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LISTE DES ABRÉVIATIONS, SIGLES ET ACRONYMES

ACV	Analyse du cycle de vie
ACCV	Analyse des coûts sur le cycle de vie
AADT	Débit journalier moyen annuel (Annual Average Daily Traffic)
AFSSE	Agence française de sécurité sanitaire environnementale
CBA	Analyse coûts-bénéfices (Cost-Benefit Analysis)
CO	Monoxyde de carbone
CO_2	Dioxyde de carbone
FHWA	Administration fédérale des routes (Federal Highway Administration)
FQRNT	Fonds québécois de la recherche sur la nature et les technologies
HC	Hydrocarbure
HDM-4	Système de développement et de gestion des routes (Highway Development and Management)
IPA	Méthode du cheminement d'impact (Impact Pathway Approach)
LCA	Analyse du cycle de vie (Life Cycle Analysis)
LCCA	Analyse des coûts sur le cycle de vie (Life Cycle Cost Analysis)
MTQ	Ministère des transports du Québec
NOx	Oxyde d'azote
NPV	Valeur actuelle nette (Net Present Value)
PEIM	Modèle des impacts environnementaux des chaussées (Pavement Environmental Impact Model)
PM	Particule de matière
$PM_{2.5}$	Particule de matière de diamètre supérieur à 2,5 micromètres
PM_{10}	Particule de matière de diamètre supérieur à 10 micromètres

PMS	Pavement Management System
RBC	Ratio bénéfices-coûts
SAAQ	Société d'assurance automobile du Québec
SO_2	Dioxyde de soufre
TNM	Modèle de bruit routier (Traffic Noise Model)
TRI	Taux de rendement interne
UN	Nations Unies (United Nations)
VAN	Valeur actuelle nette
VOC	Composé organique volatil (Volatile Organic Compound)
WHO	Organisation mondiale de la santé (World Health Organization)

LISTE DES SYMBOLES ET UNITÉS DE MESURE

%HV	Pourcentage de véhicules lourds, en pourcentage
D_{RR}	Distance entre la chaussée et le récepteur (Distance from receptor to road), en m
IRI	Indice de rugosité international (Internation Roughness Index), en m/km
Lden	Indicateur du niveau de bruit global pendant une journée complète, en dBA

INTRODUCTION

Il est désormais internationalement reconnu que les transports ont des impacts importants sur leur environnement (United Nations, 2001; WHO, 2000). Plus particulièrement, le transport routier est responsable de nombreuses nuisances. Boiteux (2001) rapporte entre autres : la pollution atmosphérique, les changements climatiques, le bruit, la dégradation du cadre de vie, ainsi que les coûts aux usagers (coûts d'exploitation des véhicules, retards, accidents, etc.).

La qualité de l'air est ainsi une préoccupation majeure pour les organismes de santé publique (Kunzli et al., 2000). De nombreuses études montrent l'influence importante qu'exercent les rejets de gaz polluants sur la santé des populations vivant à proximité des routes (voir par exemple Han et Naeher, 2006; Kongtip et al., 2006; Kunzli et al., 2000; Roussou et Behrakis, 2005; World Health Organization (WHO), 2013). En effet, la circulation routière engendre d'importants rejets tels que le monoxyde de carbone, les hydrocarbures et oxydants photochimiques, les oxydes d'azote, les particules volatiles, et le dioxyde de soufre (Ising, Lange-Asschenfeldt et Eilts, 2005; Kunzli et al., 2000; Wright et Dixon, 2004).

Parmi les gaz émis par la circulation routière, les gaz à effet de serre (notamment le dioxyde de carbone) contribuent aux changements climatiques qui entraînent des coûts sociaux importants (IPCC, 2007). Le protocole de Kyoto a d'ailleurs mené à l'émergence d'une valorisation du carbone des gaz à effet de serre émis dans l'atmosphère (Schreyer et al., 2004). Il est désormais acquis que le secteur du transport, et plus particulièrement celui du transport routier, contribue pour une large part à ces émissions via la consommation de carburant (IPCC, 2007).

De même, le bruit de la circulation routière a une influence néfaste sur la santé des individus. Il cause des problèmes cardiovasculaires et empêche un sommeil profond chez les personnes exposées chroniquement au bruit (Babisch, 2005a; Kim et al., 2012; Passchier-Vermeer et Passchier, 2005; van Kempen et Babisch, 2012). Outre ces effets physiologiques facilement décelables, le bruit est suspecté d’engendrer de nombreux problèmes d’ordre psychologique (Moshammer, Hutter et Schmidt, 2005). Par ailleurs, le bruit est susceptible de diminuer la concentration des gens lors de leurs activités. Cette perturbation de la concentration peut induire une diminution de la productivité des populations riveraines des routes, ce qui entraîne à son tour un manque à gagner pour la société (Miedema, 2007).

Encore bien d’autres nuisances reliées au transport routier, autres que celles mentionnées précédemment, existent même si elles sont moins extensivement étudiées. Parmi les impacts reliés à ces nuisances, il y a, par exemple, la pollution des sols par le ruissellement des précipitations sur les chaussées (Fletcher, Andrieu et Hamel, 2013) et la fragmentation de l’habitat naturel de la faune (Nega et al., 2012).

Le type de matériau utilisé pour le revêtement de la chaussée, la texture de ce revêtement ou encore son uni sont autant de caractéristiques impliquées dans les mécanismes d’émission des nuisances (China et James, 2012; Liao et al., 2014). Par conséquent, l’envergure et l’intensité des impacts environnementaux liés aux nuisances émises par la circulation routière sont influencées de façon significative par les caractéristiques des chaussées sur lesquelles les véhicules circulent. Or, les caractéristiques des chaussées en général et l’état du revêtement des chaussées en particulier résultent des choix de gestion des administrations en charge du maintien de l’état des réseaux routiers. Il apparaît donc que la gestion des chaussées a la capacité de moduler les divers impacts environnementaux issus de la circulation routière.

Toutefois, ces impacts environnementaux dépassent largement les champs de compétence et de réflexion traditionnels des administrations routières. Ainsi, dans la pratique, les administrations routières qui prennent en compte les impacts environnementaux liés à leurs décisions de gestion sont très rares (Chan, Keoleian et Gabler, 2008; Gosse, Smith et Clarens, 2013). Les impacts environnementaux induits par leurs activités de gestion sont en effet souvent considérés comme étant hors de leur champ de compétence (Chan, Keoleian et Gabler, 2008). Pourtant, ces impacts environnementaux ont une réelle répercussion sur la société, induisant des coûts importants tels que, par exemple, les dépenses de santé pour soigner les maladies liées au bruit ou à la pollution atmosphérique (Haucke et Brückner, 2010), les pertes de production agricole liées à la pollution des sols et de l'atmosphère (van Essen et al., 2011), les dépenses de réfection des façades des bâtiments affectés par la pollution atmosphérique (Rabl et Spadaro, 1999) et les manques à gagner dus à la baisse de productivité des personnes gênées par le bruit (Miedema, 2007). Au final, ces coûts, dus à l'exploitation des réseaux routiers, sont supportés par les individus bien que ceux-ci n'aient aucun contrôle sur les nuisances qui en sont à l'origine.

Ainsi, si une solution de gestion est considérée comme optimale par l'administration routière, cette solution peut ne pas s'avérer optimale pour la société dans son ensemble. Pourtant, la planification des systèmes de transport a pour but ultime d'améliorer le bien-être de la société (Schultink, 2000), et les systèmes de gestion en particulier devraient au final bénéficier à la société dans son ensemble (Haas, 1997). Par conséquent, afin de poursuivre un développement durable, et d'assurer notamment les équités intergénérationnelle et intragénérationnelle, il paraît primordial d'intégrer dans les processus de prise de décision de la gestion des chaussées les impacts environnementaux liés à la gestion des chaussées. L'hypothèse de travail qui est testée dans cette thèse est par conséquent que la prise en compte des impacts environnementaux dans la gestion des chaussées permet une gestion plus durable des infrastructures routières. Plus précisément, il est suggéré que d'élargir le champ de compétence des administrations routières pour qu'elles prennent en compte les impacts environnementaux liés à leurs activités permet de gérer les infrastructures routières d'une façon réellement optimale du point de vue de la société dans son ensemble.

En s'appuyant sur cette hypothèse, l'objectif principal de cette thèse est de fournir un nouvel outil, destiné aux gestionnaires des réseaux routiers, permettant l'intégration dans la gestion des chaussées des impacts environnementaux liés à la circulation routière. Plus particulièrement, cet outil doit permettre la quantification monétaire des impacts environnementaux de la circulation routière imputables à la gestion des chaussées afin de pouvoir intégrer ces coûts environnementaux dans les outils économiques traditionnellement utilisés en gestion des chaussées.

L'atteinte de cet objectif général passe par la réalisation des objectifs spécifiques suivants :

1) la proposition d'un cadre pour une gestion durable des infrastructures routières qui précise notamment les impacts environnementaux à considérer, ainsi que les échelles spatiales et temporelles que devraient adopter les analyses de ces impacts;
2) le recensement, sans discrimination, des nuisances environnementales liées à l'exploitation des réseaux routiers;
3) l'analyse des mécanismes régissant ces nuisances environnementales, de leur génération à leur dispersion, afin de valider leur potentielle intégration dans un outil d'aide à la gestion;
4) l'identification de la méthode la plus appropriée pour l'intégration des impacts environnementaux dans la gestion des chaussées;
5) le développement de modèles liant les caractéristiques des chaussées, les nuisances environnementales induites par ces caractéristiques et les impacts environnementaux liés aux nuisances;
6) la quantification de ces impacts environnementaux en fonction de la nature et de la densité des récepteurs affectés par ces impacts;
7) l'évaluation économique de ces impacts environnementaux sur le cycle de vie des chaussées.

Afin d'atteindre les objectifs mentionnés ci-dessus, cette thèse s'appuie à la fois sur un examen des pratiques et des avancées scientifiques en gestion des chaussées et sur un examen des pratiques et connaissances scientifiques issues d'autres domaines, où l'intégration des impacts environnementaux est plus commune. Le développement de l'outil d'aide à la gestion repose ainsi sur la construction d'un nouveau modèle, adapté au contexte québécois, qui estime la valeur économique des impacts reliés aux principales nuisances environnementales, soit le bruit, la pollution atmosphérique ainsi que les gaz à effet de serre. Ce modèle, dénommé Pavement Environmental Impact Model (PEIM), évalue tout d'abord la génération et la dispersion des nuisances environnementales en intégrant différents modèles présentés dans la littérature scientifique et technique. Le cas échéant, le PEIM quantifie ensuite les effets sanitaires des nuisances en utilisant les fonctions dose-réponse et concentration-réponse, développées en médecine. Ces fonctions permettent de prévoir l'occurrence et la gravité des effets sanitaires selon la dose de nuisance absorbée par le récepteur ou selon la concentration de nuisance observée à l'endroit où se trouve le récepteur. Par la suite, le PEIM assigne à chaque effet sanitaire ainsi qu'à chaque impact non sanitaire une valeur économique basée principalement sur les coûts observés sur les marchés. Finalement, ces coûts associés aux impacts environnementaux peuvent être intégrés, au même titre que les dépenses encourues par l'administration, dans les outils de gestion des chaussées traditionnels afin d'évaluer les alternatives de gestion sur le cycle de vie de la chaussée. L'originalité de cette thèse repose donc tout d'abord sur le fait qu'aucun outil d'aide à la gestion des chaussées de ce type n'existe actuellement ni dans les administrations routières, ni dans la littérature scientifique. Elle repose de plus sur une approche méthodologique novatrice qui intègre plusieurs outils et techniques provenant de disciplines différentes (ingénierie, économie, sciences de l'environnement et sciences de la santé).

Le corps du document de la thèse est structuré en quatre chapitres. Le chapitre 1 présente une revue de la littérature qui examine quelles sont les méthodes employées en gestion des chaussées, quels sont les impacts environnementaux liés à la gestion des chaussées et quelles sont les méthodes déjà existantes pour l'intégration des impacts environnementaux dans les pratiques de gestion (en gestion des chaussées et autres). Le chapitre 2 propose un modèle conceptuel développé dans un article intitulé *Incorporating environmental impacts in pavement management systems* et soumis à la revue *Civil Engineering and Environmental Systems*. Ce modèle conceptuel définit clairement quels impacts doivent être traités dans le projet de recherche, identifie les liens existant entre la gestion des chaussées, d'une part, et les impacts environnementaux, d'autre part, et prouve la faisabilité de l'intégration des impacts environnementaux dans la gestion des chaussées. Le chapitre 3 est constitué par un article intitulé *Influence of pavement condition on environmental costs* et soumis à la revue *Journal of Transportation Engineering*. Ce chapitre présente principalement la structure du modèle de quantification et de monétarisation des coûts environnementaux liés à la circulation routière, le PEIM. De plus, ce chapitre valide le modèle en s'appuyant sur une analyse de sensibilité ainsi que sur la comparaison des résultats du modèle aux résultats disponibles dans la littérature scientifique. Le chapitre 4 met en application le modèle développé au chapitre 3 dans un article intitulé *Life cycle environmental benefits of pavement surface maintenance* et soumis à la revue *Canadian Journal of Civil Engineering*. Ce chapitre s'attache à démontrer l'importance significative des impacts environnementaux liés à la gestion des chaussées en s'appuyant sur une étude de cas réalisée dans le contexte québécois. Les coûts environnementaux y sont notamment calculés sur le cycle de vie de la chaussée pour différentes alternatives de gestions afin de démontrer la pertinence et l'utilité de leur prise en compte dans les outils de gestion des chaussées. La thèse se termine par une conclusion générale qui rappelle les principaux résultats et analyses obtenus lors de ce projet de recherche. Cette conclusion souligne également les principales contributions scientifiques.

CHAPITRE 1

REVUE DE LA LITTÉRATURE

Ce chapitre décrit tout d'abord les différents processus et méthodes qui sont usuels en gestion des chaussées ainsi que les plus récentes avancées dans le domaine. Dans un deuxième temps, ce chapitre présente une revue des méthodes d'intégration de l'environnement dans les processus de décision utilisées en gestion des transports, dans le but d'investiguer les solutions potentielles pour la prise en compte des impacts environnementaux en gestion des chaussées.

1.1 Gestion des chaussées

Les décisions que doivent prendre les gestionnaires des réseaux routiers sont de deux types principaux. Elles peuvent être stratégiques et concerner le réseau routier dans son ensemble (gestion de niveau réseau), ou bien être techniques et ne porter que sur une section de route (gestion de niveau projet). Quel que soit le niveau de gestion, les administrations routières disposent cependant d'outils les assistant dans leurs prises de décisions.

1.1.1 Historique du développement des outils de gestions

Les premiers systèmes de gestion des chaussées sont nés en Occident dans la deuxième moitié du XXième siècle tandis que les réseaux routiers étaient en grande partie achevés. Les objectifs des administrations routières sont alors passés du développement des réseaux routiers à leur préservation (Kulkarni et Miller, 2003).

Les systèmes de gestion des chaussées sont nés de la nécessité de maintenir les qualités des chaussées tout en tenant compte des ressources disponibles. Dès les années 1970, la Federal

Highway Administration (FHWA) donnait au système de gestion des chaussées la définition suivante (Haas, Hudson et Zaniewski, 1994) :

> A system which involves the identification of optimum strategies at various management levels and maintains pavements at an adequate level of serviceability. These include, but are not limited to, systematic procedures for scheduling maintenance and rehabilitation activities based on optimization of benefits and minimization of costs.

Dans leurs premières années, les systèmes de gestion des chaussées ne visaient l'optimisation de la planification des interventions à réaliser sur le réseau que sur un horizon d'une année. Désormais, ils permettent d'établir une planification des interventions sur une période de plusieurs années (Kulkarni et Miller, 2003). En plus d'aider à l'allocation efficace des ressources dans le but de maintenir l'état des chaussées, les systèmes de gestion des chaussées présentent trois objectifs supplémentaires, soit :

1) améliorer l'efficacité des prises de décisions;
2) donner un retour sur les décisions prises;
3) assurer la cohérence des décisions prises à chaque niveau de gestion (Haas, 1997; Tessier, 1990).

Ces objectifs poursuivis par la gestion des chaussées impliquent l'intégration de toutes les étapes de la vie des chaussées, de sa planification à sa réhabilitation. Les décisions prises à l'aide des systèmes de gestion des chaussées permettent de suivre la voie la plus économique à long terme.

1.1.2 Caractéristiques des systèmes de gestion usuels

En intégrant et contrôlant toujours plus de paramètres, les systèmes de gestion ne cessent de se complexifier dans le but de développer des stratégies d'interventions optimales ainsi que des planifications d'interventions les plus efficientes possible.

<u>Données</u>

Pour des fins d'efficacité, les systèmes de gestion des chaussées sont basés sur des bases de données regroupant les informations disponibles sur le réseau routier (par exemple : matériau des chaussées et historique des interventions) ainsi que sur les contraintes de gestion (par exemple : budget disponible et coût d'une intervention). Le Tableau 1.1 présente, classés par catégories, les différents paramètres intégrés dans de telles bases de données. Ces bases de données recensent donc les variables à prendre en considération lors de chacune des étapes de la vie de la chaussée, de sa conception à sa reconstruction.

Tableau 1.1 Paramètres typiques des systèmes de gestion des chaussées
Adapté de Haas, Hudson et Zaniewski (1994)

Catégorie de données	**Paramètres typiques**
Performance	uni déformations de surface frictions longitudinale et transversale déflexion propriétés des couches de matériaux
Historique	chronologie de la maintenance historique de la construction historique de la circulation historique des accidents
Politique	budget alternatives possibles
Géométrique	dimensions en section courbure pente transversale (dévers) pente longitudinale accotements
Environnemental	drainage climat
Budget	coût d'une nouvelle construction coût d'entretien coût de réhabilitation coût pour l'usager

Les bases de données à partir desquelles les systèmes de gestions se construisent sont au cœur de toutes les décisions, tant au niveau réseau qu'au niveau projet. La Figure 1.1 montre comment les systèmes de gestion englobent toutes les activités liées à la gestion des chaussées et comment celles-ci s'articulent autour de la base de données du système.

Les activités de gestion des chaussées, que ce soit au niveau réseau ou au niveau projet, reposent toutes sur la base de données qui, lorsqu'elle est complète, permet de prendre les décisions de gestion plus éclairées.

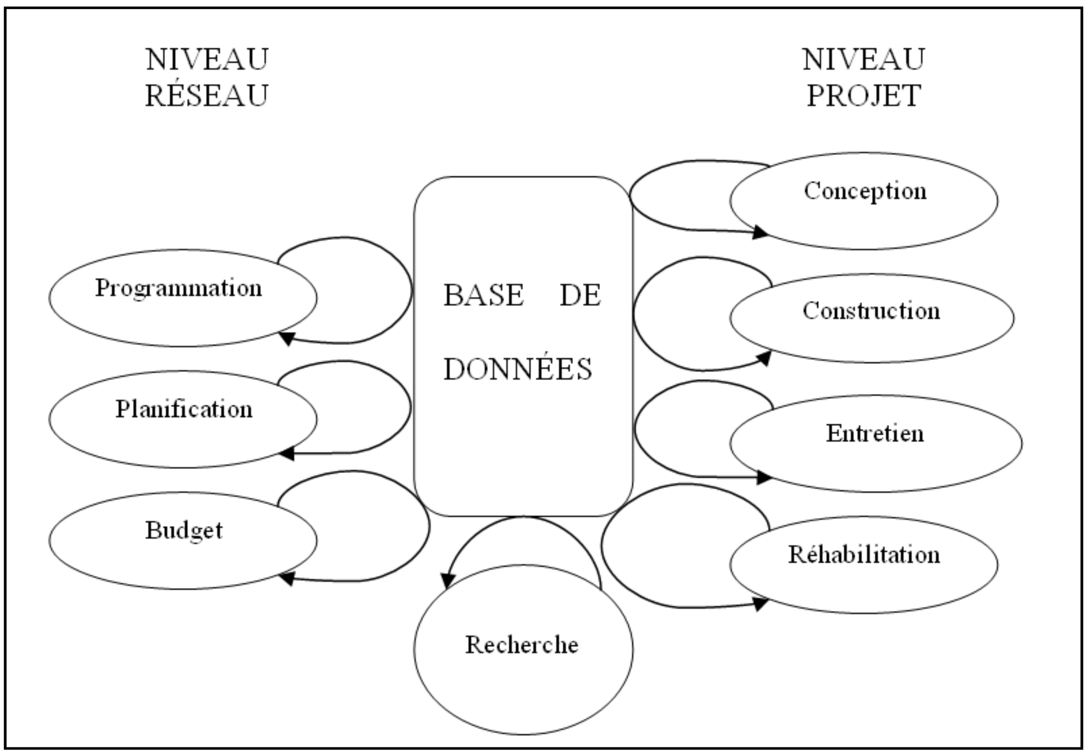

Figure 1.1 Principales composantes des systèmes de gestion des chaussées.
Adaptée de Haas, Hudson et Zaniewski (1994)

Analyse économique

En gestion des chaussées, la méthode de prédilection des administrateurs routiers est l'analyse des coûts sur le cycle de vie (ACCV) (Office of Asset Management, 2002). L'analyse ACCV est un outil d'analyse économique des coûts et bénéfices qui jalonnent le cycle de vie de la chaussée.

