made are discussed in the review note sent to CIRAIG in April 2009. In order to integrate the comments from the review, CIRAIG chose to revise the March 2009 report.

We believe our verifications provide a reasonable basis for the opinion expressed below on the environmental accounts found in the final version of the final report, which integrates the comments from the review and was received on September 28, 2009.

OPINION ON THE ENVIRONMENTAL ACCOUNTS PRESENTED

We confirm that:

- The methods used by CIRAIG are consistent with the ISO 14040 and ISO 14044 standards related to life-cycle assessments, and that the environmental accounts are in order and transparent;
- The methods used by CIRAIG are technically and scientifically sound;
- The interpretations accurately reflect the limitations identified in the study;
- The report is transparent and coherent;
- The executive summary of the study adequately reflects the study's findings and limitations.

The author of the critical review recommends paying special attention to the temporal representativeness of the data used, as well as the techniques chosen for the study. It does not seem reasonable to make a conclusion on the positioning of either type of pavement over a 50-year horizon, since the environmental impacts are based on current production techniques and data, which will likely evolve over the next 50 years. While this study may guide the Policy's reflection on the environmental impacts of chosen pavement types, it must encourage the different industry sectors to get further involved in steps undertaken to achieve environmental progress, both by encouraging them to commit to reducing the environmental impacts of pavement life cycles (which includes the production of materials, pavement placement, pavement influence on vehicle fuel consumption and end-of-life pavement management) and by encouraging sectors to further innovate in road pavement techniques.

To promote a better understanding of results by readers who are not life-cycle assessment experts, we wish to recall that the indicators used to assess environmental impacts describe potential impacts, not actual phenomena. There is still no scientific basis that can be used to estimate the likelihood that the potential impacts assessed will actually materialize. The environmental impacts presented in the study describe the intensity of environmental changes initiated throughout the life cycle of pavement types; it is in those terms that the strengths and weaknesses of both types of pavement can be correctly interpreted.

Yannick Le Guern
BIO Intelligence Service
September 30, 2009

Three stakeholder groups were also consulted to get their opinion of the study conducted for the MTQ, namely:

- For the cement industry:
  - Pierre-Louis Maillard, Cement Association of Canada (CAC)
- For the asphalt industry:
  - Catherine Lavoie, Bitume Québec (BQ)
  - René Dufresne, Petro-Canada
- For the road construction industry:
  - Charles Abesque and Olivier Bouchard, Québec Road Builders and Heavy Construction Association (QRBHCA).

Their comments on the study appear below, along with the responses given.

Réponses aux commentaires et questions de l'ACC suite à la présentation du renouvellement de l'orientation du MTQ sur le choix des types de chaussées du 25 juin 2009

1 - Le premier point qui a déjà été soulevé et dont la réponse ne figure pas dans la présentation du 25 juin 2009 concerne la façon dont l'énergie et les émissions des raffineries ont été associées à la portion bitume. De plus, les informations sur ce sujet fournies par Pétro Canada et Bitume Québec sont-elles comparables aux données génériques et si non, lesquelles ont été utilisées dans l'ACV?

Concernant les données sur la production de bitume : le CIRAIG a utilisé les données fournies par Pétro-Canada et Bitume Québec mais a également réalisé des analyses de sensibilité avec des données d'autres origines : données issues de la base de données Eco-Invent et données d'Eurobitume. Les données de ces différentes sources diffèrent car les règles méthodologiques utilisées pour les établir diffèrent. Cette analyse de sensibilité permet donc de voir si le positionnement des deux types de chaussées diffère selon l'origine des données sur la production de bitume. Les résultats de cette analyse ont montré que si les résultats en valeur absolue changent en fonction de l'origine des données, le positionnement des deux types de chaussées ne s'en trouve pas modifié.

Les données de consommation sur la production de bitume, représentatives de l'ensemble des raffineries de Montréal, ont été spécifiées sur la base de la raffinerie Pétro-Canada de Montréal (données fournies par M. René Dufresne). Les émissions associées à la raffinerie ont été tirées du site de l'Inventaire national des rejets de polluant (INRP) d'Environnement Canada pour l'année 2006, les facteurs de mises à l'échelle de celles-ci au kilogramme de bitume ont été fournis par M. Dufresne. Plus précisément, la consommation d'énergie totale annuelle de la raffinerie et la consommation d'énergie pour la production de 1 kg de bitume ont été spécifiées, ce qui a permis de convertir les données annuelles d'émissions et d'obtenir les émissions par kilogramme de bitume produit.