L'analyse ACCV est destinée à intégrer, dans les processus de gestion, les coûts impliqués tout au long de la vie de la chaussée. Par conséquent, l'analyse ACCV aide à prendre les décisions les meilleures pour une gestion durable des réseaux routiers (Yusoff, Hansen et Ibrahim, 2005). Traditionnellement, les coûts à inclure dans une analyse ACCV sont les suivants (Walls et Smith, 1998) :

1) les coûts de construction;
2) les coûts d'entretien;
3) les coûts de réhabilitation;
4) la valeur résiduelle de la chaussée (considérée comme un bénéfice).

La Figure 1.2 présente une visualisation de ces coûts qui sont directement liés aux diverses interventions à réaliser sur la chaussée tout au long de son cycle de vie afin de maintenir son niveau de performance. L'intégration de ces coûts permet de choisir les stratégies de conception et d'entretien des chaussées les plus efficaces et les plus rentables sur une échelle de temps qui assure une relative durabilité au projet et au réseau. Elle permet ainsi de maintenir sur le long terme un niveau de performance acceptable en optimisant l'allocation des ressources. De plus, afin de comparer équitablement les alternatives de gestion n'ayant pas la même durée de vie, l'analyse ACCV prend en compte tous les coûts auxquels font face les gestionnaires sur une période d'analyse généralement excédant la durée de vie de la construction initiale.

Les coûts intégrés dans les outils de gestion sont habituellement actualisés en fonction du moment de leur occurrence. Ainsi, les coûts apparaissant à un horizon lointain auront une valeur moindre que ceux apparaissant dans les premières années. Le taux d'actualisation utilisé dans les projets routiers diffère d'un pays à l'autre et d'une administration à l'autre mais reste généralement un taux constant sur la période d'analyse (Lee, 2002). Transport Canada (1994) suggère ainsi un taux constant de 10% avec une analyse de sensibilité entre 7,5 et 12,5%. À titre de comparaison, le taux d'actualisation est de 7% en Nouvelle-Galles du Sud avec une analyse de sensibilité entre 4 et 10% (James et Gillespie, 2002).

Afin de comparer chacune des alternatives en jeu, les analyses économiques peuvent faire appel à trois indicateurs (Pearce, Atkinson et Mourato, 2006) :

1) la valeur actuelle nette (VAN);
2) le ratio bénéfices-coûts (RBC);
3) le taux de rendement interne (TRI).

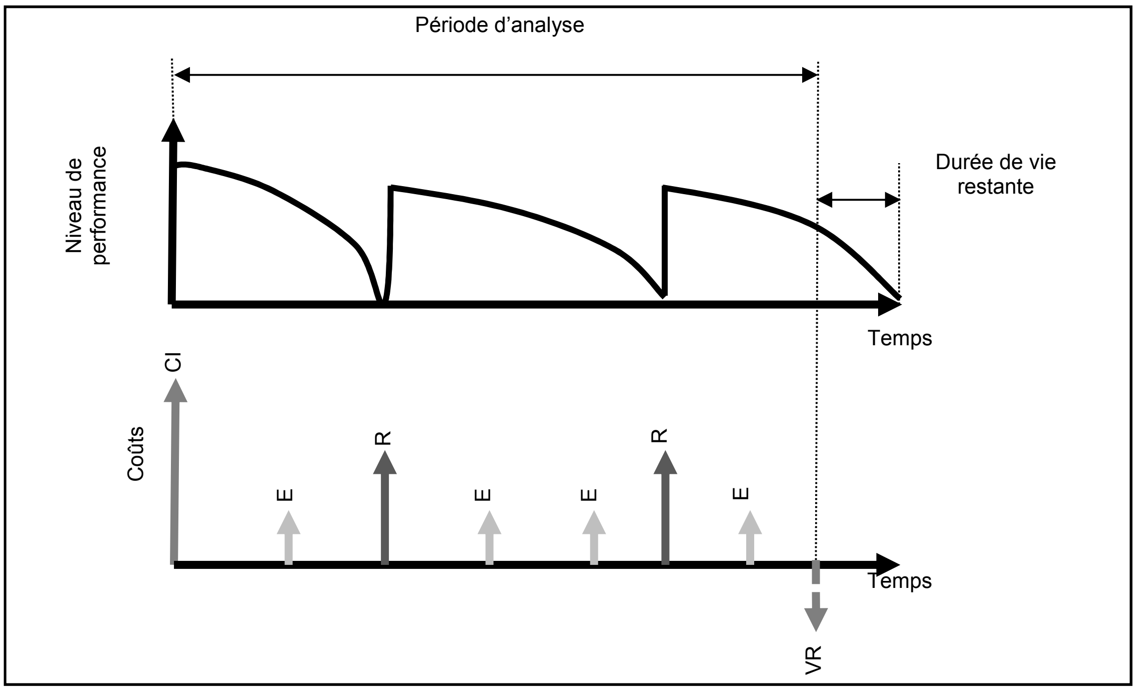

Figure 1.2 Coûts impliqués traditionnellement dans l'analyse ACCV d'une chaussée en vue du maintien de son niveau de performance : construction initiale (CI), entretien (E), réhabilitation (R), valeur résiduelle (VR) Adaptée de Haas, Hudson et Zaniewski (1994)

La VAN est la somme arithmétique des coûts et bénéfices. C'est le critère clé pour accepter ou refuser un projet à cause de sa relative simplicité. Le RBC est un des critères les plus populaires pour les preneurs de décisions. Il permet la sélection de l'alternative avec le RBC le plus élevé. Toutefois, le rapport coût-bénéfice est reconnu pour favoriser l'acceptation des alternatives d'envergure relativement modeste. Le TRI représente le taux d'escompte pour lequel la valeur présente nette est égale à zéro. Le TRI est connu pour favoriser les projets à court terme même si ceux-ci sont moins économiques sur le long terme. De plus, le TRI ne peut pas être utilisé lorsque les alternatives sont exclusives (Pearce, Atkinson et Mourato, 2006).

Coûts aux usagers

En plus des coûts et bénéfices traditionnellement supportés par l'administration routière, les coûts supportés par les usagers sont de plus en plus intégrés dans les systèmes de gestion des chaussées, malgré les hésitations persistantes de la plupart des administrations (Salem et al., 2013). Parmi ces coûts aux usagers, on retrouve notamment les coûts d'exploitation des véhicules, les retards dus aux travaux ainsi que les coûts liés aux accidents routiers (Office of Asset Management, 2002).

Le principe de l'intégration des coûts aux usagers dans la gestion des chaussées semble communément accepté puisque la chaussée est construite et entretenue afin d'assurer la circulation confortable et sécuritaire de ses usagers (Salem et al., 2013). Ainsi les coûts aux usagers sont appelés à être intégrés dans les processus de prise de décision et dans les outils économiques de gestion des chaussées, au même titre que les dépenses des administrations (Kulkarni et Miller, 2003).

Par ailleurs, certains auteurs définissent les coûts aux usagers comme des coûts externes; ils sont alors qualifiés de coûts environnementaux (voir par exemple Boiteux, 2001). Cependant, en suivant l'approche de Schreyer et al. (2004), ces coûts aux usagers sont internes à la gestion des chaussées puisqu'ils concernent les véhicules, eux-mêmes intégrés dans les processus de gestion. Par exemple, le dimensionnement des chaussées intègre déjà les types et nombre de véhicules circulant sur la chaussée.

Autres coûts

Les coûts aux usagers n'étant pas traditionnellement pris en compte dans les systèmes de gestion des chaussées, leur intégration représente un premier pas vers l'intégration dans les outils de gestion de tous les effets supportés par la société dans son ensemble mais qui sont attribuables aux décisions prises par les gestionnaires des réseaux routiers. Haas, Hudson et Zaniewski (1994) prônent ainsi l'élargissement des coûts pris en compte lors de la détermination de la stratégie de programmation optimale afin d'y intégrer, par exemple, ceux liés à l'environnement de la route. Ainsi, en plus des coûts déjà mentionnés précédemment (coûts des travaux, coûts d'opérations des véhicules, coûts liés au retard et coûts liés à la sécurité), ils suggèrent notamment d'intégrer les coûts liés aux dommages causés à l'environnement par les travaux routiers. L'intégration de ces coûts, bien que mentionnée, ne fait malheureusement pas l'objet d'un développement de la part des auteurs. Cela traduit, dans les faits, à la fois l'importance et la difficulté relative à prendre en compte ces coûts supplémentaires liés aux impacts de la route sur l'environnement. Cela traduit également le manque d'intérêt au niveau des gestionnaires concernant ces impacts, « externes » à leurs préoccupations traditionnelles, qui affectent pourtant la société dans son ensemble (Friedrich, Rabl et Spadaro, 2001). Ainsi, jusqu'à présent, les coûts dits « environnementaux », tels que ceux liés aux impacts sur la santé des riverains, la production agricole et la biodiversité, demeurent exclus des pratiques de gestion des chaussées.

1.2 Environnement des chaussées

Ces deux dernières décennies, sous la pression du public, les administrations routières se sont engagées sur la voie du développement durable et adaptent graduellement leurs systèmes de gestion afin d'intégrer dans leurs processus de prise de décision les principes sous-jacents du concept de développement durable. Toutefois, il apparaît que les administrations pionnières sur cette voie éprouvent des difficultés à bien cerner les implications d'une telle intégration (voir Zhang, Keoleian et Lepech, 2013).

1.2.1 Durabilité des systèmes de gestion des chaussées

La première définition du développement durable qui a fait référence est celle proposée par la Commission Brundtland (World Commission on Environment and Development, 1987). La Commission définit le développement durable comme suit :

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Toutefois, même s'il existe un consensus sur cette définition du concept, les implications qu'on lui reconnaît ne sont pas forcément évidentes. Ainsi, de nombreuses autres définitions ont été proposées pour des fins de mise en application de ce principe (voir Beatley, 1995; Janic, 2006; Litman et Burwell, 2006). Transport Canada (2007) suggère notamment que :

> A sustainable transportation system is one that is safe, efficient and environmentally friendly. Sustainable transportation is about integrating economic, social and environmental considerations into decisions affecting transportation activity.

Aucune de ces définitions ne permet toutefois de formuler des règles explicites et pratiques en vue de l'application du concept de développement durable. Ainsi, initialement, le principe de durabilité n'était appliqué que dans des contextes de préservation des ressources et de contrôle de la pollution. Désormais, l'application de ce principe a été élargi pour englober les impacts économiques, sociaux et environnementaux (Janic, 2006; Litman, 2007).

Cela ne fait que peu de temps que les gestionnaires routiers intègrent les principes sous-jacents au concept de durabilité. En 2004, Ozbay et al. (2004b) ont noté que, mis à part en Californie, aucune des autres administrations routières aux États-Unis n'intégrait les impacts sociaux pour des fins de gestion. En 2005, selon Venner (2005), aucun des systèmes de gestion des chaussées n'intégrait les impacts environnementaux. Les modalités de l'incorporation des principes du développement durable dans les méthodes de gestion des chaussées ne sont par conséquent pas encore établies.

Il est cependant clair que, lorsque les gestionnaires des réseaux analysent et comparent des alternatives d'interventions, ainsi que leurs impacts, il leur est nécessaire de définir clairement la portée de leur analyse de façon à pouvoir intégrer ces principes du développement durable. Cette étape de la définition du domaine d'analyse est importante car c'est d'elle que dépend le choix des échelles spatiales et temporelles de l'analyse qui influence la manière dont sont appréhendées les équités intergénérationnelles et intragénérationnelles, corollaires du concept de développement durable (Ramani et al., 2011).

Dans ce contexte, la gestion des chaussées est appelée à intégrer une multitude d'impacts aux caractéristiques très variées. Par exemple, certaines nuisances dues à la gestion des chaussées induisent des impacts qui peuvent, tels les changements climatiques, être globaux, tandis que d'autres, tel le bruit, restent locaux. Dans ce contexte, il peut exister une tentation des administrations routières de limiter les impacts qu'elles internalisent aux impacts locaux (Giuliano, 2007). Toutefois, le principe d'équité intragénérationnelle exige que les impacts doivent être pris en compte, peu importe que les personnes qui souffrent des nuisances se trouvent dans ou hors de la région administrative concernée.

Par ailleurs, le principe d'équité intergénérationnelle suppose de ne pas altérer les capacités des générations futures à vivre. Or, pour comparer des alternatives, Transport Canada (1994) ne se base que sur des critères techniques et recommande que la période d'analyse n'excède pas la durée de vie de l'alternative la plus durable. Les auteurs précisent de plus que rien n'indique qu'il soit nécessaire d'avoir une période d'analyse de plus de 30 ans. Si la durée de vie de l'alternative est de plus de 30 ans et excède donc la durée maximale suggérée de la période d'analyse, une évaluation économique de la durée de vie résiduelle est effectuée (Office of Asset Management, 2002). Toutefois, si une période de 30 ans peut paraître appropriée à la prise en compte des coûts liés aux interventions de l'administration routière, les impacts environnementaux de ces interventions peuvent toutefois être cumulatifs et ne se révéler que bien après la période d'analyse. De plus, pour des décisions plus stratégiques qui, potentiellement, pourraient engendrer des impacts de grande envergure, une période d'analyse plus longue ne peut être que souhaitable puisque ceux-ci seraient susceptibles d'affecter les générations futures (Gowdy, 2005; James et Gillespie, 2002).

1.2.2 Impacts environnementaux

Afin d'assurer que, dans une perspective de développement durable, les pratiques de gestion des chaussées soient optimales pour la société, il convient d'identifier de quelle façon la gestion des chaussées influe sur le développement de la société. Dans ce contexte, les impacts de la gestion des chaussées sur la société sont qualifiés d'« environnementaux », dans le sens systémique du terme, puisque la société constitue un système extérieur à celui des chaussées. La pollution atmosphérique, les changements climatiques et le bruit sont les trois principaux types de nuisances environnementales recensés dans la littérature qui peuvent induire des impacts environnementaux significatifs. La pollution atmosphérique et les changements climatiques sont les nuisances les plus fréquemment incorporées dans les études sur la gestion des chaussées tandis que le bruit l'est très rarement (Santero, Masanet et Horvath, 2011b).

Pollution atmosphérique

Dans le contexte de la gestion des chaussées, la pollution atmosphérique est liée à la fois aux travaux effectués sur la chaussée, aux activités qui y sont afférentes, telles que l'extraction et le transport des matériaux (Chan et al., 2011), et au ralentissement de la circulation dû au chantier (Huang, Bird et Bell, 2009). Elle est également due à la circulation routière dont les émissions de gaz et de particules sont significativement reliées à l'état du revêtement de la chaussée (Dahl et al., 2006; Gillespie et McGhee, 2007).

Une gestion des chaussées appropriée peut limiter cette pollution atmosphérique de deux façons. Premièrement, une planification appropriée des travaux permet de limiter les travaux à réaliser. Deuxièmement, par le choix de matériaux appropriés et d'une conception durable notamment, la gestion des chaussées peut maintenir sur le long terme un bon uni (c'est-à-dire une faible rugosité).

Gaz à effet de serre

Les gaz à effet de serre reliés à la gestion des routes proviennent de deux types d'émissions :

1) l'émission supplémentaire de gaz à effet de serre par les véhicules circulant sur un revêtement en mauvais état (Wang et al., 2012);
2) l'émission de gaz à effet de serre due aux travaux d'entretien des chaussées (Chan et al., 2011) et aux congestions liées à ces travaux (Huang, Bird et Bell, 2009).

Par ailleurs, Hubert (2004) montre qu'il existe un lien direct entre l'émission des gaz à effet de serre par les véhicules (par combustion du carburant) et la consommation en carburant de ces mêmes véhicules. Ainsi, tel que le montrent Bartholomeu et Caixeta Filho (2009), plus la rugosité de la chaussée est élevée plus il y a de gaz à effet de serre émis par les véhicules qui y circulent. En améliorant l'uni du revêtement et en limitant les interventions sur la chaussée, la gestion des chaussées peut contribuer à la réduction des émissions de gaz à effet de serre.

Bruit

Le bruit routier provient principalement de trois sources (Bernhard et McDaniel, 2005) : 1) les frottements de l'air sur les véhicules; 2) les moteurs des véhicules; 3) l'interface pneumatique/chaussée. Dans de nombreuses combinaisons de conditions de vitesses et de trafic, le bruit produit par les véhicules eux-mêmes (par les frottements de l'air et le moteur) est dominé par le bruit issu des frottements à l'interface pneumatique/chaussée (Herman, Withers et Pinckney, 2006; Sandberg, 1987).

Ce bruit produit à l'interface pneumatique/chaussée dépend notamment de l'âge (Bendtsen, Lu et Kohler, 2009) et de la texture (Sandberg, 1987) du revêtement. Ainsi, en choisissant adéquatement la fréquence des interventions et la durabilité des matériaux utilisés, la gestion des chaussées peut limiter le niveau de bruit émis.

Autres impacts

Il existe également des nuisances autres que les trois principales développées précédemment. Ainsi, parallèlement au bruit, les vibrations provoquent également des nuisances aux riverains (Crispino et D'Apuzzo, 2001; Hajek, Blaney et Hein, 2006). L'effet des vibrations est toutefois difficilement dissociable de celui du bruit puisqu'ils sont naturellement liés l'un à l'autre (Austroads, 2000). Ainsi, aucune étude sur la gestion des chaussées n'intègre les impacts dus aux vibrations.

La pollution des sols et des eaux lors du ruissellement des précipitations sur les chaussées peut également se traduire par des impacts significatifs lorsque la pollution atteint, par exemple, la nappe phréatique dans laquelle de l'eau est puisée (Fletcher, Andrieu et Hamel, 2013) ou bien un terrain agricole (Ayers et Westcot, 1985). Bien que ces impacts soient connus, jusqu'ici, aucune étude n'a tenté leur incorporation dans un système de gestion des chaussées.

Finalement, la consommation d'énergie est également intégrée dans plusieurs études. Selon Santero, Masanet et Horvath (2011b), l'énergie est d'ailleurs le critère le plus employé lors de l'évaluation sur le cycle de vie d'une chaussée. Pourtant, en tant que telle, l'énergie n'est pas une nuisance mais plutôt une ressource. Il n'apparaît donc pas judicieux de considérer la consommation d'énergie en tant qu'impact environnemental et de l'intégrer à ce titre dans l'évaluation d'une alternative de gestion. Alternativement, les impacts environnementaux liés à la production de la quantité d'énergie consommée pourraient être intégrés dans les processus de prise de décision de la gestion des chaussées.

1.3 Méthodes d'intégration des impacts environnementaux dans les processus de prise de décision

Que ce soit en gestion des chaussées ou dans d'autres domaines, plusieurs méthodes ont été développées afin de répondre au besoin des administrations d'intégrer les impacts environnementaux dans leur processus de prise de décision.

1.3.1 Méthode du cheminement d'impact

La méthode du cheminement d'impact (Impact pathway approach – IPA) est une méthode qui a été utilisée intensivement en Europe lors des projets de recherche ExternE (1997). Cette méthode est historiquement utilisée afin de quantifier sous forme monétaire les répercussions environnementales des décisions politiques concernant les transports et l'énergie (Panis et al., 2004). Dans les faits, les études utilisant la méthode du cheminement d'impact évaluent principalement les coûts sanitaires liés aux nuisances environnementales. Généralement, ces études portent sur les conséquences sanitaires de la pollution atmosphérique (voir par exemple Panis et al., 2004; Spadaro et Rabl, 1999). Ces dernières années, cependant, la méthode du cheminement d'impact est de plus en plus utilisée afin de quantifier les impacts d'autres nuisances que la pollution atmosphérique. Ainsi, de plus en plus d'études portant sur les conséquences sanitaires du bruit s'appuient sur la méthode IPA (voir par exemple Hofstetter et Müller-Wenk, 2005; Weisbrod, Lynch et Meyer, 2009).

La méthode du cheminement d'impact assigne une valeur économique aux impacts environnementaux en s'appuyant sur la description de différents mécanismes en jeu, depuis la génération de la nuisance jusqu'à l'évaluation économique de ses impacts. La méthode consiste en quatre étapes successives (Bickel et al., 2006) :

1) le calcul de l'émission d'une nuisance à partir de la source à l'étude. Cette étape permet par exemple l'évaluation de la quantité de gaz carbonique émise dans l'atmosphère par un véhicule;

2) l'évaluation de la dispersion de la nuisance dans l'espace et dans le temps. Cette étape aboutit par exemple à la concentration en particules de matière émises par un véhicule sur le lieu d'un hôpital, deux jours après leur émission;
3) la quantification de l'impact causé par la nuisance. À cette étape des fonctions du type dose-réponse permettent par exemple d'évaluer le degré de gravité d'une maladie pulmonaire causée par l'absorption d'un polluant atmosphérique particulier;
4) la monétarisation de l'impact. À l'aide de techniques économiques adaptées à l'impact monétarisé, cette étape consiste à assigner un coût à chaque impact, en fonction de son degré de gravité.

La méthode du cheminement d'impact, malgré son succès pour la quantification des impacts environnementaux des politiques de transport, n'a jamais été appliquée dans le contexte de la gestion des chaussées. Elle est cependant reconnue comme une méthode participant à la promotion des principes du développement durable (di Valdalbero et Valette, 2011; Zhan et Zhang, 2009).

1.3.2 Analyse du cycle de vie

Même si l'analyse du cycle de vie (ACV) est un outil initialement développé pour le milieu industriel, il est de plus en plus utilisé pour évaluer l'impact environnemental des matériaux et procédés utilisés lors de la construction, de l'entretien et de la réhabilitation des chaussées (Santero, Masanet et Horvath, 2011b). L'analyse ACV est une procédure normalisée au niveau international qui décrit la marche à suivre afin d'inclure les impacts environnementaux liés au cycle de vie des produits (Jullien et Ventura, 2007). L'analyse ACV s'intéresse plus particulièrement à tous les impacts advenant lors des activités d'un projet, allant de l'extraction des matériaux nécessaires à la construction de la chaussée au recyclage de ces mêmes matériaux à la fin de la durée de vie de la chaussée. L'analyse ACV permet ainsi de comparer les impacts environnementaux advenant sur le cycle de vie des différents produits ou alternatives de gestion.

L'analyse ACV est reconnue comme un outil permettant de favoriser les alternatives les plus durables puisqu'il prend en compte tous les impacts environnementaux advenant tout au long du cycle de vie du produit (Rebitzer et al., 2004). Toutefois, Jullien and Ventura (2007) montrent que les routes diffèrent des productions industrielles pour lesquelles la méthode a été développée. La phase d'utilisation d'une route est de loin la plus longue des phases du cycle de vie pendant laquelle la plupart des impacts vont avoir lieu. Il est donc nécessaire d'adapter le cadre de la méthode présentée dans les normes ISO afin de prendre en compte les impacts advenant pendant la phase d'utilisation du produit.

1.3.3 Analyse des coûts sur le cycle de vie

L'analyse des coûts sur le cycle de vie (ACCV) a été mentionnée à la section 1.1.2. Elle consiste en l'analyse économique d'une alternative de gestion sur le cycle de vie de la chaussée à l'étude. L'analyse ACCV est la méthode actuellement la plus répandue pour les prises de décision au niveau projet (voir par exemple Li et al., 2010; Santos et Ferreira, 2013) et elle est de plus en plus utilisée au niveau réseau (voir par exemple Chen et Flintsch, 2007; Zhang, Keoleian et Lepech, 2013).

Toutefois, l'Office of Asset Management (2002) reconnaît que l'analyse ACCV seule ne peut pas déterminer la meilleure alternative du point de vue de la société dans son ensemble sans l'intégration de certains paramètres, tels que les impacts environnementaux. Pour utiliser cette méthode afin d'évaluer les alternatives de gestion les plus respectueuses des principes du développement durable, une solution consiste en l'intégration de tous les impacts économiques, sociaux et environnementaux causés par le choix de gestion. Dans la pratique, les analyses ACCV effectuées par les gestionnaires des chaussées n'incorporent pas ces impacts (Ozbay et al., 2004b; Venner, 2005). Cependant, ces dernières années, plusieurs auteurs ont développé des méthodes permettant l'intégration de certains coûts environnementaux dans l'analyse ACCV (voir par exemple Lidicker et al., 2013; Zhang, Keoleian et Lepech, 2013).

1.3.4 Indices

Dans la pratique, lorsque les impacts sur l'environnement sont évalués, ils n'entrent généralement pas directement en compte dans la gestion en terme monétaire mais apparaissent plutôt sous la forme d'indices (Amekudzi et Meyer, 2005; Marsden, Kelly et Snell, 2006; Quintero, 1997). Les indices sont utilisés par les administrations afin de mesurer le degré d'atteinte de leurs objectifs (Litman, 2007; Marsden, Kelly et Snell, 2006). L'avantage d'utiliser des indices est qu'ils rassemblent de grandes quantités de données en un seul chiffre facile à analyser. C'est pourquoi les indices sont de plus en plus utilisés dans le domaine des transports pour mesurer la performance de la gestion (Marsden, Kelly et Snell, 2006). Plus particulièrement, la durabilité de la planification et de la gestion en transport est généralement évaluée à l'aide d'un ensemble d'indices (Jullien et Ventura, 2007; Litman et Burwell, 2006; Lucas et al., 2007).

Toutefois, le choix d'utiliser des indices pour évaluer une alternative de gestion peut être problématique. En effet, il convient de sélectionner des indices capables de traduire les besoins de la société et non pas les seuls besoins des administrations routières (Marsden, Kelly et Snell, 2006). De plus, l'utilisation d'indices pousse les administrations routières à rester focalisées sur l'amélioration du score de l'indice plutôt que de chercher à améliorer la situation réelle. Finalement, la comparaison d'alternatives de gestion est difficile lorsque plusieurs indices sont utilisés (Marsden, Kelly et Snell, 2006). L'établissement d'une pondération pour chacun des indices impliqués est alors critique et peut introduire une incertitude sur le résultat final.

1.4 État de l'art de l'intégration de l'environnement en gestion des chaussées

Afin d'assurer le développement durable des réseaux routiers, l'estimation environnementale et sociale des projets routiers est incontournable. Au niveau international, les Nations Unies (United Nations, 2001) proposent ainsi une évaluation continue de l'impact des projets routiers sur leur environnement en se plaçant au niveau politique (participation de la population, des professionnels, méthodologie d'évaluation des impacts). L'établissement de politiques reste toutefois éloigné des préoccupations pratiques des gestionnaires des chaussées, que ce soit au niveau réseau ou bien au niveau projet.

Au Québec, l'intégration des préoccupations environnementales aux projets routiers se traduit notamment, en 1978, par la création du BAPE, un organisme faisant partie « [d'] une procédure d'évaluation et d'examen des impacts sur l'environnement faisant appel à la participation du public » (Bureau d'audiences publiques sur l'environnement, 2005). Le MTQ (ministère des Transports du Québec), pour sa part, présente dans son *Guide de préparation des projets routiers* (MTQ, 2007) une annexe traitant de l'intégration des préoccupations environnementales dans les projets routiers. Toutefois, aucun guide pratique ni outil ne permet l'évaluation systématique et exhaustive des impacts environnementaux des alternatives de gestion.

Dans la pratique, les administrations routières ne semblent pas avoir encore pris conscience de la nécessité de l'intégration des impacts environnementaux pour assurer une gestion des chaussées plus profitable pour la société dans son ensemble (Chan, Keoleian et Gabler, 2008). Les gestionnaires des chaussées ne tiennent d'ailleurs que très rarement compte des impacts environnementaux (Chan, Keoleian et Gabler, 2008). Ainsi, afin de faire évoluer les pratiques et d'aider les gestionnaires dans la détermination des alternatives optimales, plusieurs auteurs ont récemment développé des outils impliquant une quantification des impacts environnementaux (voir par exemple Lidicker et al., 2013; Wang et al., 2012; Zhang, Keoleian et Lepech, 2013). Toutefois, jusqu'à présent, ces nouveaux outils de gestion apparaissent souvent limités à la production et la mise en place des matériaux (Gosse, Smith et Clarens, 2013; Jullien et Ventura, 2007; Pennington et al., 2004; Santero, Masanet et Horvath, 2011b) ou bien ne se concentrent que sur certains impacts tels que le bruit (voir par exemple Ahammed et Tighe, 2010), les émissions atmosphériques (voir par exemple Yu et Lu, 2012) ou, plus spécifiquement, les changements climatiques (voir par exemple Wang et al., 2012). Ainsi, il apparaît qu'il n'existe aucun outil pratique, à la fois exhaustif et systématique, destiné à l'incorporation des impacts environnementaux dans la gestion des chaussées.

1.5 Conclusion

Dans le contexte actuel où les principes du développement durable sont appelés à intégrer les pratiques de gestion, il apparaît nécessaire d'inclure les impacts environnementaux dans la gestion des chaussées. La plupart des méthodes actuellement disponibles ne sont pas directement transposables au domaine de la gestion des réseaux routiers. Toutefois, l'analyse des coûts sur le cycle de vie (ACCV) propose un cadre d'intégration intéressant puisqu'elle est déjà largement utilisée par les administrations routières mais également parce que plusieurs auteurs s'en sont déjà servi pour l'intégration de certains impacts environnementaux. L'utilisation de l'analyse ACCV pour fin d'intégration des impacts environnementaux reste toutefois perfectible. En effet, jusqu'ici, les différents outils proposés se limitent à quelques impacts environnementaux choisis sans réel fondement scientifique. De plus, la plupart du temps, les méthodologies permettant la quantification des impacts environnementaux font appel à l'extrapolation d'observations plutôt que de procéder à la modélisation des phénomènes menant aux impacts environnementaux.

Par ailleurs, suivant l'approche de Schreyer et al. (2004), les impacts environnementaux traités dans cette thèse sont limités à ceux affectant les récepteurs non pris en compte par les administrations routières lors de la gestion des chaussées. Ainsi, les coûts aux usagers ne sont pas considérés comme faisant partie des coûts environnementaux.

Les prochains chapitres s'appuient sur ces constats pour établir un cadre clair de ce qu'un outil de gestion devrait considérer comme type d'impact, et pour construire un outil novateur assurant la prise en compte adéquate des impacts environnementaux dans la gestion des chaussées.

CHAPITRE 2

INCORPORATING ENVIRONMENTAL IMPACTS IN PAVEMENT MANAGEMENT SYSTEMS

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2.1 Abstract

Environmental nuisances (such as greenhouse gases and noise) may be generated during the use phase of the pavement life cycle, with these known to significantly affect the environment. However, no attempt has yet been made to gather information concerning the processes involved in the generation of environmental impacts, and to evaluate them. To address this issue, this paper first reviews the knowledge base and relevant methods relating to environmental impact assessment and pavement management. It then presents a new conceptual model, integrating Impact Pathway Approach and Life Cycle Cost Analysis principles, and providing modelers with a comprehensive framework; the model and framework could support the development of practical tools for quantification and incorporation of environmental impacts into pavement management. This study demonstrates that pavement management influences environmental impacts occurring during the use phase of the pavement life cycle. It establishes causal links between pavement management and nuisance generation, between nuisances and their impact on four receptors (human welfare, ecosystems, buildings and infrastructure, and crops), and finally, between these impacts and their environmental costs. This study also proves the feasibility of incorporating environmental impacts into pavement management systems and describes how existing methodologies and tools may be integrated to support this incorporation. Finally, this study

underlines that the scope of this conceptual model is limited to network-level decisions until more accurate knowledge and data become available.

2.2 Introduction

From a sustainability perspective, it is important for road agencies to recognize and integrate relevant environmental and social damages into their decision-making process (Chan, Keoleian and Gabler, 2008; Haas, 1997), given that road transportation induces adverse environmental impacts that, in turn, social welfare (Verhoef, 1994). However, although environmental nuisances due to road traffic (such as noise and air pollution) are directly related to pavement characteristics and condition, pavement management departments rarely consider associated impacts. Proper incorporation of such environmental impacts into pavement management systems indeed appears challenging. The use phase has received little attention to date, notwithstanding the fact that this is the longest phase of the pavement life cycle, and the one during which most relevant environmental nuisances are emitted (Gosse, Smith and Clarens, 2013; Santero, Masanet and Horvath, 2011b). This is partly because scientific knowledge in this area is scarce. Fundamentally, the lack of clear definition of what the environment consists of prevents several environmental impacts from being adequately understood. Unclear identification of environmental impacts, which are sometimes considered to comprise emissions (e.g. Nathman, McNeil and Van Dam, 2009; Yu and Lu, 2012) and at other times a mixture of emissions and effects (e.g. Huang, Bird and Heidrich, 2009; Weisbrod, Lynch and Meyer, 2009), results in inappropriate quantification of such impacts. This leads to ignoring significant environmental impacts during the decision-making process, consequently leading to non-optimal sustainability decisions.

Best practices in pavement management often account for only a few selected environmental impacts, or use sustainability indicators that cannot be incorporated into pavement management systems (Zhang, Keoleian and Lepech, 2013). However, suitable models are available to quantify and monetize environmental impacts (Chan, Keoleian and Gabler, 2008). The quantification of environmental impacts in pavement management may be performed via two different approaches: life cycle assessment (LCA), which is not specific to transportation, is the typical method used to integrate environmental concerns (Santero, Masanet and Horvath, 2011b), while life cycle cost analysis (LCCA), which is widely used by road agencies (particularly in pavement management systems), represents a suitable framework for integration of sustainability concerns into pavement management (Ozbay et al., 2004a).

The aim of this study is thus to formulate a conceptual model that provides an efficient and sustainable framework for the incorporation of environmental impacts occurring during the use phase in pavement management. This study organizes available methods and knowledge. First, the environment system of pavement management is defined. Second, existing techniques that currently support pavement management departments in their decision-making processes are briefly summarized. Third, tools available from other disciplines that may complement conventional pavement management methods with respect to the incorporation of environmental impacts are discussed. Finally, the conceptual model derived on the basis of these methods and tools is presented, with a discussion of data needed to implement the model, and of the latter's limitations.

2.3 The environment system

The environment system and environmental impacts are defined in very different ways, depending on the scope and methodology of study. Table 2.1 compiles a list of environmental impacts, derived from different authors of studies with different scopes and perspectives. While some authors consider environmental impacts to comprise emissions, such as noise or air pollution (e.g. Nathman, McNeil and Van Dam, 2009; Ozbay et al., 2007), others consider them to be emissions, midpoint (e.g. air acidification), and endpoint effects (e.g. health effects) at the same time (e.g. Huang, Bird and Heidrich, 2009; Samberg, Bassok and Holman, 2011). Such different approaches result in a confused definition of environmental impacts. Moreover, even among studies that adopt the same scope or framework, no consensus exists about environmental impacts that should be considered. For example, Gosse, Smith and Clarens (2013) only include climate change, while Zhang, Keoleian and Lepech (2013) include human health effects due to air pollution and noise, but do not include climate change.

Whereas the concept of environment varies widely across different studies, we define environment in relation to the transportation system, for the purposes of our current study. Based on a systems approach, the environment system is considered to comprise what is not in the transportation system, i.e. what is out of the control of agencies. Similarly, in the pavement management context, the environment system encompasses what is not included in the pavement system. Figure 2.1 illustrates the boundaries of both pavement and environment systems.

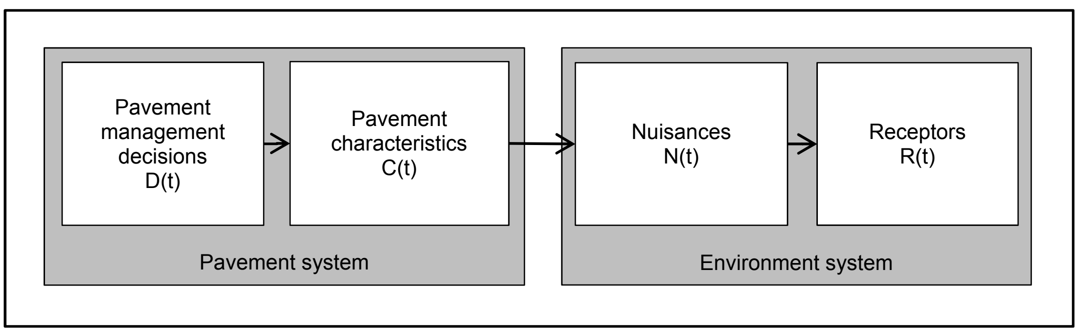

Figure 2.1 Schematic representation of the link between pavement management decisions and the environment system

Even if the environment system is well defined, it remains difficult to integrate environmental concerns into pavement management systems based on categorization of environmental impacts, given that no consensus exists on what the latter consist of. To circumvent this issue, Figure 2.1 identifies causal links between pavement management decisions and receptors, clarifying how pavement management decisions may modify pavement characteristics that in turn affect the generation of environmental nuisances, with the potential to impact receptors. For example, changes at the maintenance level trigger changes at the network level, or changes in maintenance technique at the project level induce a change in pavement characteristics. In turn, a change in pavement characteristics (for example, in pavement condition) may influence the emission of environmental nuisances, comprising chemical and physical emissions (e.g. greenhouse gases and noise) from both vehicles and pavement. Finally, a change in the magnitude of nuisances emitted may change the intensity of the corresponding impact on receptors (e.g. severity of sleep disturbance). Consequently, incorporating environmental concerns into pavement management systems may be based on categorization of receptors of environmental nuisances, rather than on categorization of environmental impacts, without loss of information. The conceptual model presented in this paper is therefore developed on the basis of a receptor-oriented perspective. Receptors potentially impacted by pavement management decisions, and consequently by pavement characteristics, are categorized in four different classes, as detailed below.

Human welfare is known to be affected by road traffic. Noise and atmospheric emissions are the two main road traffic nuisances that have been proven to significantly impact human health (Babisch, 2005b; Kunzli et al., 2000; Müller-Wenk, 2004). Meanwhile, noise and emissions depend on pavement characteristics and condition (Bernhard and McDaniel, 2005; China and James, 2012; Sandberg, 1987). For example, an increase in pavement roughness induces an increase in fuel consumption, in turn causing an increase in vehicle tailpipe emissions (Chatti and Zaabar, 2012).

Ecosystems are widely impacted by road nuisances, such as noise and air pollution. For example, some air pollutants lead to acidification and eutrophication that adversely impact flora (Lee, Davies and Power, 2012; van Essen et al., 2011), while air pollution and noise may affect the quality of faunal habitats (Fahrig and Rytwinski, 2009; Jaeger et al., 2005). Ecosystems provide society with essential services, such as purification of air or maintenance of fish stocks for the fishing industry, and these are negatively altered by road nuisances (Parks and Gowdy, 2013). As an influential factor in road nuisances emission, pavement condition is thus expected to affect ecosystems, and consequently, to affect society.

Table 2.1 Environmental impacts identified in road transportation, pavement, and other transportation-related studies

Source	Scope of the study	Study framework (LCA, LCCA or CBA* or Other)	Environmental impacts included: Human health damage	Crop yield and quality	Biodiversity /nature/ ecosystem damage	Building and infrastructural damage	Climate change / global warming	Air pollution	Soil pollution	Water pollution	Noise	Vibrations	Loss of space / Habitat fragmentation	Visual intrusion	Depletion of natural resources	Ozone	Acidification / Eutrophication
Austroads (2000)	Road transportation	CBA	x	x	x	x	x	x		x	x	x	x	x		x	
Zhan and Zhang (2009)	Road transportation	Other	x		x		x	x	x	x	x						
Glazebrook (2009)	Road transportation	Other			x		x	x		x	x						
Ozbay et al. (2007)	Road transportation	Other						x			x						
Santos et al. (2010)	Road transportation	Other	x	x	x		x	x			x	x		x			
Zhang, Keoleian and Lepech (2013)	Pavement	LCCA					x	x									
Santero, Masanet and Horvath (2011a)	Pavement	LCA			x		x	x		x							
Yu and Lu (2012)	Pavement	LCA					x	x									
Huang, Bird and Heidrich (2009)	Pavement	LCA	x				x	x		x	x				x	x	x
Nathman, McNeil and Van Dam (2009)	Pavement	LCA					x	x									
Gosse, Smith and Clarens (2013)	Pavement	Other					x										
Weisbrod, Lynch and Meyer (2009)	Other	CBA	x		x		x	x		x	x			x	x		
Samberg, Bassok and Holman (2011)	Other	LCCA	x	x	x		x	x		x	x	x	x		x		
Thoft-Christensen (2011)	Other	LCCA					x	x	x	x	x	x	x				
Joumard, Gudmundsson and Folkeson (2011)	Other	Other	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

* CBA: Cost-Benefit Analysis

Buildings and infrastructure may be damaged by vibrations and air pollution, especially in urban areas where traffic intensity is higher. Vibrations may lead to deleterious effects on the structure of buildings (Hajek, Blaney and Hein, 2006; Hao, Ang and Shen, 2001), while air pollution affects soils and degrades the facades of buildings, due to both particulate matter

(Rabl, 1999) and acidifying pollutants (van Essen et al., 2011). As pavement condition is known to influence air pollution and vibrations (Al-Hunaidi, Rainer and Tremblay, 1996; Hajek, Blaney and Hein, 2006), pavement condition is thus also expected to influence buildings and infrastructure, with damage resulting from road traffic.

Crops are affected by air, water, and soil contamination. An increase in the concentration of acidifying pollutants in these media is expected to cause a decrease in crop yields, implying a shortfall of food for society (van Essen et al., 2011). Ozone, a secondary air pollutant formed by volatile organic compounds (VOC) and nitrogen oxides (NO_x), is also a relevant concern. Similar to acidifying pollutants, ozone is well known to have detrimental effects on crops (Tong et al., 2007; Vlachokostas et al., 2010). Since traffic emissions affect crops directly through acidifying pollutants and indirectly through ozone, it can be concluded that crops are affected by pavement condition, to a certain extent.

Human welfare, ecosystems, buildings and infrastructure, and crops are thus receptors of nuisances that depend on pavement condition and characteristics. These four receptors should therefore be incorporated into pavement management tools that investigate environmental impacts. Although other receptors (such as natural resources) are included in many studies, environmental impacts affecting other potential receptors are considered less critical in this study, because the scope of this study is limited to the use phase of the pavement life cycle.