2 - À la figure 1, pourquoi le « Marquage » est isolé dans un bloc au dessus des autres? Les matériaux de marquages peuvent être considérés au même titre que les autres dans les cases « PRODUCTION MATÉRIAUX DE CONSTRUCTION » et » MISE EN PLACE » des blocs « CONSTRUCTION, ENTRETIEN et RECONSTRUCTION ».

Concernant les schémas de présentation des étapes du cycle de vie considérées (figure 1) : il ne s'agit que d'une présentation visuelle.

Le schéma concorde avec la façon dont la modélisation a été effectuée et avec la façon dont les données ont été fournies. La modélisation des systèmes aurait tout de même pu être réalisée de manière à inclure la boîte «marquage» dans les boîtes «construction», «entretien» et «reconstruction», bien que ceci ne change aucunement les résultats obtenus, mais seulement la façon de les présenter.

3 - Dans le cas de la reconstruction du revêtement durant la période de 50 ans, quels sont les impacts qui ont été considérés dans l'analyse: la totalité ou seulement une proportion? Par exemple dans le cas d'une reconstruction à la 47ème année, tous les impacts ont-il été considérés ou seulement 3/47èmes?

Concernant la reconstruction du revêtement pour arriver à une période de 50 ans : les impacts sont effectivement calculés au prorata de la durée nécessaire pour arriver à 50 ans (3/47ème dans votre exemple).

Plus particulièrement, comme la reconstruction peut intervenir à différents moments pour les seize cas-types, les impacts environnementaux de cette dernière ont été imputés aux systèmes de produits au prorata des années incluses dans la période de cinquante ans considérée dans la présente étude sur la durée de vie de la chaussée reconstruite.

Par exemple, pour le cas-type 16 pour la chaussée en béton de ciment, la reconstruction est multipliée par un facteur 4/46, soit le nombre d'années permettant d'atteindre le cycle de 50 ans considéré divisé par la durée de vie de la dalle de béton reconstruite.

4- La présentation mentionne que les fumées de bitume n'ont pas été prises en compte lors de la production et de la mise en place de l'enrobé bitumineux. Qu'en est-il de l'énergie et des autres émissions associées aux usines d'asphalte? Ont-t-elles été considérées? De plus l'ACC a transmis un document NIOSH 01-110 Health Effects of Occupational Exposure to Asphalt où étaient identifiées toutes les substances émises dans les fumées de bitume et /ou d'asphalte.

La prise en compte de l'énergie et des différentes émissions (autres que les fumées de bitume) liées à la production de bitume et à la mise en place de l'enrobé ont bien été prises en compte dans l'étude et via les différentes analyses de sensibilité réalisées (cf. réponse 1). En particulier, les données sur la production d'enrobé bitumineux ont été fournies par l'ACRGTQ. L'énergie consommée durant la production de l'enrobé a été déterminée en combinant les informations fournies par M. Olivier Bouchard de l'ACRGTQ à celles tirées du rapport Road Rehabilitation Energy Reduction Guide for Canadian Road Builders de Ressources Naturelles Canada (2005).

Concernant les fumées de bitume, toutefois, aucune émission à l'usine d'enrobé n'a été considérée, faute d'un manque de données. En effet, bien que le document « *Health Effects of Occupational Exposure to Asphalt* » identifie toutes les substances émises dans les fumées de bitume et /ou d'asphalte, les quantités exactes pouvant être émises ne sont pas connues. Or,

Suite à une revue succincte des informations disponibles sur les fumées de bitume, il a été trouvé que le benzo(a)pyrene est l'HAP le plus cancérigène pour l'homme et peut être présent dans le bitume à une concentration allant jusqu'à 5,53 µg/g (Huynh et al.)[1]. Il a donc été décidé d'ajouter cette quantité de benzo(a)pyrene aux émissions à l'air associées à la production d'enrobé (selon la quantité de bitume contenue dans l'enrobé).

Les conclusions de l'analyse de sensibilité démontrent qu'un ajout important des émissions d'HAP ne modifie pas les conclusions de l'étude. Bien que la différence entre les deux systèmes quant à l'indicateur de santé humaine diminue, le système BB est alors toujours favorisé pour cette catégorie de dommage (et les autres indicateurs demeurent inchangés).