2.4 Methods for integration of environment into pavement management

2.4.1 Commonly used methods

Two distinct and complementary evaluation techniques are available to road agencies - life cycle assessment (LCA) and life cycle cost analysis (LCCA). For the purpose of integration of environmental impacts into pavement management practices, these techniques may be used separately, or in a complementary manner. LCA is a technique commonly used to assess environmental impacts caused by products (Rebitzer et al., 2004), and it is increasingly being applied in the pavement management literature (Huang, Bird and Heidrich, 2009). Its primary goal is to incorporate into decision-making processes all environmental impacts that occur through the life cycle of a product, from the extraction of materials to the disposal of residuals. The range of impacts usually considered in LCA may encompass very different concerns, ranging from climate change and depletion of resources, to noise or land use (Rebitzer et al., 2004). The pavement life cycle typically consists of five phases: material, construction, use, maintenance and rehabilitation, and end of life (Santero, Masanet and Horvath, 2011b; Yu and Lu, 2012). Even if LCA is usually applied by agencies in a wide range of projects (including pavement management), very few agencies appear to use this technique adequately, and clearly tend to overlook impacts occurring during the use phase (Santero, Masanet and Horvath, 2011a).

LCCA has been a widely used tool in pavement management for decades (Santos and Ferreira, 2013). Similarly to LCA, LCCA provides a way to incorporate all life cycle impacts of a product into the decision-making process. The particularity of LCCA is that it incorporates costs, including agency costs, user costs, or even other costs, that are estimated according to cost-benefit analysis principles (Lee, 2002; Walls and Smith, 1998). Such a tool is designed to recognize the most efficient investment alternative, i.e. the one having lowest long-term total cost, from among a range of options, (Chan, Keoleian and Gabler, 2008; Office of Asset Management, 2002). Incidentally, LCCA is expected to enhance the sustainability of the road network, since it provides a means to minimize impacts of the road in the long term (Gransberg and Molenaar, 2004). However, the state of practice reveals that LCCA rarely incorporates non-user costs and may thus favor non-optimal alternatives (Chan, Keoleian and Gabler, 2008; Thoft-Christensen, 2011).

In conclusion, LCA and LCCA already provide agencies with two powerful tools that may contribute to enlarging the scope of their responsibilities, and to include environmental impacts in their decision-making processes. In practice, however, some deficiencies have been noted in the use of these tools with respect to their application for properly accounting for environmental impacts. Besides, even recent literature appears to limit the scope of study to a few environmental impacts, or to exclude those impacts occurring during the use phase (e.g. Gosse, Smith and Clarens, 2013; Santos and Ferreira, 2013; Yu and Lu, 2012; Zhang, Keoleian and Lepech, 2013).

2.4.2 Economic value

Pavement management deals not only with technical issues but also with external impacts of various types, including user (e.g. fuel consumption, safety, vehicle damages, etc.) and non-user environmental costs (e.g. air pollution, noise, greenhouse gases emission, etc.). One of the problems faced in incorporating these different impacts into pavement management relates to the difficulty of establishing a standard metric that enables agencies to compare impacts, and to take them into account together with other costs. Whereas agencies that employ LCA avoid this issue by using a set of indicators in addition to agency costs, the ones that employ LCCA use monetary units as standard metrics. The framework of LCCA is thus more suitable to incorporate user and non-user environmental impacts into the decision-making process. Besides, user costs have been incorporated into LCCA within the pavement management sector for almost 20 years (Chan, Keoleian and Gabler, 2008; Salem et al., 2013; Walls and Smith, 1998). Since it is already commonly used, LCCA is thus a convenient tool to incorporate user impacts into pavement management, and as such provides an ideal framework to also incorporate non-user impacts.

Environmental impacts imply market costs as well as non-market costs (Maibach et al., 2008). The incorporation of market costs is easily accomplished by considering damage / repair costs, or control / prevention costs associated with an adverse impact (Maibach et al., 2008; Weisbrod, Lynch and Meyer, 2009). However, incorporating non-market costs along with agency and user costs remains challenging, because of the difficulty in monetizing these aspects. Cost-benefit analysis techniques include several methods, subdivided into revealed or stated preference methods (Figure 2.2). The former method values an impact by observing prices in a surrogate market affected by a particular impact, whereas the latter method relies on surveys from which investigators infer willingness to pay and willingness to accept compensation (i.e. how much people would pay, or what payment people would expect to receive, in order to respectively avoid or accept a particular impact). A detailed presentation of these methods may be found in Pearce, Atkinson and Mourato (2006).

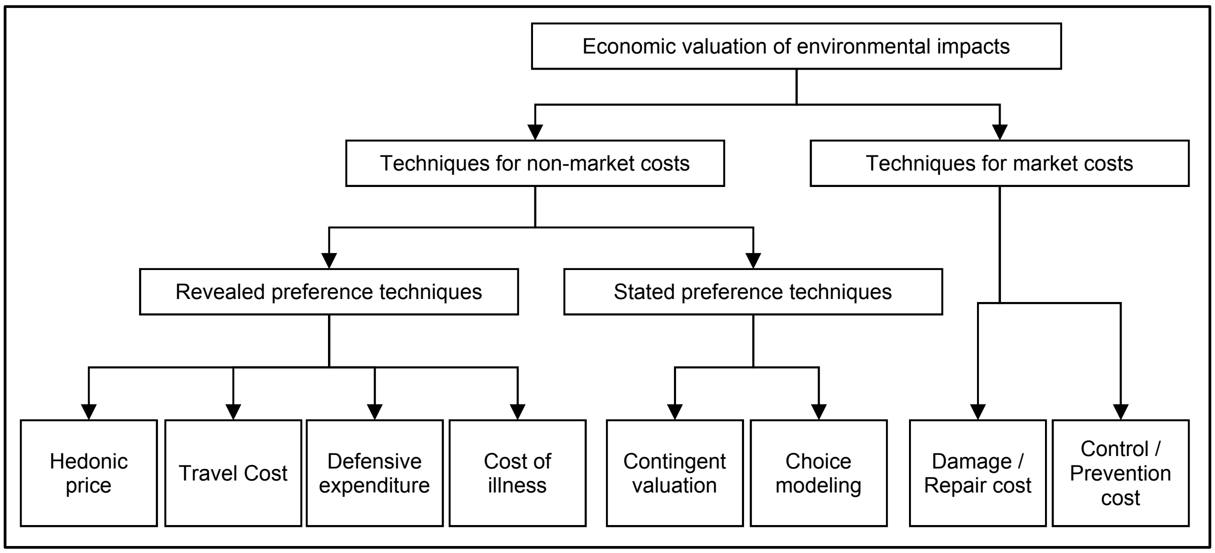

Figure 2.2 Families of techniques for economic valuation of environmental impacts

2.4.3 The impact pathway approach

The impact pathway approach (IPA) has been developed by ExternE projects, independently of tools such as LCA or LCCA. IPA is a bottom-up approach based on determining the economic cost of adverse environmental impacts by following the pathway of nuisances from source emissions, to environmental quality changes, to physical impacts on receptors, and then to costs related to those impacts (Bickel et al., 2006; ExternE, 2004). As such, this approach is similar to the one more recently developed by Joumard, Gudmundsson and Folkeson (2011) that describes causal chains connecting human activities to their associated impacts on a final target (e.g. resources and human health). Used in Europe for over two decades, IPA allows for both monetization of transportation impacts on the environment, and incorporation of these impacts in cost-benefit analysis for policy-making support and assessment (di Valdalbero and Valette, 2011). Figure 2.3 presents the five principal steps of IPA, namely: source, nuisance, concentration, impact, and cost. Each step is linked to the previous by a causal relationship that may be described by a specific model. It must be noted that an outstanding advantage of IPA lies in its use of reliable and transparent monetary valuation of damages, rather than non-market cost techniques (Bickel et al., 2006).

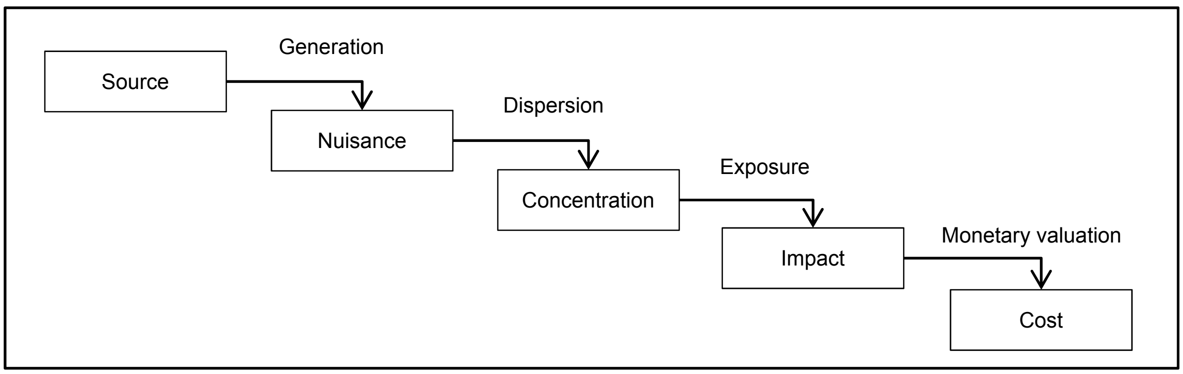

Figure 2.3 Impact pathway method
Adapted from di Valdalbero and Valette (2011)

Primarily designed for incorporating air pollution into life cycle assessment, this approach has recently also been used for the incorporation of noise into the process (Hofstetter and Müller-Wenk, 2005; Michiels et al., 2012; Spadaro and Rabl, 2001). The ability of IPA to both describe how nuisances may affect various receptors, through a sequence of causal relationships, and give transparent economic values for each impact, makes it a versatile approach that is able to provide the conceptual model presented in this paper with reliable market-based economic values associated with environmental nuisances caused by pavement characteristics and condition.

2.5 Conceptual model

Road management decisions, at the project or network level, may cause a change in pavement characteristics that in turn may cause a change in nuisance levels that may in turn lead to a change in impact severity. However, no pavement management tool has yet succeeded in taking into consideration (let alone incorporating) all significant environmental impacts of pavement management. Based on the IPA presented above, the conceptual model described in Figure 2.4 proposes a comprehensive method, formalizing the mechanisms producing nuisances and the links between, on the one hand, nuisance levels and environmental impacts, and, on the other hand, environmental impacts and their associated environmental cost.

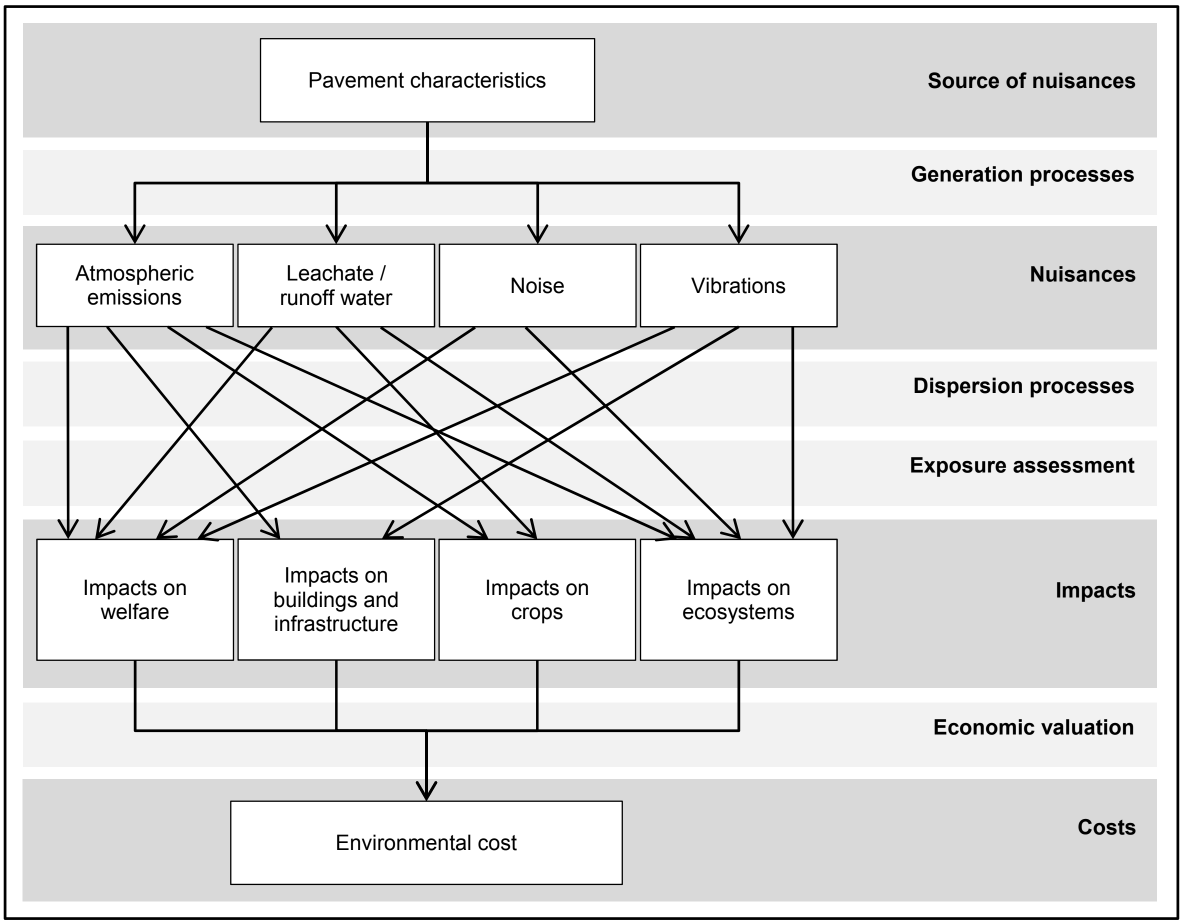

Figure 2.4 Schematic representation of the conceptual model

From a sustainability perspective, every environmental impact induced by pavement management should be taken into account by road agencies. To this end, the conceptual model incorporates all impacts affecting the four sets of receptors identified in Section 2.3.

2.5.1 Identification of nuisance generation processes

As shown in Figure 2.5, nuisances related to pavement management result primarily from pavement characteristics. On a given road, supporting a given level of traffic, the generation of nuisances will be influenced by pavement texture and roughness, as well as pavement materials. First, chemicals present in pavement materials react over time and may migrate from the pavement material to stormwater flowing over the pavement or percolating through it (Apul, Miller and Jain, 2010; Ball, Jenks and Aubourg, 1998; Legret et al., 2005; Santero, Masanet and Horvath, 2011b).

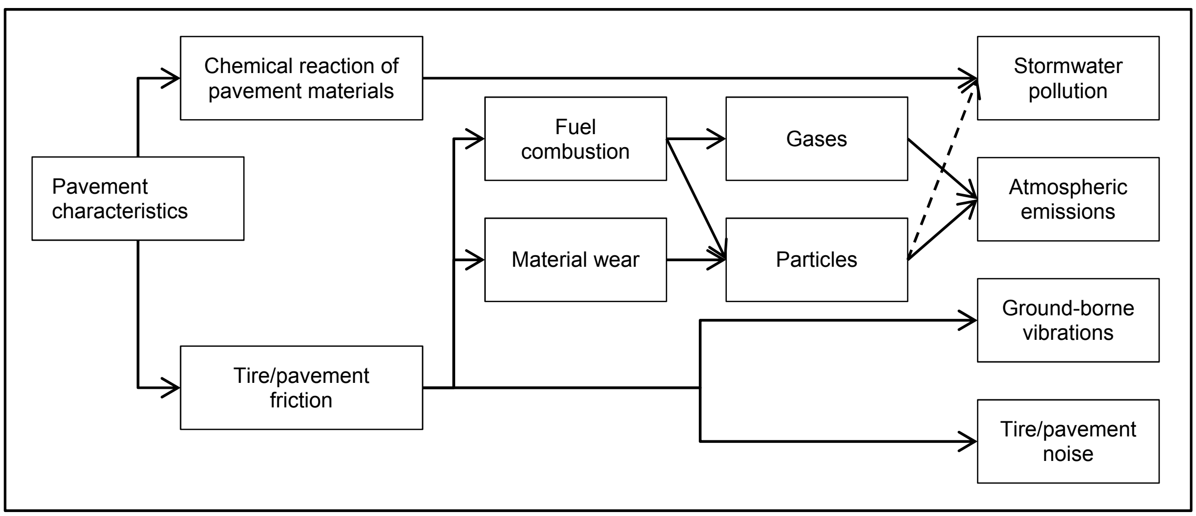

Figure 2.5 Mechanism of nuisance generation

Second, pavement texture (and particularly pavement roughness), affect tire rolling resistance, and thus friction at the tire/pavement interface. Friction at the tire/pavement interface induces: 1) wear of pavement and tire surfaces, producing particles that are suspended in air or deposited on the pavement surface (Dahl et al., 2006; Thorpe and Harrison, 2008), and 2) change in air- and ground-borne vibrations, with the former constituting noise and the latter affecting buildings (Ahammed and Tighe, 2010; Crispino and D'Apuzzo, 2001). Moreover, rolling resistance influences the power needed to move vehicles, consequently requiring an increase in fuel combustion, in turn leading to an increase in exhaust gases and particle emissions (Gillespie and McGhee, 2007; Ropkins et al., 2009). These particles, which additionally contribute to air pollution, are in part deposited on the pavement surface along with particles from tire and pavement wear. Such deposits are then either resuspended in air because of traffic and wind turbulence, thus contributing to air pollution and affecting drinking water (Berger and Denby, 2011; Lin et al., 2008), or are transported by stormwater, affecting runoff and leachate (Apul, Miller and Jain, 2010; Kayhanian et al., 2009).

2.5.2 Quantification of the impact of nuisances on receptors

Figure 2.6 shows how environmental nuisances (atmospheric emissions, stormwater pollution, tire/pavement noise, and vibrations) impact the four classes of receptor previously identified (human welfare, buildings and infrastructure, crops, and ecosystems). For the purpose of quantifying these impacts, the relevant mechanisms are described in the following sections.

2.5.2.1 Atmospheric emissions

Figure 2.6(a) outlines the two types of atmospheric emissions that may be distinguished for the purpose of estimating their impacts on the environment: (i) short-range emissions, having local and regional impacts, and (ii) long-range emissions, having global impacts.

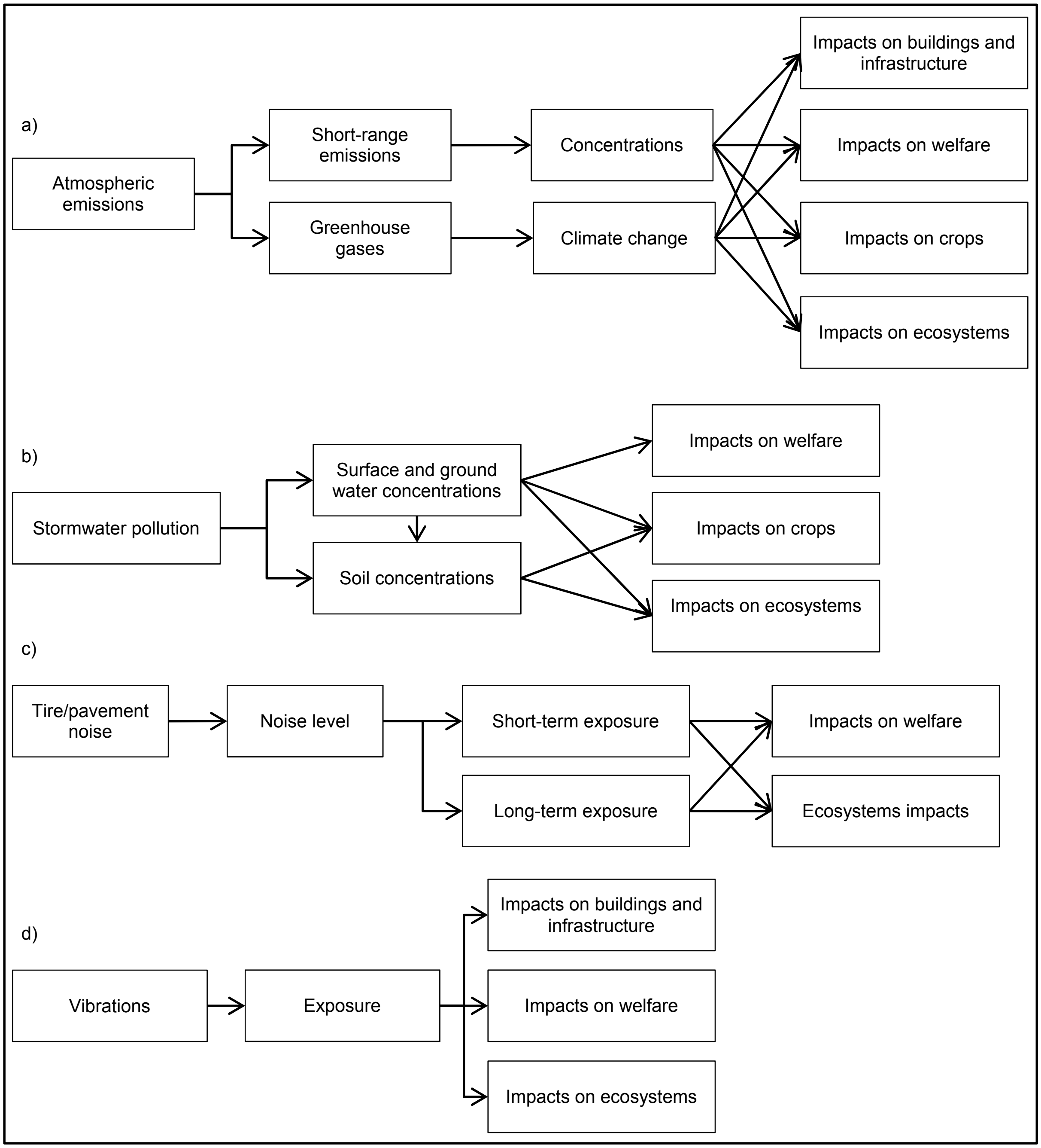

Figure 2.6 Impacts caused by a) atmospheric emissions, b) stormwater pollution, c) noise, and d) vibrations

Short-range emissions arise mainly from pollutants such as PM, SO_x, and NO_x (Gullì, 2006). Dispersion of short-range atmospheric emissions occurs mainly due to wind. The concentration of pollutants depends on wind direction and strength, as well as on distance between the road and the point at which concentrations are measured (Lin et al., 2008; Venkatram et al., 2009). Receptor exposure to a certain atmospheric emission thus depends on its position relative to the source, i.e. the road. Receptors affected by atmospheric pollutants are human welfare (Kunzli et al., 2000), buildings (Rabl and Spadaro, 1999), crops (van Essen et al., 2011), and ecosystems (Bignal et al., 2007), with each of these affected by different kinds of impacts, as detailed in Section 2.3. The severity of an impact associated with an atmospheric pollutant may be assessed through the use of dose-, concentration- or exposure-response functions (Hoek et al., 2009; Lepeule et al., 2012). For example, these functions can be used to estimate an increase in mortality or an increase in hospital admissions due to an increase in PM concentrations over a certain period of time.

Long-range emissions are mostly related to greenhouse gas emissions that contribute to global warming, inducing changes in climate (Gullì, 2006). Given that global warming occurs due to an increasing concentration of greenhouse gases in the global atmosphere, and given that concentrations of these gases are not affected by the location of their sources, modeling dispersion of such long-range emissions is not necessary. Impacts of climate change are well known, and have implications for welfare, crops, ecosystems, as well as for buildings and infrastructure (Steen, 1999; van Essen et al., 2011; Watkiss, 2011). However, the severity of impacts affecting these receptors remains somewhat uncertain, relative to impacts arising from atmospheric pollutants, because of the unpredictability of: (i) political decisions to address climate change, (ii) future socio-economic growth that may constrain choices regarding mitigation of greenhouse gas emissions, (iii) future technology that helps mitigate greenhouse gas emissions, and (iv) non-climate policy impacts on greenhouse gas emissions (IPCC, 2007).

2.5.2.2 Leachate and runoff water

Leachate and runoff water, when converted to stormwater, which is polluted by road traffic, directly and indirectly affects human welfare, crops and ecosystems, as shown in Figure 2.6(b). Stormwater pollutants are diluted in surface water and then percolate through the soil to reach groundwater, thus directly affecting human welfare, particularly in locations where people drink water supplied by groundwater wells (Fletcher, Andrieu and Hamel, 2013). Moreover, crops watered with contaminated water are negatively affected, (Ayers and Westcot, 1985), as are ecosystems in areas contamination (Moiseenko and Sharov, 2011).

Soils may also absorb pollutants dissolved in stormwater flowing on its surface or percolating through it (Fletcher, Andrieu and Hamel, 2013). Species (including both agricultural crops and species within natural ecosystems) growing on soils contaminated by stormwater are consequently contaminated by pollutants accumulated in soil (Fernández, Vega and Tarazona, 2006; Tijani, 2009; Yu and Zhao, 2012). Additionally, the health of people eating crops grown on such soils may be affected by whatever pollutant residue is present (Tijani, 2009; Yu and Zhao, 2012).

Although well identified, impacts of stormwater pollution on human welfare, crops, and ecosystems have never been specifically quantified in terms of severity, most probably because of the complexity of the impact pattern of water pollution (Maibach et al., 2008). Efforts have, however, been made to assess the impacts of contamination levels on different species, and to describe the pathway that pollutants follow to eventually contaminate crops, ecosystems, and human consumers (European Union, 2010; Potting and Hauschild, 2005).

2.5.2.3 Noise

The impact of noise, which is a mechanical wave transmitted through air, is reduced with distance from the source, because of the dissipation of noise energy in air (Cucurachi, Heijungs and Ohlau, 2012; Herman and Withers, 2005). For example, if the distance between the receptor and the road doubles, the noise level decreases by 3dB. Furthermore, in the case of a receptor located sufficiently far from the road, the ambient noise level at the receptor location may not be significantly affected by noise emitted at the road. This explains why noise impacts tend to only be assessed with reference to receptors located along the road. However, one should consider whether traffic noise is contributing significantly to ambient noise, or whether it is affecting receptors located further away (Müller-Wenk, 2002; Rymer and Donavan, 2011).

Impacts of noise on human welfare depend not only on the level of noise during exposure but also on the duration of exposure (Cucurachi, Heijungs and Ohlau, 2012). A simplified description of the mechanism is presented in Figure 2.6(c). Short-term exposure to noise provokes temporary hearing impairment, interference with speech communication, and sleep disturbance (WHO, 1999). Long-term or high-level exposure to noise induces physical health concerns such as permanent hearing impairment or cardiovascular diseases (Babisch, 2002; WHO, 1999). The nature and severity of these impacts affecting human welfare are usually assessed by means of dose-response functions (Babisch, 2002; 2005b; Cucurachi, Heijungs and Ohlau, 2012; Laszlo et al., 2012).

Noise also has an influence on animals, by damaging their health and habitat (Nega et al., 2012; Neus and Boikat, 2000; Slabbekoorn, 2010). Since ecosystems provide society with a variety of services, such as opportunities for hunting or fishing, noise impacts affecting ecosystems also affect society (Parks and Gowdy, 2013). The nature of impacts of noise on ecosystems is similar to the nature of impacts of noise on human welfare; however, no study has yet quantified the impact of a change in noise level on ecosystems (Cucurachi, Heijungs and Ohlau, 2012; Neus and Boikat, 2000). Still, scientific progress in this domain facilitate the future incorporation of such impacts (Cucurachi, Heijungs and Ohlau, 2012).

2.5.2.4 Vibrations

Vibrations caused by traffic mainly occur in the form of ground-borne mechanical waves; as a result, the amplitude of vibrations becomes lower with increase in the distance between the receptor and the source, because of the dissipation of energy in the ground (Hajek, Blaney and Hein, 2006). Ground dissipation of waves is greater than dissipation of waves through the air; due to this fact, the assessment of vibration impacts differs from that of noise impacts. Assessment of vibration impacts on receptors located along a road should be an automatic consideration. With respect to receptors located further away, one should first determine whether any traffic-induced vibrations will be experienced.

Vibrations damage building structure; this is particularly true for historical urban centers, within which are old buildings that have not been designed to resist heavy traffic-induced vibrations, (Bickel et al., 2006; Crispino and D'Apuzzo, 2001). As shown in Figure 2.6(d), vibrations may also impact human welfare and ecosystems, in a similar manner to noise (Hao, Ang and Shen, 2001; Hunaidi and Tremblay, 1997; United Nations, 2001).

No general formal relation has been formulated to quantify the response of buildings and infrastructure to vibrations, mainly because of the difficulty of apportioning vibration damages resulting from road traffic (Austroads, 2000; Hunaidi and Tremblay, 1997). As in the case of other nuisances, the impacts of vibrations on human welfare and ecosystems may be described by exposure-response functions; to the best knowledge of the authors, however, no such functions have yet been developed. Given that noise and vibrations, both being mechanical waves, are emitted in conjunction, their associated damages are expected to be correlated (Austroads, 2000). Thus, Austroads (2000) notes that in most cases estimation of noise impacts incorporates vibration impacts, which consequently do not deserve to be separately assessed.

2.5.3 Monetization of the impact of nuisances

Giving an economic value to environmental impacts induced by pavement management is essential for the purpose of incorporating them into LCCA. Based on a literature survey (Austroads, 2011; Bickel et al., 2006; Maibach et al., 2008; van Essen et al., 2011; Weisbrod, Lynch and Meyer, 2009), Table 2.2 presents the preferred approaches to value environmental impacts on each kind of receptor. For the purpose of this conceptual model, the monetization process is performed primarily on the basis of damage and repair cost approaches, with alternatives and/or complements from other approaches. The rationale behind this is that damage and repair costs are based on reliable objective market costs, whereas alternative and complementary valuation methods are mainly based on less transparent costs, which are derived from surveys and observations of market behavior.

Table 2.2 Economic valuation methods, according to receptor impacted

Impact receptors	**Main valuation approach**	**Alternative and/or complementary valuation approach**
Buildings and infrastructure	Repair cost	
Welfare	Repair cost (medical cost)	Contingent valuation Hedonic price
Crops	Damage cost	
Ecosystems	Repair cost	Contingent valuation Compensation cost

Several authors assess building and infrastructure impacts through the repair cost approach (Austroads, 2000; Maibach et al., 2008; Murphy and Delucchi, 1997), and this approach is adopted in this work. The cost of these impacts is considered to comprise the cost associated with repairing the infrastructure and the building structure, as well as the cost associated with repairing and cleaning of the building envelope. In the specific case of damage due to vibrations, the repair cost of the building may be approximated with the repair cost of the pavement located in front of the building, provided that this repair cost covers the repair of damages caused by vibrations (Murphy and Delucchi, 1997; Rabl and Spadaro, 1999).

Welfare impact costs represent the largest share of total environmental cost (ExternE, 2004; van Essen et al., 2011). The welfare impact cost may be appraised by the use of what are referred to as health costs. Health costs encompass market costs (such as medication costs), as well as non-market costs (such as costs related to productive and leisure time loss or to annoyance) (Boesch et al., 2008; Molemaker, Widerberg and Kok, 2012; Turner et al., 2004; van Essen et al., 2011). A portion of health-related market costs (e. g. medication, hospital admission) may be classified as “repair” costs associated with the healing process of affected people. Welfare impacts related to annoyance or time loss are intangible costs that may be valued according to the willingness to pay of affected people (Nijland and van Wee, 2008;

van Essen et al., 2011). Also considered as a welfare impact, mortality is appraised using the value of a statistical life estimated by contingent valuation, i.e. derived from surveys (Kruger and Svensson, 2009; Molemaker, Widerberg and Kok, 2012; Vassanadumrongdee and Matsuoka, 2005). Conversely, when no market costs are available, non-market costs may be inferred through contingent valuation or revealed preference techniques. The hedonic market approach is an example of the latter, which has been extensively used in the valuation of noise impacts (Austroads, 2011; Nijland and van Wee, 2008).

Impacts on crops are usually quantified as a decrease in crop yields. Impacts associated with this decrease are thus valued through a damage cost approach that assigns a market value to crop losses (Austroads, 2000; Bickel et al., 2006; Turner et al., 2004; van Essen et al., 2011). Valuing ecosystem impacts is, however, a rather difficult task, because of gaps in scientific knowledge concerning how ecosystems function and how ecosystem services are interrelated (Pearce, Atkinson and Mourato, 2006; Turner et al., 2004). Despite these difficulties, the repair cost approach, which implies costing the restoration of impacted ecosystems, represents the best available way to value ecosystem impacts (Austroads, 2000; ExternE, 2004; Maibach et al., 2008; van Essen et al., 2011). Alternatively, when no restoration cost is available, contingent valuation methods, such as the willingness to pay approach, may be applied (Turner et al., 2004). Moreover, the specific cost associated with loss of habitat may be assessed as the cost of creating a compensatory ecosystem, similar in quality to the lost one (Maibach et al., 2008).

2.6 Discussion

From a sustainability perspective, the traditional scope of responsibility of pavement management departments is delimited by three kinds of boundaries: (i) it only includes pavement condition; (ii) it only considers their administrative area; and, (iii) it covers relatively short-term effects. However, incorporating sustainability concerns into pavement management implies that pavement management departments need to enlarge the scope of their analyses. On the basis of recent studies (e.g. Huang, Bird and Heidrich, 2009; Santos et al., 2010; Thoft-Christensen, 2011), the conceptual model presented here proposes a framework that stretches the limits of standard pavement management, by incorporating environmental impacts, including long-term impacts (such as chronic health issues) and wide-ranging impacts (such as climate change).

In accordance with the principles underlying the impact pathway (ExternE, 2013) and causal chain approaches (Joumard, Gudmundsson and Folkeson, 2011), the conceptual model describes how environmental nuisances induced by pavement condition affect specific receptors. First, this description results in defining the environment system as being limited to four receptors affected by pavement condition (namely human welfare, ecosystems, buildings and infrastructure, and crops), with these also recognized as receptors of environmental nuisances in other studies (see e.g.Cucurachi, Heijungs and Ohlau, 2012; Joumard, Gudmundsson and Folkeson, 2011; Santos et al., 2010). Second, this description leads to a detailed characterization of processes involved in the generation and dispersion of nuisances, of mechanisms generating impact on receptors, and of methods of economic valuation of those impacts. The conceptual model thus provides a comprehensive and transparent framework for the purpose of developing practical pavement management tools within which environmental impacts are integrated.

Through the identification of receptors affected by environmental nuisances, and through evaluation of the causal links between nuisances and receptors, the conceptual model helps modelers avoid three major issues. The first issue relates to some causal links, for which methods may be missing or for which methods require improvement. This is the case for impact pathways of nuisances other than noise or air pollution that are known to require further investigation (Chan, Keoleian and Gabler, 2008; Turner et al., 2004), and for the mechanistic relationship between pavement characteristics and fuel consumption that still needs to be elaborated (Santero, Masanet and Horvath, 2011a). However, the significance of knowledge gaps and their relative impact on the development of a suitable tool may be circumvented in some cases. For instance, the absence of a mechanistic relationship between pavement characteristics and fuel consumption is not prohibitive, since this does not prevent modelers from using existing empirical and reliable relationships (see Bennett and Greenwood, 2001).

Second, monetization of environmental impacts is often considered uncertain and thus unreliable (Pearce and Seccombe-Hett, 2000). Although uncertainty does not prevent a practical tool based on this conceptual model from providing a pavement management department with useful information, modelers may want to further reduce the uncertainty of costs resulting from the tool. Thus, by clearly describing causal links between nuisances and their associated costs, the conceptual model helps modelers determine which impact pathways are most subject to uncertainty because of lack of scientific data. This helps modelers identify which impact pathways need to be detailed, so that methods and knowledge used to put the conceptual model into practice involve less uncertainty. For example, developing the noise health effects pathway by determining the number of cases of health effects related to noise would allow the use of a "medication costs" variable; such variables would be more reliable than economic values usually determined through revealed preference techniques.

Third, lack of understanding of mechanisms linking nuisances and their effects on receptors leads to some impacts being neglected or others being double-counted (Joumard, Gudmundsson and Folkeson, 2011; Santero, Masanet and Horvath, 2011b). For instance, impacts of ozone may already be considered under the umbrella of impacts of air pollution, since ozone results from chemical reaction of primary air pollutants. Such issues can be avoided by defining simple and transparent relationships between nuisances and their various impacts on receptors, consequently allowing for gaps to be identified, with respect to reliable methods and practical tools.

The design of a practical tool based on the conceptual model and intended to assist pavement management departments in their decision-making process may involve challenges related to both methods and data. Processes (e.g. how vibrations affect human health) and data (e.g. magnitude of climate change) involved in impact pathways may be unclear or uncertain due to gaps in scientific knowledge (Hunaidi and Tremblay, 1997; van Essen et al., 2011) and, as mentioned above, mechanistic models may be unavailable because of a lack of scientific evidence or due to gaps in scientific knowledge. However, since environmental impact assessment is a recent but fast progressing field of research, one should pay attention to newly available methods that might help bridge gaps for model development. Furthermore, in most cases, empirical models remain appropriate and sufficient for the purpose of incorporating costs related to environmental impacts into pavement management processes. In fact, even if practical tools do not provide reliable environmental costs for certain purposes, they still provide estimates of the order of magnitude of associated costs. Thus, the use of practical tools developed on the basis of this conceptual model should at first be limited to strategic decisions at the network level; the latter does not require accurate figures but rather, orders of magnitude. In later stages, as data becomes available and the knowledge base is improved, tools will be able to provide more accurate and precise estimates suitable for use in management at project level.

Finally, it must be noted that, unlike in the case of management methods, models developed for a specific region may not apply to another region (Hofstetter and Müller-Wenk, 2005). Thus, local data collection supporting parameterization of these models is essential in order to ensure reliable quantitative results. Data required to develop a practical tool includes road and traffic data, climatic data, receptor data, and economic data. Road and traffic data (e.g. roughness of pavement types and vehicle speed distribution), which are essential to calculate nuisance generation, are typically collected by a road agency. Climatic data (e.g. average wind velocity and direction), which help refine nuisance dispersion models, are obtained from meteorological offices. Receptor data, needed in order to quantify impacts caused by road traffic, may be collected in the field (e.g. distance from the road) or from national health organizations (e.g. prevalence of disease related to noise and air pollution). Economic data, which allow the monetization of environmental impacts, may be available from national health organizations (e.g. cost of medication) or obtained through field studies (e.g. economic values captured by contingent valuation, such as the value of a statistical life).

2.7 Conclusion

The impacts of pavement characteristics on the environment are now well established and are believed to significantly affect social welfare, inducing costs that are eventually borne by the public. Nonetheless, the incorporation of environmental impacts into agencies' decision-making processes is considered to be barely feasible, because of insufficient scientific knowledge, especially in the case of impacts occurring during the use phase of the pavement life cycle. However, the impact pathway approach (IPA) is able to estimate the costs of many environmental impacts. Moreover, given that life cycle cost analysis (LCCA) is a widely used and accepted approach in pavement management, LCCA represents a suitable tool to use for incorporation of environmental impacts related to pavement condition into pavement management.

The conceptual model presented in this paper thus relies on the integration of IPA and LCCA for the purpose of supporting a sustainable decision-making process. On the basis of this conceptual model, this study demonstrates that pavement management influences environmental impacts occurring during the use phase of the pavement life cycle. It establishes causal links between pavement management and nuisance generation, between nuisances and their impact on four classes of receptors (human welfare, ecosystems, buildings and infrastructure, and crops) and, finally, between these impacts and their environmental costs. This study also proves the feasibility of incorporating environmental impacts into pavement management systems and describes how existing methodologies and tools may be integrated to support this incorporation.

The conceptual model presented in this paper thus represents a comprehensive framework, which can provide a basis for building practical tools intended for incorporating environmental impacts into pavement management systems. It also helps modelers identify and circumvent issues pertaining to the development of practical tools. It appears that, at first, such tools can only be used for strategic network-level management decisions, because of current inaccuracies in scientific knowledge and limitations of available data. Later, as scientific knowledge progresses and more data become available, practical tools may be developed based on this conceptual model, to support project-level decisions that require more accuracy.

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CHAPITRE 3

INFLUENCE OF PAVEMENT CONDITION ON ENVIRONMENTAL COSTS

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3.1 Abstract

Pavement conditions significantly influence the generation of nuisances that influence the environment and induces costs borne by society. This paper presents a new tool designed to monetize and incorporate environmental impacts in decision-making processes. The Pavement Environmental Impact Model (PEIM) is the first attempt to adapt the Impact Pathway Approach (IPA) to assess the emission, dispersion, and impacts of noise, air pollution, and greenhouse gases so that environmental impacts can be included in the economic model of pavement management units. Results of a simulation performed with PEIM for an urban collector road with an annual average daily traffic of 10,000 vehicles per day and a linear density of 240 people per kilometer show that environmental costs ranged from 876,000 to 1,983,000 Canadian dollars per kilometer per year for pavement roughness ranging from 1 to 4 m/km. Moreover, although noise cost is consistently disregarded in pavement management, it represented 55% of the total environmental cost when pavement roughness was above 1.75 m/km. Results demonstrate that PEIM is a suitable tool to roughly estimate environmental costs and to help pavement management units choose the optimal alternative of management.

3.2 Introduction

Road traffic is recognized as a major source of environmental nuisances, such as noise (World Health Organization (WHO) 2011), air pollution (WHO 2013), and greenhouse gases (Environmental Protection Agency, 2012). These nuisances significantly and adversely influence the environment in the long term and, consequently, the sustainable development of our society. Because pavement characteristics have a significant influence on the generation of environmental nuisances (Santero et Horvath, 2009; Zhang et al., 2010), road agencies are expected to incorporate environmental concerns in their decision-making processes to improve the sustainability of the pavement network.