5 - Au niveau de la présentation des résultats du tableau II, celle-ci, tout d'abord ne permet pas de visualiser dans chacune des catégories l'écart réel entre le BB et le BC. Toute l'information serait donnée en présentant les résultats, pour les 16 cas types, selon la figure 3-4.4 page 11 du document IMPACT 2002+ USER GUIDE (version 2.1 d'octobre 2005) (Voir page ci-dessous). Le même commentaire s'applique aussi pour le regroupement des 4 catégories de dommages et dont on ne connait pas la pondération des différentes catégories d'impacts qui le compose (Voir page ci-dessous figure 3-4.5). D'autre part, le choix de couleur de ce tableau devrait être modifié car il illustre en rouge les éléments favorables au béton !

Concernant la présentation des résultats, une proposition telle que celle de votre document a été proposée au CIRAIG. Celui-ci n'avait pas les ressources nécessaires (en termes de temps) pour présenter les résultats sur ce type de format car cela nécessite de modifier le modèle de calcul. En effet, les profils ne sont pas individuels (profil pour le système BC et profil pour le système BB) mais de type comparatif (Système BC – Système BB), et certaines données utilisées pour la modélisation concernent les variations entre les deux systèmes, et non les valeurs exactes pour chacun des deux systèmes. Ceci avait été établi avec le MTQ que l'ACV serait de type comparatif, et l'unité fonctionnelle concerne le cycle de vie d'une chaussée en béton de ciment comparativement à une chaussée en enrobé bitumineux.

Il a été convenu avec le MTQ qu'il était plus parlant de présenter les résultats aux Endpoints, c'est-à-dire pour les quatre indicateurs de dommage. Puisque deux catégories d'impacts ne sont pas contenues dans ces dommages, le CIRAIG a choisi de les présenter aussi dans les résultats finaux.

6 - En comparant qualitativement les résultats du CIRAIG avec ceux de CIMBÉTON qui compare sensiblement les même indicateurs, comment se fait-il qu'il y ait des résultats très différents d'autant plus que cette étude à utilisé les résultats d'Eurobitume pour les chaussées en enrobé? Voir conclusions 3 et 4.

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[1] HUYNH, C.K., VU DUC, T., LE COUTALLER, P., F. SURMONT, F. et DEYGOUT, F. Exposition professionnelle aux HAP dans le bitume et dans la fumée de bitume - analyse des HAP par gc-ion-trap ms et hplc-fluorescence. Lausanne, Institut universitaire romand de la Santé au Travail.

De manière général, il n'est pas aisé de comparer des résultats d'analyses de cycle de vie sans avoir accès à l'ensemble des hypothèses et données utilisées.

Le système BB de l'étude du CIRAIG est en fait aussi plus favorable aux impacts réchauffement climatique, eutrophisation (à part pour les cas 8, 12 et 16) et toxicité humaine non-cancer. Le Système BC de l'étude du CIRAIG est aussi plus favorable à l'indicateur de dommage de l'utilisation des ressources.

Par contre, certaines conclusions ne sont pas en accord : la donnée d'inventaire indique que c'est le Système BC qui consomme le plus d'eau et qui possède des indicateurs d'impact d'acidification et d'écotoxicité aquatique plus élevés.

Toutefois, la méthodologie qui a été employée pour l'étude de CIMBÉTON comporte plusieurs lacunes :

- La modélisation est effectuée en utilisant une base de données datant de 1996 (Oekoinventare 1996) ;
- La méthode EQUER employée pour obtenir les indicateurs n'est pas une méthode ACVI reconnue par la communauté scientifique en ACV. En fait, le document «International Reference Life Cycle Data System (ILCD) Handbook»
du European Platform on LCA (présentement en consultation) discute des méthodes ACVI à utiliser en ACV, et la méthode ÉQUER n'y figure par (voir site http://lct.jrc.ec.europa.eu/eplca/deliverables/consultation-on-international-reference-life-cycle-data-system-ilcd-handbook).
- Aucun document de «peer review» n'est disponible pour cette méthode, et aucun support scientifique de cette méthode n'a pu être trouvé.
- Le choix des indicateurs semble aléatoire, et n'est pas expliqué dans le champ de l'étude de l'ACV. De plus, les indicateurs ne sont pas tous des indicateurs d'impact. Il ne faut pas mélanger les indicateurs d'inventaire (énergie, eau) avec les indicateurs d'impact.
- L'indicateur déchet n'a pas de sens. Les déchets sont traités à l'intérieur des frontières du système, et donc sont déjà compris dans l'inventaire.
- En ACV, aucun indicateur pour l'impact odeur n'a à ce jour été développé. Aucune explication sur le développement de cet indicateur dans ÉQUER n'a pu être trouvée.

Il est aussi important de spécifier que les systèmes de l'étude CIMBÉTON et de l'étude du CIRAIG ne sont pas les mêmes. De plus, les hypothèses et données employées pour la modélisation des systèmes des deux études ne sont pas équivalentes.

7- Dans la production de ciment, l'étude a-t-elle considéré le fait que les cimenteries utilisent des combustibles alternatifs qui autrement seraient incinérés ou enfouis et contamineraient ainsi l'air, les sols et les eaux? Au Québec les combustibles alternatifs représentent aujourd'hui 26% de l'énergie utilisée pour la production de ciment et dans un proche avenir représenteront environ 50%.

Oui, les données de l'étude d'Athéna incluaient des combustibles alternatifs qui ont été intégrés à la modélisation du processus de production du ciment.

8- Pour la production de béton, a-t-on considéré l'utilisation de ciment ternaire dans lequel il y a environ 30% de matières post industrielles recyclées (fumée de silice, laitier et cendres volantes) ce qui diminue l'intensité énergie et émissions de CO2 associée à la production de ciment?

Oui, les mélanges de béton de ciment utilisés pour les chaussées sont les types IIIA et IIIB et un ciment ternaire a été considéré. La recette du béton de ciment incluait de la fumée de silice, des cendres volantes et du laitier.

9-Est-ce que le CIRAIG a considéré les effets sur la santé humaine des fibres d'amiante contenues dans certains mélanges d'asphalte?

Le type d'enrobé considéré dans l'étude est l'enrobé typiquement employé par le MTQ sur les routes. Les recettes d'enrobé qui ont été transmises ne comportaient pas d'amiante.

Valeur intrinsèque du bitume

À l'intérieur de son étude ACV comparant les chaussées en bitume à celles fabriquées en béton, le modèle (LUCAS) considère que le bitume utilisé et ultimement intégré à la chaussée, constitue une ressource non-renouvelable consommée par le processus de fabrication de la route.

Nous sommes d'avis que ce postulat du modèle est erroné et offrons les points suivants pour supporter notre position que la seule portion de la ressource que représente le bitume qui soit imputable à la construction de la chaussée est la perte d'enthalpie que le bitume subit au cours du vieillissement de la chaussée, soit moins de 5% du contenu original.

1. La valeur intrinsèque du bitume possède deux branches: comme « colle » et comme « combustible ». S'il est vrai que le bitume perd certaines propriétés agglutinantes en vieillissant, il n'en demeure pas moins que le bitume des chaussées peut être régénéré et réutilisé. Encore plus important, sa valeur comme combustible est à peine réduite.

2. La valeur intrinsèque du bitume ne dépend pas de sa position géographique. Que la ressource soit à 2,500 mètres sous la mer dans une formation rocheuse ou dans une pile de 20 mètres près d'une carrière, la masse de bitume représente la même ressource.

3. Même s'ils existent de nombreux procédés de « revalorisation » des fractions lourdes du pétrole tel le bitume, la revalorisation ne vise qu'à changer la qualité de l'énergie : d'un mazout lourd que seuls les navires et larges industries peuvent utiliser, au diesel et l'essence pour les consommateurs. En passant, l'extraction du bitumen des sables bitumineux s'apparente assez bien à l'extraction du bitume des chaussées. Si nous croyons que les sables bitumineux sont une ressource, alors nous croyons aussi que le bitume des chaussées **est** une ressource, non a été une ressource.

4. La valeur imputée à l'utilisation (consommation) du bitume, semble correspondre au contenu calorifique (enthalpie) du bitume utilisé. Si c'est le cas, alors le processus devrait recevoir un crédit pour l'enthalpie résiduelle à la fin du cycle d'utilisation.