Over the past two decades, several studies addressing the link between environmental impacts and road traffic have provided techniques and tools to help road agencies account for social and environmental concerns. Two main methods arose from these studies. First, life cycle assessment (LCA), which is not specific to transportation, is a typical method to integrate environmental concerns (Santero, Masanet and Horvath, 2011b). Second, life cycle cost analysis (LCCA), which is widely used by road agencies, represents a suitable framework for integration of sustainability concerns in pavement management (Ozbay et al., 2004a). However, most LCA and LCCA applications ignore environmental impacts that occur during the use phase of a pavement's life cycle, such as environmental impacts caused by road traffic, although this is by far the longest phase of a pavement's life cycle (Chan, Keoleian and Gabler, 2008; Gosse, Smith and Clarens, 2013; Santero, Masanet and Horvath, 2011b).

Zhang, Keoleian and Lepech (2013) recently integrated LCA and LCCA into a single tool to establish environmental impacts occurring during the use phase. However, environmental impacts included in their study are limited to global warming and air pollutant effects on human health and the corresponding environmental costs are roughly estimated with respect to the unit damage cost of each pollutant. Based on LCCA and Impact Pathway Approach (IPA) principles, the conceptual model developed by Pellecuer, Assaf and St-Jacques (under

review), shows that current knowledge is available from different research fields for integration into a comprehensive practical tool suitable for pavement management units.
Thus, the purpose of this study is to develop a new tool for assessment of environmental costs. Based on the conceptual model of Pellecuer, Assaf and St-Jacques (under review), this tool assesses the annual environmental impact during the use phase of a pavement's life cycle and estimates the associated costs. This tool, referred to as the Pavement Environmental Impact Model (PEIM), is intended to assess environmental nuisance emission, dispersion, and impacts, and also to assign an economic value to these impacts that can be used in LCCA. The following section presents the model's architecture and describes how pavement characteristics influence environmental impacts related to atmospheric emissions and noise. The model is then evaluated using a sensitivity analysis and the results of a case study. The paper concludes with a discussion of the results and an assessment of the potential and limits of PEIM.

3.3 Model description

3.3.1 Model architecture

PEIM is designed to appraise the economic value of annual environmental impacts due to traffic on a road section. PEIM integrates current scientific knowledge to estimate environmental nuisance generation and dispersion as well as to quantify and monetize the resulting environmental impacts. A graph of the PEIM architecture including the links between the inputs required to run the model, modules that compose the model, and outputs provided by the model is presented in Figure 3.1.

Four types of input are required to run the model: traffic data, climate data, receptor data, and road data. In order to ensure wide suitability to pavement management units, the required data is easily accessible or can be easily estimated. Traffic data comprises annual average daily traffic (AADT), cumulative traffic volume, percentage of heavy vehicles, and average vehicle speed. Receptor data includes the distance from the receptor to the road and the linear population density along the road section. Climate data is limited to average wind velocity and direction. Road data encompasses geometric data typically available at road agencies (length of the road section as well as width and number of traffic lanes) and pavement characteristics that are usually monitored by pavement management units (pavement roughness, texture, deflection, and surface age). Distresses such as cracking and potholes are also part of road data and are usually monitored by pavement management units. Such distresses are expected to influence the intensity of environmental nuisances and the resulting environmental impacts. However, they are not considered in PEIM because of the lack of scientific knowledge on the link between the severity of pavement distresses and the intensity of environmental nuisances.

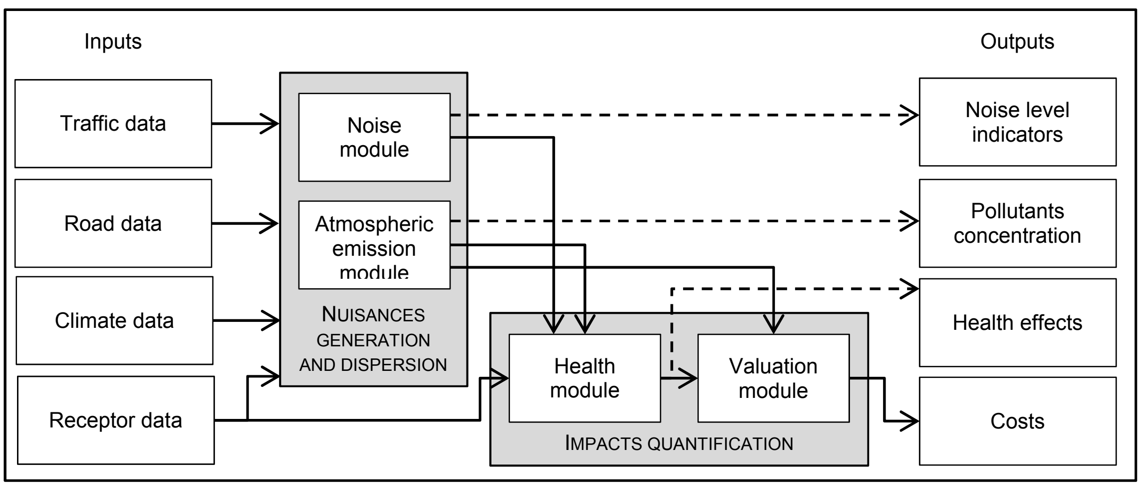

Figure 3.1 Schematic architecture of PEIM with arrows representing the links between inputs, modules, and outputs (dashed arrows emphasize the link between modules and intermediate outputs)

Based partially on the IPA, PEIM consists of four modules describing the impact pathways of noise and atmospheric emissions from the generation and dispersion of these nuisances, and the quantification and valuation of the associated impacts.

The atmospheric emission module computes the fuel consumption of vehicles travelling on the studied road section, the associated amount of chemicals released into the atmosphere, and the concentration of air pollutants at the receptor location.

The noise module computes the noise energy emitted from road traffic and the resulting noise level at the receptor location.

The health module estimates the human health damage from air pollution and noise on receptors with concentration- and exposure-response functions, respectively, which establish the relationship between air pollutant concentration and noise level, and the number and severity of health cases.

The valuation module assigns an economic value to each of the health cases determined by the health module and to each amount of atmospheric emission estimated by the atmospheric emission module that causes environmental impacts other than human health effects (e.g., global warming and building damage). This last economic valuation is performed with exposure-response and exposure-cost functions that describe the relationship between the amount of chemicals released into the atmosphere and the associated environmental impacts and costs.

Given that PEIM aims to compare pavement management alternatives, the assessment of environmental impacts due to controlled intersections, congestion, change in road grade, road alignment, vehicle load and condition, and driving style are out of the scope of this study. This implies that both engine and vehicle speeds are assumed to remain constant, and consequently, changes in the generation of environmental nuisances are assumed to be solely due to changes in pavement characteristics and surface conditions. As mentioned above, pavement surface conditions are estimated based on pavement roughness and do not include distresses such as cracking and potholes. Thus, pavement roughness is assumed to adequately represent the pavement condition.

The main output of PEIM is the total annual environmental cost of a road section (in $CA\$_{2000}$). However, detailed environmental costs may be obtained for noise and atmospheric emissions (e.g., noise annoyance costs and global warming costs). In addition, intermediate outputs may be extracted from the noise module (e.g., noise level at the receptor location), the atmospheric emission module (annual amount of CO_2 emitted), and the health module (e.g., number of myocardial infarction).

The area of application of PEIM is limited by the assumptions described above and by the uncertainties pertaining to the model and the values of parameters. These limitations and the related impact they have on the model outputs are listed in Table 3.1.

Table 3.1 Limitations of PEIM

Source	**Limitation**	**Impact**	
		Precision of the outputs	**Minimization of the total cost**
Lack of knowledge	Not all types of pavement distresses considered	x	
	Not all impacts considered		x
	Not all receptors considered		x
Hypothesis	Road considered as a straight line	x	
	Traffic considered continuous	x	
	Engine and vehicle speed considered constant	x	
	Roughness considered to represent pavement condition	x	
	Pavement considered always dry	x	
	Exposure-response and exposure-cost functions considered to be the same in North America and Europe	x	
	No noise barrier considered	x	
	Unit costs considered to be the same in North America and Europe	x	

3.3.2 Atmospheric emissions

Atmospheric emissions caused mainly by fuel combustion (Bennett and Greenwood, 2001) by traffic cause different types of adverse impacts on the environment (e.g., health damages and biodiversity loss). Thus, to assess the environmental impacts of atmospheric emissions, PEIM computes the fuel consumption and estimates the amount of chemicals released into the atmosphere based on the fuel combustion reaction. Then, regarding human health effects, PEIM estimates the concentration of air pollutants at receptors' location, determines the nature and severity of the impacts with concentration-response functions that provide the number of the different health cases, and assigns an appropriate economic value to each health case. Regarding effects other than those on human health, an exposure-cost function is directly applied to the amount of chemicals released into the atmosphere to estimate the cost of atmospheric emissions.

3.3.2.1 Fuel consumption and atmospheric emissions

Fuel consumption is required mainly to overcome traction forces, including rolling resistance that is caused by pavement characteristics. Rolling resistance for vehicle class i on road section s ($Fr_{i,s}$) is given by Equations 3.1 and 3.2 as presented in Bennett and Greenwood (2001) and calibrated by Chatti and Zaabar (2012) for US conditions.

$$Fr_{i,s} = CR2_{i,s} * FCLIM * \left(b11_i * Nw_i + CR1_i * \left(b12_i * M_i + b13_i * v_{i,s}^2\right)\right) \quad [N] \tag{3.1}$$

$$CR2_{i,s} = Kcr2_i * (a0_i + a1_i * Tdsp_s + a2_i * IRI_s + a3_i * DEF_s) \tag{3.2}$$

where $CR2_{i,s}$ is the rolling resistance factor for vehicle class i on road section s, $FCLIM$ is a climatic factor related to the percentage of driving on snow or wet surfaces, $b11_i$ to $b13_i$ are rolling resistance parameters for vehicle class i, Nw_i is the number of wheels for vehicle class i, $CR1_i$ is the rolling resistance tire factor for vehicle class i, M_i is the mass of vehicle class i (tons), $v_{i,s}$ is the vehicle speed on road section s (m/s), $Kcr2_i$ is the calibration factor for vehicle class i, $a0_i$to $a3_i$ are rolling resistance coefficients for vehicle class i, $Tdsp_s$ is the texture depth of road section s obtained from the sand patch method (mm), IRI_s is the roughness of road section s (m/km), and DEF_s is the Benkelman Beam rebound deflection of road section s (mm). For the purpose of this study, it is assumed that the pavement is always dry; therefore, the value of the variable $FCLIM$ is set to 1.

Fuel consumption for vehicle class i on road section s ($FC_{i,s}$) is modeled by the HDM-4 equation that has been calibrated by Chatti and Zaabar (2012) for US conditions:

$$FC_{i,s}=\frac{10^3}{v_{i,s}} * \left(\max\left(\alpha_i,\xi_{i,s} * \left(P_{tr_{i,s}}+P_{engaccs_{i,s}}\right)\right)\right) \quad [mL/km] \tag{3.3}$$

where $v_{i,s}$ is the speed of vehicle class i on road section s (m/s), α_i is the fuel consumption at idling for vehicle class i (mL/s), $\xi_{i,s}$ is the engine efficiency for vehicle class i on road section s (mL/kW/s), $P_{tr_{i,s}}$ is the power required by vehicle class i on road section s to overcome traction forces calculated with Equation 3.1 (kW), and $P_{engaccs_{i,s}}$ is the power required by vehicle class i to overcome internal engine friction and to support engine accessories on road section s (kW). Equations providing $\xi_{i,s}$ as well as $P_{tr_{i,s}}$ and $P_{engaccs_{i,s}}$ are given in Chatti and Zaabar (2012).

Several atmospheric emissions from vehicle fuel combustion adversely impact the environment. Therefore, quantifying these emissions is crucial in assessing their impact on the environment. Estimations of the emission of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), and particulate matter with a diameter of 10 µm or less (PM_{10}) are based on Equation 3.4 and presented in Bennett and Greenwood (2001). Carbon dioxide (CO_2) emissions are inferred from other emissions by using the chemical equation based on carbon balance presented in Journard et al. (2007). The emission of particulate matter with a diameter of 2.5 µm or less ($PM_{2.5}$) is inferred from the PM_{10} emission, assuming that the ratio $PM_{2.5}/PM_{10}$ equals 0.6 (Agence française de sécurité sanitaire environnementale (AFSSE) 2004).

$$TPE_{i,j,s} = EOE_{i,j,s} * CPF_{i,j} \quad [g/km] \tag{3.4}$$

where $TPE_{i,j,s}$ is tailpipe emission of emission j for vehicle class i on road section s, $EOE_{i,j,s}$ is the engine emission of emission j from vehicle class i on road section s (g/km), which is a function of $FC_{i,s}$ and $v_{i,s}$ (see Bennett and Greenwood (2001)), and $CPF_{i,j}$ is the catalyst pass fraction of emission j from vehicles of class i as defined in Bennett and Greenwood (2001). For tailpipe emission, the instantaneous emission rate for vehicle tailpipe emission j on road section s ($ER_{j,s}$) is given by

$$ER_{j,s} = \frac{1}{8.64*10^{10}} * \sum_i TPE_{i,j,s} * a_i * AADT_s \qquad [\mu g/s/km] \qquad (3.5)$$

where $AADT_s$ is the annual average daily traffic on road section s, a_i is the proportion of vehicle class i in the annual average daily traffic, and the factor of $8.64*10^{10}$ is a conversion factor (from g/day/km to μg/s/km).

3.3.2.2 Atmospheric emissions dispersion

Because environmental impacts assessed in this study are either local or global, atmospheric emissions are split into two classes: short range emissions encompassing local and regional atmospheric emissions (e.g., particulate matter) and long range emissions (e.g., greenhouse gases). The severity of the impacts due to short range emissions depends on the concentration of the emission at the receptor location, while the severity of the impacts due to long range emissions depends on the global concentration of the gases. Therefore, estimation of emissions dispersion is only required for short range emissions.

Given that road traffic is a continuous linear source, dispersion of short range emissions may be assessed by considering plume dispersion modeling as explained in Hanna, Briggs and Hosker (1982). Equation 3.6 provides the additional concentration of emission j due to traffic on road section s at receptor location ($C_{j,s}(x^{eff})$) (Venkatram and Horst, 2006).

$$C_{j,s}(x^{eff}) = \sqrt{\frac{2}{\pi}} * \frac{ER_{j,s}*10^3}{U_s*\cos\theta_s*\sigma_{Z_s}(x^{eff})} \qquad [\mu g/m^3] \qquad (3.6)$$

where x^{eff} is the effective downwind distance from the receptor to the road (m). $ER_{j,s}$ is the emission rate of emission j from road section s (µg/s/km), U_s is the average wind velocity on road section s (m/s), θ_s is the angle to the normal of road section s at which wind blows, and $\sigma_{Z_s}(x^{eff})$ is the vertical dispersion parameter as defined by Hanna, Briggs and Hosker (1982):

$$\sigma_{Z_s}(x^{eff}) = 0.14 * (1 + 0.0003 * x^{eff})^{-1/2} \qquad [\text{m}] \tag{3.7}$$

3.3.2.3 Impacts quantification

Atmospheric emissions impact human welfare (Kunzli et al., 2000), ecosystems (Bignal et al., 2007), buildings and infrastructure (Rabl and Spadaro, 1999), and crops (van Essen et al., 2011). Because the field of human health has attracted major research efforts, the relationship between the level of air pollution and human health is well understood and quantified. Health impacts associated with air pollution encompass the following health outcomes: mortality, respiratory hospital admission, cardiac hospital admission, cardiac emergency visit, restricted activity day, asthma symptom day, acute respiratory symptom day, adult bronchitis case, and child bronchitis case (Feng and Yang, 2012; Kunzli et al., 2000; Ostro, 1994).

In order to quantify these health impacts, it is necessary to compute the number of annual additional cases due to air pollution. The number of annual additional cases $N_{j,s,h}$ for health outcome h due to traffic-induced atmospheric emissions j from road section s is assessed with Equation 3.8. This equation is modified from Kunzli et al. (2000).

$$N_{j,s,h} = CRF_{j,h} * C_{j,s} * N_h * P_s \tag{3.8}$$

where $CRF_{j,h}$ is the concentration-response function, that is, the relative risk for health outcome h associated with an increase by one unit of the concentration of emission j (µg⁻

$^{1}.m^{3}$), N_h is the base number of cases for health outcome h per person per year, P_s is the population exposed to traffic emissions from road section s.

Effects of different emissions may not be fully independent from one another, and therefore, summing up the number of cases due to each emission may lead to double counting in some cases. To avoid overestimation, we chose to calculate the total number of cases for health outcome h due to all traffic-induced atmospheric emissions from road section s as the number of cases due to the most adverse emissions (see Equation 3.9). Thus, this approach is conservative because it may neglect some cases due to less adverse emissions.

$$N_{s,h} = \max_{j}\left(N_{j,s,h}\right) \tag{3.9}$$

Equations 3.8 and 3.9 should only be used when emissions feature reliable concentration-response functions. This is the case for PM_{10} and $PM_{2.5}$. Other emissions, such as greenhouse gases, sulfur dioxide (SO_2), and ozone (O_3), may also significantly impact human health. However, when no impact pathway is available, no reliable concentration-response function is available to quantify the impact of these emissions. The severity of their impact is thus directly measured in economic value, with exposure-cost functions. Additionally, the impact pathway leading to receptors that are not related to human welfare (e.g., deterioration of adjacent buildings and infrastructures as well as ecosystems) are poorly described in literature. Thus, direct exposure-cost functions are used to assess the costs related to these impacts. Finally, atmospheric emissions have detrimental effects on crop production mainly due to ozone (Tong et al., 2007). However, because ozone chemistry is difficult to assess spatially and temporally in the context of pavement management, atmospheric emission impacts on crops are not considered in PEIM.

3.3.2.4 Impacts monetization

The economic value associated with impacts of atmospheric emissions due to road traffic V_s is calculated using Equation 3.10. V_s is the sum of the cost associated with health impacts, global warming, biodiversity loss, and building facade soiling and erosion. Health costs include treatment costs, productivity loss costs, and inconvenience costs; global warming costs are those related to damages caused by global warming; biodiversity loss costs are estimated as the damage or restoration costs of the loss; and building damage costs are building facade cleaning and renovation costs.

$$V_s = \sum_h UV_h * N_{s,h} + UV_{CO_{2equ}} * 31.536 * ER_{CO_{2equ},s} * L_s + \sum_j UVBL_j * C_{j,s} + UVBD_{PM} * 31.536 * ER_{PM,s} * L_s \quad [\text{CA\$}_{2000}] \tag{3.10}$$

where UV_h is the economic value for one case of health outcome h (CA$$_{2000}$/case), $UV_{CO_{2equ}}$ is the economic value of an additional gram of CO_{2equ} (CA$$_{2000}$/g), $ER_{CO_{2equ},s}$ is the emission rate of carbon dioxide (CO_2) on road section s (µg/s/km), L_s is the length of road section s (km), $UVBL_j$ is the economic value of biodiversity loss due to change in the concentration of emission j per ton of emission j (CA$$_{2000}$/ton), $UVBD_{PM}$ is the economic value of building damage due to change in the concentration of particulate matter (PM) per ton of PM (CA$$_{2000}$/ton), $ER_{PM,s}$ is the emission rate of PM on road section s (µg/s/km), and the factors of 31.536 are conversion factors (from µg/s/km to g/year/km).

The economic value associated with health effects corresponds to the sum of treatment costs, which are observed market costs. The economic value associated with carbon dioxide is based on the social cost of carbon, which is an estimate of damages caused by carbon dioxide emissions or, conversely, the benefit of reducing those emissions. This value depends on the climate sensitivity to carbon dioxide concentration, the level of climate damages expected at low temperatures, the level of damages at high temperatures, and the discount rate (Ackerman and Stanton, 2012). The economic value associated with biodiversity loss is based on the restoration cost of the ecosystem influenced by the atmospheric emissions from road traffic. The economic value associated with building damage is inferred from the observed cleaning and renovation expenditure.

3.3.3 Noise

Noise is a major source of environmental impacts in urban areas. According to WHO (1999), noise influences human welfare in both short term (e.g., sleep disturbance) and long term (e.g., cardiovascular diseases) at a degree that depends on the noise level. To assess the nature and severity of noise impacts, PEIM first computes the noise energy emitted by traffic and estimates the noise level at the receptor location. Then, the dose-response functions used by PEIM provide the number of annoyed people and the number of health cases due to the estimated noise level. Finally, the value of noise impacts is estimated by assigning an appropriate economic value to each annoyed person and each health case.

3.3.3.1 Emission of sound energy

The noise module is partly based on the Federal Highway Administration's traffic noise model (TNM). TNM is based on sound energy calculation, for different vehicle classes and different pavement types, in one-third-octave bands (Menge et al., 1998). PEIM is based on version 2.1 of the TNM instead of the subsequent versions because the earlier version has been reported to provide better results than the later versions (Li, 2005).
The sound energy associated with a vehicle from vehicle class i travelling on road section s is calculated using

$$E_{0_{i,s}} = E_{emis,i,upper,ff} + E_{emis,i,lower,ff} \qquad [\text{J}] \tag{3.11}$$

where $E_{emis,i,upper,ff}$ and $E_{emis,i,lower,ff}$ are the sound energies emitted from the upper and lower subsources of vehicle class i travelling on road section s without intervening ground (Menge et al., 1998).

TNM takes into account the change in noise emission due to a change in pavement type but not to pavement aging. To overcome this shortcoming, Equation 3.12 incorporates an adjustment factor developed by Bendtsen, Lu and Kohler (2009). The adjustment factor is calculated as in Equation 3.13.

$$E_{i,s} = E_{0_{i,s}} + 10^{\frac{\Delta L_S}{10}} \quad [J] \tag{3.12}$$

$$\Delta L_s = 0.25 * \Delta L_A * A_s + \frac{0.75 * \Delta L_{CTV} * \mathrm{CTV}_s}{10^6 * N_s} \quad [J] \tag{3.13}$$

where ΔL_s is the increase in noise due to pavement aging for road section s, as developed in Bendtsen, Lu and Kohler (2009); ΔL_A is the age component of noise level increase (dBA/year); A_s is the age of the pavement (year); ΔL_{CTV} is the traffic component of noise level increase (dBA/10^6 vehicles); CTV_s is the cumulative traffic volume on road section s; N_s is the number of lanes on road section s.

Because noise level variations during a day may impact the calculation of the noise level indicator, the total sound energy from overall traffic on road section s is first calculated for the k^{th} hour of the day using

$$TE_{s,k} = \sum_i 0.0476 * E_{i,s} * \frac{a_i * b_k * AADT_s}{v_i} \quad [J] \tag{3.14}$$

where b_k is the proportion of the annual average daily traffic for the k^{th} hour of the day. The factor of 0.0476 takes into account the relationship between the maximum instantaneous sound energy for a single vehicle and the time-average sound energy for a stream of traffic, as explained in Menge et al. (1998).

The noise level at the source for the kth hour of the day on road section s is then estimated for a hypothetical location 15 m from the road, without any influence of intervening ground, using

$$L_{0_{s,k}} = 10 * \log(TE_{s,k}) \quad [\text{dBA}] \tag{3.15}$$

3.3.3.2 Propagation of traffic noise

Assuming that no object interferes with sound propagation, sound energy declines with increase in the distance between receptor and emitter, as it is attenuated by absorption by the atmosphere and ground. Equation 3.16 adjusts the noise level provided by Equation 3.15 to take into account the distance between dwellings and the road as well as the ground characteristics.

$$L_{s,k}(x) = L_{0_{s,k}} + 10 * \log\left(\frac{15}{x}\right)^{1+\propto} \quad [\text{dBA}] \tag{3.16}$$

where x is the distance from the receptor to the centerline of the road (m), and $\propto$ is a ground absorption effect parameter. In Equation 3.16, the receptor is assumed to be close enough to the road so that the road section length appears as infinite from the receptor position (i.e., $x \ll L_s$).

3.3.3.3 Impacts quantification

Traffic noise only influences ecosystems and human welfare. However, because of the lack of studies on the impact of noise on ecosystems, this study limits noise impacts to those influencing human welfare. Impacts of traffic noise on human welfare are twofold: health effects and annoyance.

According to Staatsen et al. (2004) and Davies and Kamp (2012), traffic noise significantly influences the following main health outcomes: myocardial infarction (which may lead to early death, days in hospital, days absent from work, and cases of morbidity), angina pectoris (which may lead to days in hospital, days absent from work, and days of morbidity), and hypertension (which may lead to days in hospital). Because the L_{den} noise level is commonly used in health impact assessment of noise, the quantification of the severity of traffic noise impact on the above health outcomes is based on L_{den}. L_{den} is a noise indicator computed as an average of the noise emitted during three different periods (day, evening, and night), with penalties for evening and night periods. Distinguishing these periods allows for consideration of the difference in sensitivity to noise during each of the periods (see Equation 3.17). Then, the number of cases for each health outcome h occurring along road section s ($N_{s,h}$) is calculated from L_{den} using Equation 3.18.

$$L_{den_s}(x) = 10 * \log\left(\frac{\sum_{k=1}^{24}\left(10^{\frac{L_{s,k}(x)+P_{den_k}}{10}}\right)}{24}\right) \quad [\text{dBA}] \tag{3.17}$$

$$N_{s,h} = a_h * \left(L_{den_s} - b_h\right) * \frac{P_s}{1000} \tag{3.18}$$

where P_{den_k} is the penalty for the k^{th} hour of the day; a_h and b_h are parameters taken from Staatsen et al. (2004), for each health outcome h; and P_s is the population exposed to traffic noise from road section s.

Annoyance severity related to traffic noise is usually expressed as the percentage of people lightly annoyed, annoyed, and highly annoyed (Miedema and Oudshoorn, 2001). These percentages are assessed using

$$XA_s = a_{XA} * \left(L_{den_s} - L_{XA}\right)^3 + b_{XA} * \left(L_{den_s} - L_{XA}\right)^2 + c_{XA} * \left(L_{den_s} - L_{XA}\right) [\%] \tag{3.19}$$

where XA_s is alternatively the percentage of lightly annoyed, annoyed, and highly annoyed people because of traffic noise; a_{XA}, b_{XA}, c_{XA}, and L_{XA} are parameters taken from Miedema and Oudshoorn (2001).

3.3.3.4 Impacts monetization

Monetization of health effects and annoyance due to traffic noise is performed using

$$V_s = \sum_h UV_h * N_{s,h} + \delta * \sum_{XA} UVA_{XA} * XA_s \qquad [CA\$_{2000}] \qquad (3.20)$$

where UV_h is the economic value for one case of health outcome h ($CA\$_{2000}$/case); UVA_{XA} is the economic value for one person alternatively lightly annoyed, annoyed, and highly annoyed per year ($CA\$_{2000}$/year); and δ is a coefficient equal to 0 when L_{den_s} is superior to 70dBA and to 1 otherwise, and which is applied in order to avoid the double counting of costs related to annoyance.

The economic value associated with health effects corresponds to the sum of treatment costs, which are observed market costs. The economic values associated with annoyance are estimated based on stated preference methods, because these three impacts are not closely related to real market costs. Stated preference methods rely on surveys from which investigators infer willingness to pay and willingness to accept compensation (i.e., how much people would pay or what payment people would expect to receive, in order to avoid or accept a particular impact, respectively). A detailed presentation of these methods is found in Pearce, Atkinson and Mourato (2006).

3.4 Simulation scenario

PEIM was applied to a hypothetical 1 km long collector road section located in a densely populated residential urban area of the province of Quebec, Canada. Parameterization of PEIM was performed to adapt the four constituting modules to the context of Quebec.

However, regarding vehicle fleet characteristics (e.g., vehicle technology), relative risk estimation (e.g., cardiovascular risk), and costs related to some environmental impacts (e.g., cost of one ton of CO_2), parameter values were taken directly from literature. The parameters values are described in Table 3.2.

Table 3.2 Description of model parameters

Eq. No.	Parameter	Unit	Description	Value
1	$FCLIM$		Climatic factor related to the percentage of driving on snow or wet surface	Assuming the road is always dry, the value is set to 1 (Bennett and Greenwood, 2001)
	$b11_i$ to $b13_i$		Rolling resistance parameters for vehicle class i	see Annex I, Table-A I-1
	Nw_i		Vehicle number of wheels for vehicle class i	see Annex I, Table-A I-1
	$CR1_i$		Rolling resistance tire factor for vehicle class i	see Annex I, Table-A I-1
	M_i	tons	Mass for vehicle class i	see Annex I, Table-A I-1
2	$Kcr2_i$		Calibration factor for vehicle class i	see Annex I, Table-A I-1
	$a0_i$ to $a3_i$		Parameters for rolling resistance coefficient for vehicle class i	see Annex I, Table-A I-1
3	α_i	mL/s	Fuel consumption at idling for vehicle class i	see Annex I, Table-A I-1
4	$CPF_{i,j}$		Catalyst pass fraction of emission j from vehicles of class i	see Annex I, Table-A I-2
5	a_i		Proportion of vehicle class i in the annual average daily traffic	see Annex I, Table-A I-3
8	$CRF_{j,h}$	$\mu g^{-1}.m^3$	Concentration-response function for health outcome h associated with an increase by one unit of the concentration of emission j	see Annex I, Table-A I-4
	N_h		Base number of cases for the health outcome h per person and per year	see Annex I, Table-A I-5
10	UV_h	$CA\$_{2000}$/case	Economic value for one case of health outcome h	see Annex I, Table-A I-6
	$UV_{CO_{2equ}}$	$CA\$_{2000}$/g	Economic value for an additional gram of CO_2	Assuming an average climate sensitivity and a 1.5% discount rate for damage valuation, low, central, and high estimates are set to 202.99, 484.24, and 765.50, respectively (adjusted from Ackerman and Stanton, 2012).
	$UVBL_j$	$CA\$_{2000}$/ton	Economic value of biodiversity loss because of change in the concentration of emission j per ton of emission j	see Annex I, Table-A I-7
	$UVBD_{PM}$	$CA\$_{2000}$/ton	Economic value of building damage because of change in the concentration of particulate matter (PM) per ton of PM	275.77 (central value only, adjusted from Rabl, 1999)
13	ΔL_A	dBA/year	Age component of noise level increase	0.4 (Bendtsen, Lu and Kohler, 2009)
	ΔL_{CTV}	dBA/10^6 veh	Traffic component of noise level increase	0.21 (Bendtsen, Lu and Kohler, 2009)
14	b_k		The proportion of the annual average daily traffic for the k^{th} hour of the day	see Annex I, Table-A I-8
16	$\propto$		Ground absorption parameter	Assuming the ground is reflective, the value is set to 1 (Hendriks et al., 2009)
17	P_{den_k}		Penalty coefficient for the k^{th} hour of the day for L_{den_s} noise level calculation	10 for k=1…6 and k=23…24, and 5 for k=19…22 (Pronello and Camusso, 2012)
18	a_h and b_h		Parameters for calculation of the number of cases for each health outcomes h occurring along road section s	see Annex I, Table-A I-9
19	a_{XA}, b_{XA}, c_{XA} and L_{XA}		Parameters for calculation of percentage of people that is annoyed by noise level	see Annex I, Table-A I-10
20	UV_h	$CA\$_{2000}$/case	Economic value for one case of health outcome h	see Annex I, Table-A I-9
	UVA_{XA}	$CA\$_{2000}$/year	Economic value for one person alternatively lightly annoyed, annoyed, and highly annoyed per year	see Annex I, Table-A I-10

On the contrary, in order to be representative of an urban collector road, traffic characteristics, namely, annual average daily traffic, vehicle speed, and percentage of heavy vehicles, were set to 10,000 vehicles, 50 km/h, and 5%, respectively.

Regarding variables describing pavement characteristics, pavement texture depth obtained from the sand patch method was set to the average value of 1.15 mm as measured by the Quebec Ministry of Transportation (MTQ, personal communication, 2013), and the Benkelman Beam rebound deflection was assumed to be equal to 0 because the collector featured a low percentage of heavy vehicles. For a given pavement structure, functional class, and traffic level, the relationship between pavement age and International Roughness index (IRI) can be estimated with deterioration models from MTQ (personal communication, 2013). For our simulation scenario, that is, an urban collector road carrying an AADT of more than 4000 vehicles and paved with a new dense-graded asphalt concrete, IRI is estimated using

$$IRI = 1 + 0.15 * age \quad \text{[m/km]} \tag{3.21}$$

Climatic and receptor characteristics followed these assumptions: the average wind direction was normal to the road and the average wind velocity was equal to 1 m/s; because the road section was in a densely populated area, the linear population density was established at 240 people/km, and the distance between the facade of houses and the road was set to 5 m.

3.5 Results

3.5.1 Sensitivity analysis

The severity and costs of environmental impacts caused by pavement management are influenced by parameters on which pavement management units have no control. Most of these parameters may be classified into two main classes: one class related to traffic (i.e., traffic volume, vehicle speed, and percentage of heavy vehicles) and another related to receptors (i.e., distance from the receptors to the road and density of receptors). The value of these parameters varies with time, is influenced by uncertainty, and requires a sensitivity analysis to be performed on the influential traffic and receptor parameters.

3.5.1.1 Sensitivity of environmental nuisance indicators

Equivalent noise level as well as pollutant and greenhouse gas emissions are widely used indicators of assessment midpoint in impact assessment studies related to environmental noise level, air quality, and global warming (Ackerman and Stanton, 2012; Cucurachi, Heijungs and Ohlau, 2012; Kunzli et al., 2000). In order to use comparable indicators, the amount of emitted $PM_{2.5}$, L_{den}, and the amount of emitted CO_2 were used to assess the environmental nuisances simulated by PEIM.

Sensitivity analysis was performed by changing the value of the vehicle speed, traffic volume, percentage of heavy vehicles, and distance from receptor to road, one at a time while keeping all other parameters at their base values. Figure 3.2 presents the change in percent of L_{den}, $PM_{2.5}$, and CO_2 emissions relative to their base values. Sensitivity to the density of receptors is not included in Figure 3.2 because this parameter is not involved in the calculation of these outputs.

On first sight, irrespective of the parameter under consideration, the responses of L_{den}, $PM_{2.5}$, and CO_2 showed dissimilar behaviors. This was because they depend on radically different processes. L_{den} depends on noise emission at pavement-tire interface, which is a mechanical process, whereas $PM_{2.5}$ and CO_2 emissions depend on fuel consumption, which involves both mechanical and chemical processes.

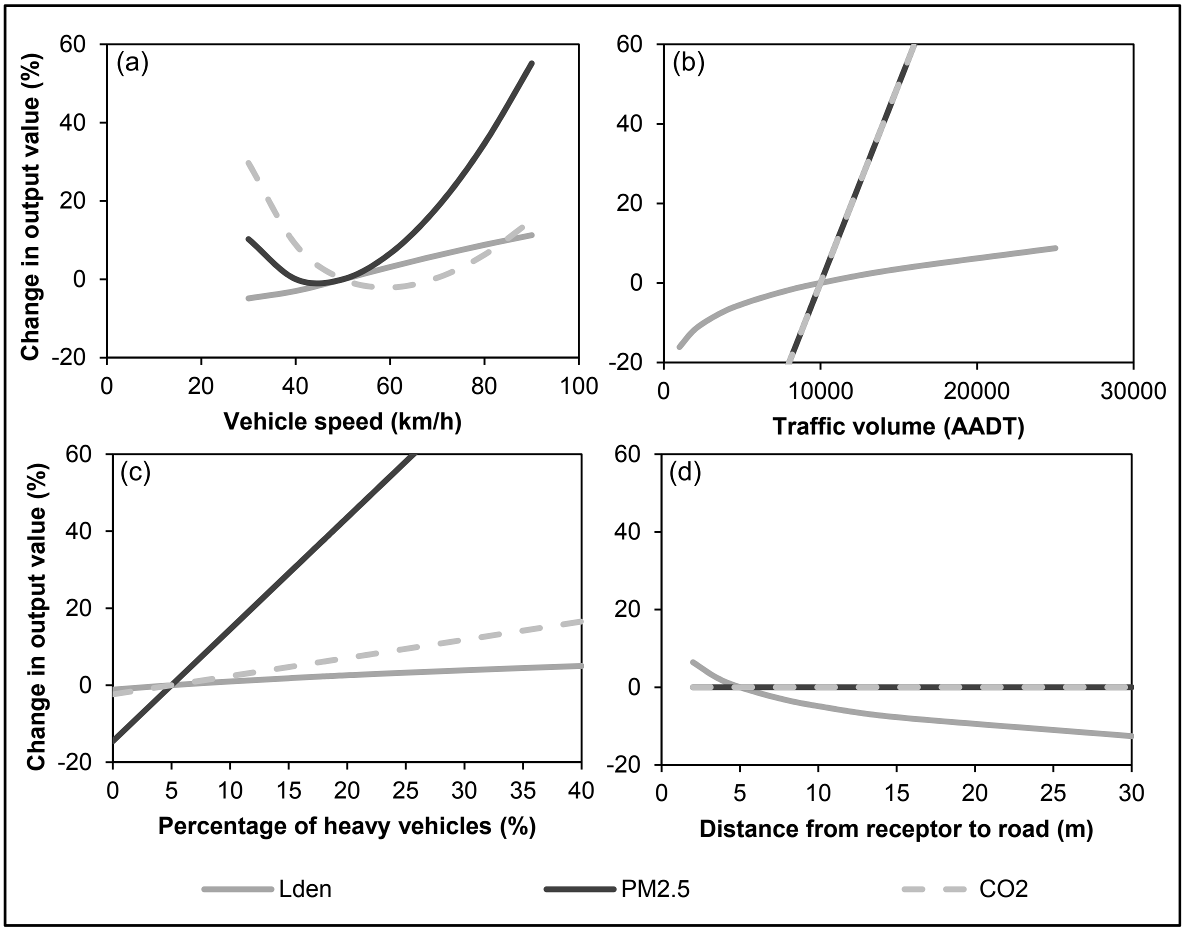

Figure 3.2 Sensitivity of L_{den} and emissions of CO_2 and $PM_{2.5}$ to (a) vehicle speed, (b) traffic volume, (c) percentage of heavy vehicles, and (d) distance from receptor to road

Three conclusions may be drawn from the sensitivity analysis to vehicle speed. First, vehicle speed influenced L_{den} almost linearly: the higher the vehicle speed, the higher was L_{den} (Figure3.2(a)). Because L_{den} is a combination of traffic noise levels at each hour of the day, the pseudo-linearity of the curve was consistent with the relationship between the instantaneous vehicle speed and the instantaneous vehicle noise level under cruising conditions as illustrated in Menge et al. (1998). At high speed, the increased friction at the pavement-tire interface induces vibrations that in turn cause noise. Consequently, as depicted in Figure 3.2(a), noise level increases with vehicle speed. Second, vehicle speed notably influenced $PM_{2.5}$ and CO_2 emissions. Minimum emissions of $PM_{2.5}$ and CO_2 were obtained for speeds equal to about 45 km/h and 60 km/h, respectively. At first glance, the curves may appear counterintuitive, especially at low speeds because $PM_{2.5}$ and CO_2 emissions from one vehicle are commonly considered to be lower when speed decreases. However, the indicators presented here are the amounts of $PM_{2.5}$ and CO_2 emitted along the road section, and at low speeds, vehicles spend more time on the studied road section, consequently emitting more $PM_{2.5}$ and CO_2 while travelling on the road section. Third, at low speeds, CO_2 was the most influenced indicator, whereas at high speeds, $PM_{2.5}$ was the most influenced. Conversely, L_{den} was never greatly influenced by vehicle speed. These observations imply that the atmospheric emission module was influenced more significantly than the noise module by vehicle speed, especially at low speeds. These observations also imply that for vehicle speeds out of the range 40–60 km/h, the vehicle speed value should be carefully estimated.

Traffic volume had a limited effect on L_{den}; an increase in traffic volume from 2000 to 25,000 vehicles induced an increase of only about 20% in L_{den} and this effect tended to decrease as traffic volume increased. This phenomenon, depicted on the graph by the concavity of the curve (Figure 3.2(b)), is consistent with the calculation method of L_{den} that involves the logarithm of traffic volume. Although its effect on L_{den} was limited, traffic volume greatly influences $PM_{2.5}$ and CO_2 emissions. Figure 3.2(b) suggests a proportional relationship between traffic volume and $PM_{2.5}$ and CO_2 emissions. Because these emissions are correlated to total fuel consumption on the road section, this observation is consistent with the fact that an increase in the number of vehicles that travel on the road section induces the same level of increase in fuel consumption. Overall, the atmospheric emission module was notably more influenced than the noise module by traffic volume. Consequently, the value of the traffic volume in the model should be carefully estimated to obtain reliable $PM_{2.5}$ and CO_2 response values. However, if noise is the only output under consideration, a meticulous appraisal of the traffic volume is only needed for relatively low values of traffic volume.

The percentage of heavy vehicles (%HV) influenced L_{den} positively, and the relationship between %HV and L_{den} was almost linear. This response was expected because heavy vehicles emit more noise than lighter ones (Figure 3.2(c)). The percentage of heavy vehicles had similar effects on $PM_{2.5}$ and CO_2 emissions: the relationship between %HV and $PM_{2.5}$

and CO_2 emissions was linear. However, the magnitude of the effect was higher for $PM_{2.5}$ emissions than for L_{den} and CO_2 emissions. This is because heavy vehicles are a lot more susceptible to emitting PM than lighter ones, whereas the difference regarding CO_2 emissions is far less marked (see coefficient values for different types of emissions in Bennett and Greenwood (2001)).Particular caution should be observed for any %HV value because a slight change in value has a significant influence on L_{den}, CO_2, and especially $PM_{2.5}$.

The distance from receptor to road (D_{RR}) had no influence on the amount of $PM_{2.5}$ and CO_2 emissions because this distance is not involved in the generation processes of atmospheric emissions. However, D_{RR} had a significant influence on L_{den} (Figure 3.2(d)). Because of the attenuation of sound energy by the atmosphere, the noise level decreases with increasing the distance of the facade of houses from the road. The curve convexity observed in Figure 3.2(d) is from the calculation method of L_{den} that involves the logarithm of D_{RR}. Consequently, the D_{RR} value that is input into the model should be carefully estimated in the case of low D_{RR} values, that is, in the case of receptors close to the road because it implies a significant change in L_{den}. Conversely, because the influence on L_{den} is minimal for high D_{RR} values, the estimation of D_{RR} does not need to be accurate.