À mon avis, la portion effectivement consommée de la ressource qu'est le bitume, est représentée par la perte d'enthalpie que le bitume subit lors de son vieillissement par les rayons ultra-violets et l'oxydation qui en résulte. Je n'ai pas cette valeur que j'estime à < 5% de l'enthalpie initiale. Mais je vais la trouver et si nécessaire la faire mesurer.

René Dufresne, Ing.

Réponse

L'énergie primaire non renouvelable exprime les quantités de ressources naturelles énergétiques non renouvelables (tel que le pétrole, le charbon, le gaz, l'uranium…) puisées dans l'environnement et qui sont mobilisées à chacune des étapes du cycle de vie du produit. Elle est exprimée dans une unité énergétique (en général en MJ) en tenant compte du contenu énergétique des différentes ressources (Pouvoir Calorifique Inférieur ou PCI). La quantité de pétrole entrant dans la composition « matérielle » du bitume contribue à diminuer la ressource pétrole. Celle-ci est exprimée au travers de l'énergie « feedstock ». Cette énergie « feedstock » n'est pas perdue dans la mesure où elle peut être récupérée en fin de vie par un processus de valorisation énergétique (c'est le cas par exemple pour les emballages en matière plastique). Il est donc nécessaire de considérer cette énergie « feedstock » dans le bilan énergie primaire. Nous approuvons donc le choix qui a été fait par les auteurs de l'étude d'intégrer cette énergie dans les bilans environnementaux des deux types de chaussées. Ce choix est conforme à la méthode IMPACT 2002+.

Par ailleurs, pour répondre à cette question précise, le CIRAIG a pris le soin de faire une analyse de sensibilité pour évaluer l'influence de la prise en compte de l'énergie inhérente du bitume. Les résultats de l'analyse sans la prise en compte de cette énergie inhérente sont présentés dans les résultats de l'étude (tableau II de la page 7 de la synthèse remise le 25 juin à l'issue de la présentation de l'étude par le CIRAIG).

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435, Grande Allée Est
Québec (Québec)
G1R 2J5

Téléphones
(418) 529-2949
1 800 463-4672
Télécopieur
(418) 529-5139

Bureau de Montréal
SECTEUR RELATIONS DU TRAVAIL

7905, boul. Louis-Hippolyte-Lafontaine
Bureau 101 A
Anjou (Québec)
H1K 4E4

Téléphones
(514) 354-1362
1 877 903-1362
Télécopieur
(514) 354-1301

Internet
Site
www.acrgtq.qc.ca
Courriel général
acrgtq@acrgtq.qc.ca

Le 1er juillet 2009 PAR COURRIEL

Monsieur Yannick Le Guern
BIO Intelligence Service S.A.S.
1, rue Berthelot
94200 Ivry-sur-Seine
France

Objet : Commentaires sur l'étude ACV

Monsieur,

Pour les commentaires spécifiques reliés à chaque matériau touché par l'ACV et pour une question de neutralité de notre part, nous laisserons les industries respectives se prononcer par eux-mêmes sur la question.

De notre côté, nous considérons que la présente étude ACV a été menée avec sérieux et rigueur compte tenu des restrictions imposées par le ministère des Transports du Québec et des intrants disponibles. Il aurait toutefois été intéressant de voir le degré de sensibilité sur les résultats obtenus si, premièrement, la matière première utilisée pour la fabrication du bitume avait été considérée comme non consommée au lieu de consommé et si deuxièmement le béton armé continu (BCR) avait été pris en compte, ce qui représentait deux points de désaccord de la part des industries.

Il serait crucial également dans l'avenir, lorsqu'il y aura consensus de la part de la communauté scientifique sur le sujet, de prendre en compte une éventuelle réduction de consommation de carburant en fonction des types de chaussées, ce qui pourrait bouleverser totalement les résultats de la présente étude.

Espérant que ces quelques commentaires seront appréciés à leur juste valeur, veuillez recevoir, Monsieur, nos salutations distinguées.

Charles Abesque, ing., Ph. D.
Secteur Sciences et techniques

CA/lp

c. c. : Pierre Tremblay, ing., dir. général adjoint – Secteur Sciences et techniques, ACRGTQ
Olivier Bouchard, ing. jr, ACRGTQ

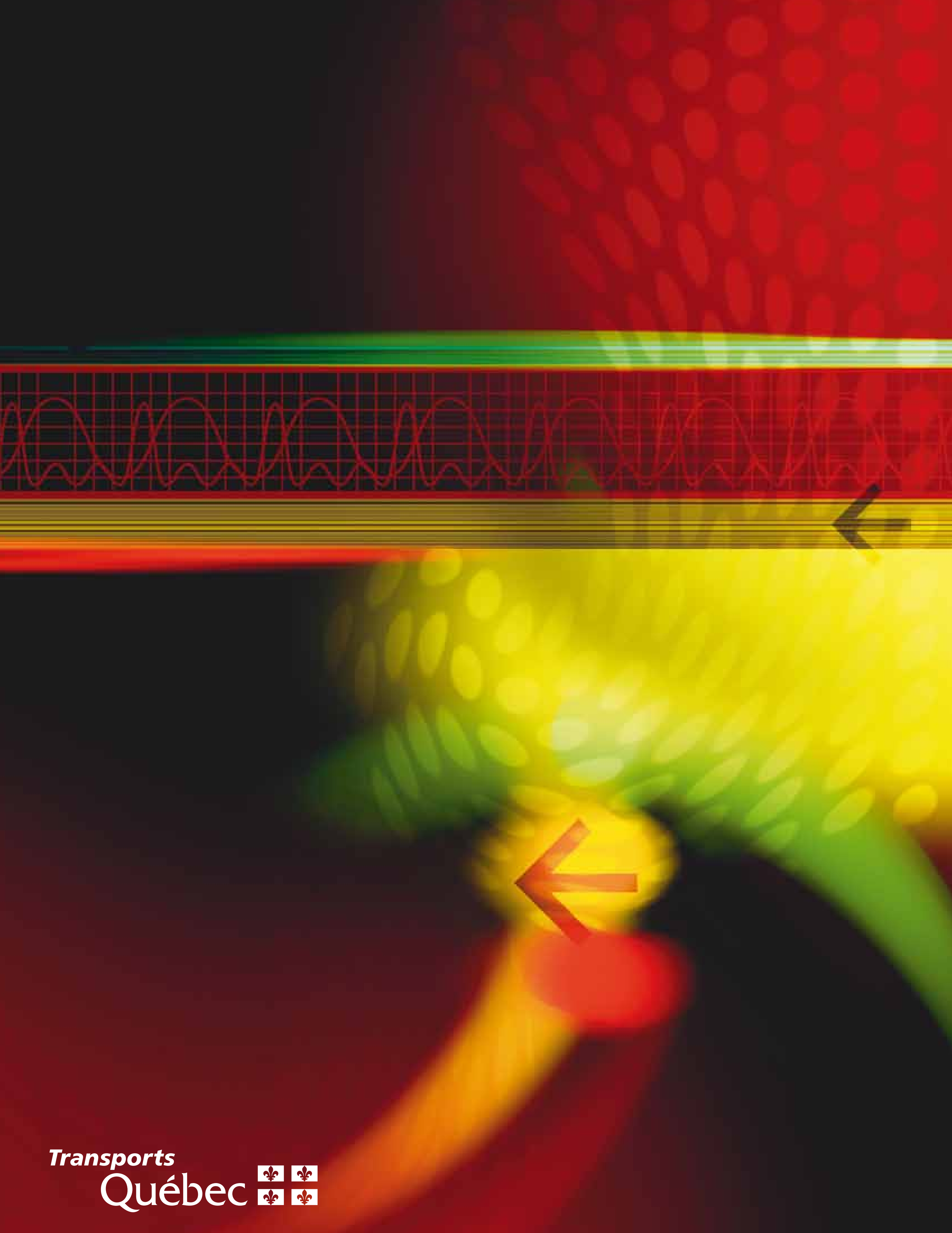
Réponse

Le 7 août 2009

Pour répondre à la question de l'énergie inhérente du bitume, le CIRAIG a pris le soin de faire une analyse de sensibilité pour évaluer l'influence de la prise en compte de l'énergie inhérente du bitume. Les résultats de cette analyse sont présentés dans les résultats de l'étude (tableau II de la page 7 de la synthèse remise le 25 juin à l'issue de la présentation de l'étude par le CIRAIG).

Par ailleurs, l'influence de la technique du béton armé continu a bien été évaluée par le CIRAIG dans une analyse de sensibilité (cf. page 9 et 10 de la synthèse remise le 25 juin).

Yannick Le Guern
BIO Intelligence Service



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