3.5.1.2 Sensitivity of health indicators

Environmental nuisances such as noise and air pollution can result in health effects such as mortality and chronic or acute diseases. These health effects are often referred to as assessment endpoints in impact assessment studies (Cucurachi, Heijungs and Ohlau, 2012; Kunzli et al., 2000). Thus, the percentage of the population that is annoyed by noise and the number of hospital admissions caused by air pollution were used to assess the health effects simulated by PEIM. With respect to the health indicator for noise impacts, the percentage of population annoyed by noise was preferred to the number of days in hospital caused by noise (which is also an output of the model), because hospital admissions due to noise only occur when noise levels are high (above 70 dBA).

Sensitivity analysis was performed by changing the value of the vehicle speed, traffic volume, percentage of heavy vehicles, and distance from receptor to road, one at a time while keeping all other parameters at their base values. Figure 3.3 presents the change in percent of the population annoyed by noise and of the hospital admissions due to air pollution relative to their base values. Sensitivity to the density of receptors is not included in Figure 3.3 because this parameter clearly does not influence the percentage of the population annoyed by noise and does clearly influences the number of hospital admissions in a proportional manner.

Because noise annoyance and hospital admissions caused by air pollution are closely linked to L_{den} and $PM_{2.5}$ respectively, it is not surprising that PEIM behavior was almost identical during the sensitivity analyses of environmental nuisance indicators and health indicators. Consequently, the conclusions drawn from the sensitivity analysis of environmental nuisance indicators remain valid for the sensitivity analysis of health indicators.

However, two further important observations can be made. First, Figure 3.3 illustrates that noise annoyance is influenced significantly more by each of the four parameters than by L_{den}: sensitivity to vehicle speed (Figure 3.3(a)) was four times higher for noise annoyance than for L_{den} (Figure 3.2(a)), while sensitivities to traffic volume (Figure 3.3(b)), %HV (Figure 3.3(c)), and D_{RR} (Figure 3.3(d)) were at least six, five, and three time higher, respectively. This implies that noise L_{den} was a less accurate indicator of noise impact than noise annoyance and that careful noise annoyance parameterization is all the more important in order to obtain reliable health outputs related to noise. Second, although D_{RR} did not influence the amount of $PM_{2.5}$ emitted by road traffic (Figure 3.2(d)), it did influence hospital admissions due to air pollution (Figure 3.3(d)). This observation is consistent with the fact that the farther the receptor is from the road, the lesser the $PM_{2.5}$ concentration is, and the convexity of the curve is because of the pollutant dispersion process. Therefore, especially at low D_{RR} values, the D_{RR} value that is input into the model should be carefully estimated.

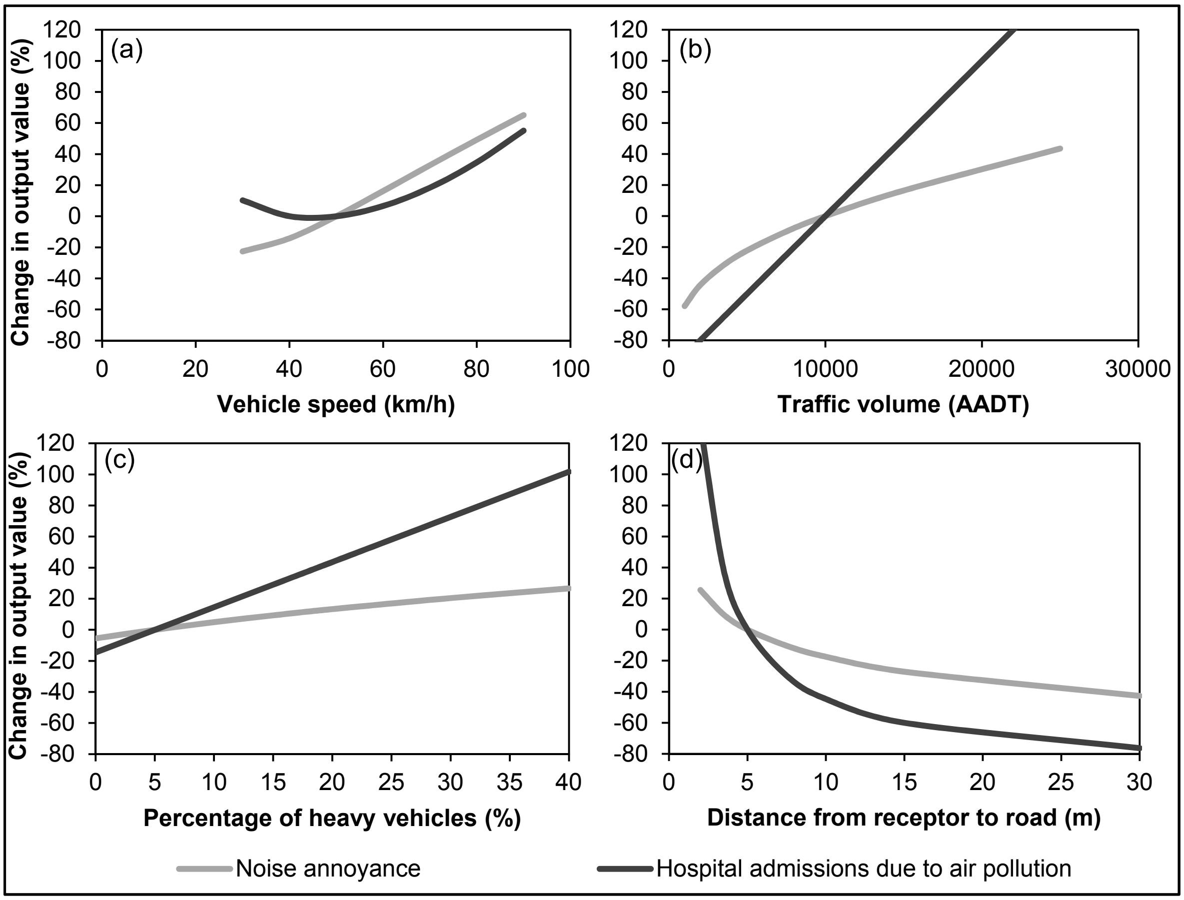

Figure 3.3 Sensitivity of noise annoyance and hospital admissions due to air pollution to (a) vehicle speed, (b) traffic volume, (c) percentage of heavy vehicles and (d) distance from receptor to road

3.5.2 Environmental costs

Assigning an economic value to environmental impacts is an effective way to incorporate them in pavement management systems along with agency and user costs. PEIM has the ability to provide annual environmental costs related to the main impacts of noise, greenhouse gases, and air pollution. To illustrate the potential of PEIM, simulations were performed for an urban collector road section located in a densely populated area and paved with a dense-graded asphalt concrete. Values of all inputs, including traffic volume, were assumed to remain stable over years, with the exception of pavement roughness that changed according to pavement age (see Table 3.3). Because the AADT of the studied road was more than 4,000 vehicles and paved with a new dense-graded asphalt concrete, change in pavement roughness was computed using Equation 3.21. Figure 3.4 presents the variations in environmental costs with the age of the pavement surface. The horizontal axis represents pavement surface age ranging from 5 to 20 years but may also be interpreted as the pavement roughness because a linear relationship between pavement age and roughness was assumed (see Table 3.3) based on the data from MTQ (personal communication, 2013).

Table 3.3 Pavement age and corresponding pavement roughness

Pavement age (year)	0	5	10	15	20
Pavement roughness (m/km)	1.00	1.75	2.50	3.25	4.00

Figure 3.4 shows the annual air pollution, global warming, and noise costs at different ages of the pavement that added to the costs occurring during the first year of the pavement. Additional costs were similar for air pollution (from 8,000 to 33,000 Canadian dollars, Figure 3.4(a)) and global warming (from 5,000 to 20,000 Canadian dollars, Figure 3.4(b)), whereas additional noise cost was one order of magnitude higher (from 950,000 to 1,053,000 Canadian dollars, Figure 3.4(c)). This difference in order of magnitude reveals that noise cost may be significantly more than other environmental costs when pavements get older. This was confirmed by the annual increase rates that were around 1,600 and 1,000 Canadian dollars per year for air pollution and global warming respectively, while this rate was around 6,800 Canadian dollars per year for noise (except at the age of 5 because of a threshold effect; see explanation below). Furthermore, the annual increase rate of the global warming cost remained constant, the annual increase rate of air pollution cost increased slightly, and the annual increase rate of noise cost significantly increased. These changes in the annual increase rate indicate an acceleration of the increase of environmental costs related to air pollution and noise, whereas global warming costs increased linearly with pavement age. Therefore, pavement surface age (or condition) influences variations in air pollution and noise costs more than variations in global warming costs.

The annual total cost of environmental impacts is presented in Figure 3.5 for different ages of the pavement surface. Remarkably, the total environmental cost more than doubled between year 0 (876,000 Canadian dollars) and year 5 (1,840,000 Canadian dollars) and then continued to increase slightly with a value of 1,983,000 Canadian dollars in year 20. The noticeable increase in year 5 is mainly due to the sudden increase in noise cost caused by an L_{den} threshold (at 70 dBA) beyond which a certain percentage of people need to be admitted to hospital. This phenomenon is also noticeable in Figure 3.4(c) where there is a very high value of the annual increase rate of noise cost in year 5. Beyond year 5, noise, global warming, and air pollution costs had the same order of magnitude: noise cost represented about 54% of the total environmental cost, global warming about 19%, and air pollution about 27%. The preeminence of noise costs has to be stressed here because noise costs are consistently omitted in pavement management studies.

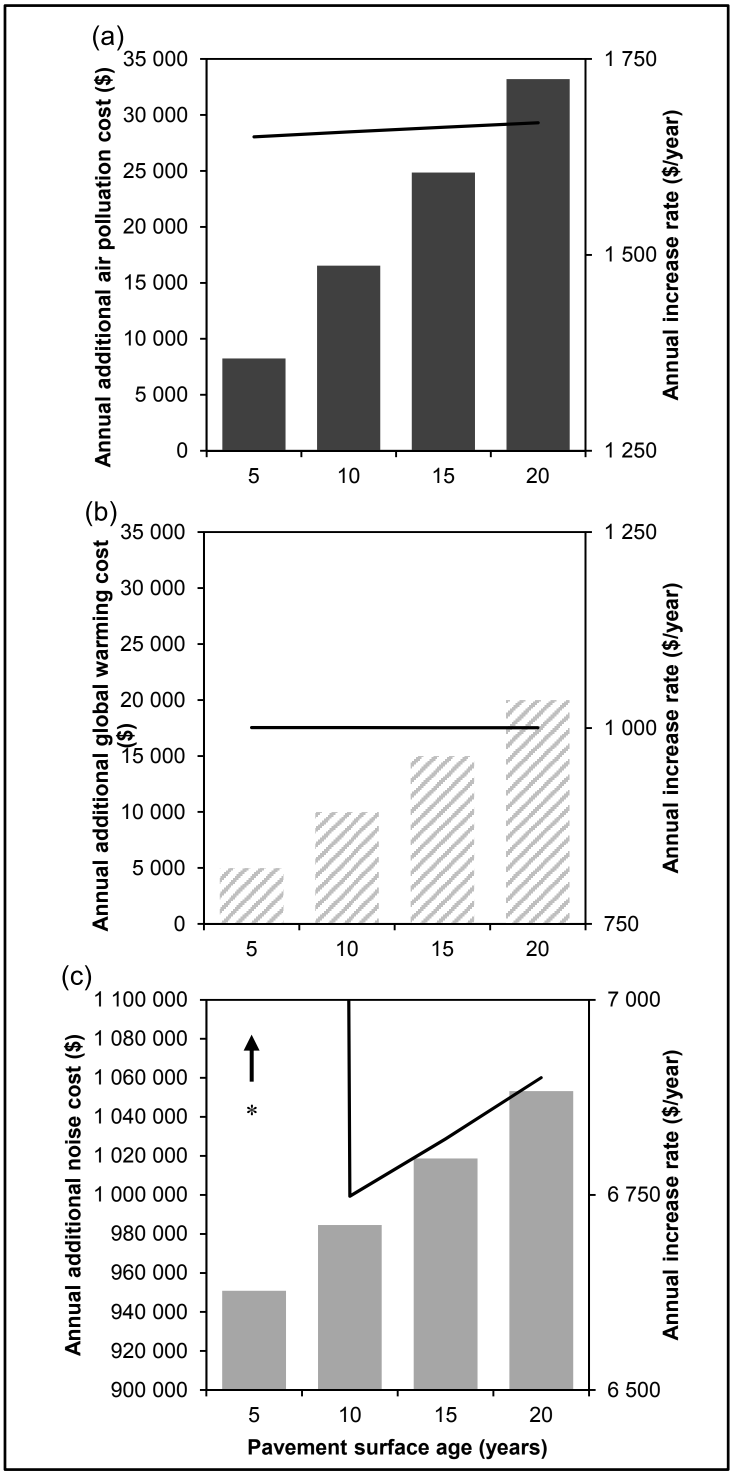

Figure 3.4 Annual additional costs and annual rate of increase in cost related to (a) air pollution, (b) global warming, and (c) noise impacts; * indicates an annual rate of increase value of 190,000 Canadian dollars per year

Errors bars shown on Figure 3.5 illustrate the uncertainty pertaining to quantification and monetization of health effects as well as to monetization of global warming impacts. These error bars were calculated with the lowest and highest estimates of parameters involved in the quantification and valuation processes for each nuisance impact. Therefore, they represent the low and high estimates of the total annual cost. These error bars do not incorporate the uncertainty regarding the monetization of noise annoyance because of the lack of sensitivity analysis regarding this process in literature. The error bars show that the high and low estimates of the environmental cost remained at the same order of magnitude as the central estimate. In year 5 and after, that is, after the L_{den} threshold is exceeded, high estimates were less than the double of central estimates (166%), whereas low estimates were more than half (60%). The estimated ranges depicted by the error bars resulted mainly from the difference between low and high estimates of air pollution costs. This difference was responsible for the difference of one order of magnitude between the low and central estimates of the total annual cost in year 0, that is, when the L_{den} threshold was not exceeded and noise cost was minimal.

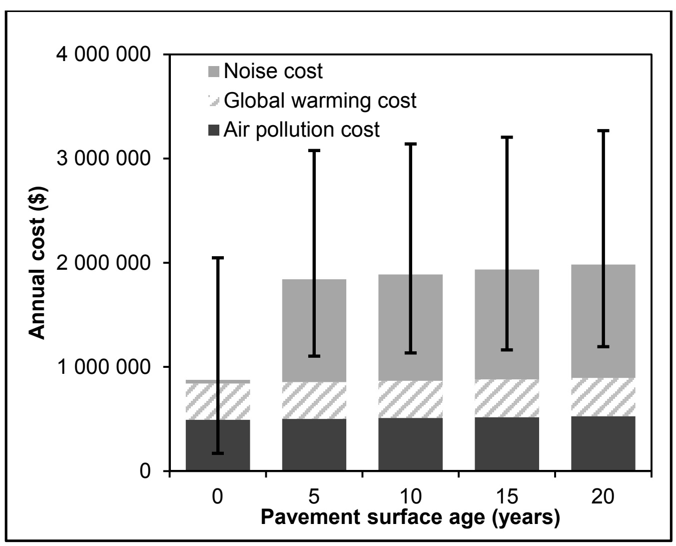

Figure 3.5 Annual total environmental costs
at different ages of the pavement surface

3.6 Discussion

Assigning an economic value to road traffic impacts on the environment is recognized to imply unavoidable uncertainties (Bickel et al., 2006; van Essen et al., 2011). PEIM is no exception and provides results that are subject to uncertainties that pertain to variable estimation, model parameterization, and gaps in scientific knowledge (see Table 3.1). First, regarding variable estimation, sensitivity analyses show that the change in the value of vehicle speeds, traffic volume, percentage of heavy vehicles, and distance from receptor to road may significantly influence model outputs. Moreover, assuming that Benkelman Beam rebound deflection is equal to zero or that the relationship between pavement roughness and age is linear, also introduces uncertainty in model outputs. Therefore, the uncertainty associated with definitions and estimation of variables is clearly reflected in the model outputs.

Second, assumptions concerning the parameters involved in the four modules are also sources of uncertainty. On one hand, parameters related to nuisance generation and dispersion modules are generally well documented and the associated uncertainty remains marginal. On the other hand, quantification and monetization of health effects imply uncertainties because of lack of scientific knowledge, e.g., knowledge on magnitude of climate change impacts, on economic valuation of biodiversity loss, or even on the existence of a threshold effect in health effects caused by noise.

Third, another source of uncertainty lies in gaps in scientific knowledge that influence impact pathways. For instance, it remains impossible to incorporate impacts related to vibration or impacts of air pollution on crops in a reliable manner. Furthermore, some impact pathways are still incomplete and use conservative aggregated exposure-cost functions instead of detailed impact pathways (e.g., biodiversity losses due to air pollution). Because PEIM does not assess a few environmental impacts and considers others in a conservative manner, the environmental costs assessed with PEIM are expected to be consistently minimal. Uncertainty due to gaps in scientific knowledge may thus influence the total environmental cost, but it can be reasonably assumed that the biggest share of total environmental cost pertains to impacts that are already well understood and documented.

Finally, it is important to stress that the three kinds of uncertainties described above are not inherent to the methodology and can be reduced by further research and careful data collection. In particular, quantification and monetization of health effects are processes that need special attention to ensure PEIM reliability.

Because of these uncertainties, which are in part illustrated by the error bars in Figure 3.5, PEIM outputs are currently limited to rough estimates of environmental costs. However, despite these uncertainties, PEIM provides an opportunity to quantify the influence of pavement age or condition on environmental costs and to provide an order of magnitude of environmental costs, which are essential in comparing the performances of pavement management alternatives.

To our knowledge, this study is the first to assign economic values to this influence, and no environmental costs related to changes in pavement age and condition are documented in literature. Bickel et al. (2006) and Weisbrod, Lynch and Meyer (2009) proposed marginal economic values for annual environmental costs due to road traffic resulting from the aggregation of data that were averaged over all classes of roads and all classes of population density and thus represented average estimates. Applying their values in the scenario defined for previous simulations resulted in the cost of environmental impacts ranging from 108,000 to 327,000 Canadian dollars. Given the uncertainties present in quantification and economic valuation of environmental impacts, and given that the environmental costs inferred from literature and those provided by PEIM remained at the same order of magnitude, the difference in their estimates seems reasonable. Moreover, this difference is all the more reasonable than the PEIM simulations that provided expectable higher estimates of environmental costs because the simulation results obtained with PEIM corresponded to a specific case of an urban collector road in a densely populated area, implying that more people were impacted by road traffic nuisances. Thus, PEIM is considered to properly estimate the magnitude of environmental costs associated with pavement age or condition.

More particularly, PEIM may be considered suitable to compare alternatives of management or to justify maintenance and rehabilitation actions. Taking the simulation performed above as an example, Figure 3.5 shows that the total environmental cost increased by around 9,000 Canadian dollars per year, yielding a total environmental cost of 75,000 Canadian dollars after 8 years, that is, a cost of 75,000 Canadian dollars for a pavement roughness increase of 1.2 m/km. According to MTQ (personal communication, 2013), preventive maintenance techniques provide a pavement roughness improvement of 1.2 m/km at a cost between 40,000 and 100,000 Canadian dollars for the simulated road section. Comparing the maintenance technique costs and the total environmental cost calculated by PEIM, it can be concluded that such a preventive maintenance action may be justified by the environmental cost alone. This brief example shows that, despite uncertainties, PEIM can help pavement management units quantify the magnitude of environmental impacts in relation to their decisions.

3.7 Conclusions

Road conditions contribute significantly adverse impacts on the environment. Methods and tools have been developed over the last two decades in pursuit of sustainability to assess environmental impacts. However, none of these methods and tools allow appropriate economic valuation of these impacts for incorporation in pavement management systems. PEIM presented in this paper is a novel approach based on IPA principles to incorporate environmental impacts due to pavement conditions in pavement management. Based on four modules describing generation, dispersion, impact quantification, and monetization of noise and atmospheric emissions, the model provides costs associated with biodiversity losses, productivity losses, building damages, and health effects that may be input in LCCA tools.

Results of the sensitivity analysis show that PEIM is reliable. These results also underline the importance of careful data collection in order to obtain reasonable output values. Additionally, a simulation for an urban collector road in a densely populated area shows that environmental costs range from 876,000 to 1,983,000 Canadian dollars per kilometer for a pavement age ranging from 0 to 20 years (or pavement roughness ranging from 1 to 4 m/km). Moreover, even if noise cost is never taken into account in pavement management, it is found to represent 54% of the total environmental impact after year 5 (or pavement roughness beyond 1.75 m/km). Finally, PEIM is shown to be the most comprehensive tool that can assist pavement management units in the assessment of the environmental impacts. However, environmental costs from PEIM should be considered with care as they may represent a low estimate of the total environmental cost as it only provides an order of magnitude of this cost. In summary, PEIM is a comprehensive tool that offers pavement management units new possibilities in their decision-making processes to achieve sustainability. By assessing and incorporating environmental nuisances caused by road traffic, PEIM provides a unique opportunity to compute costs of various types of environmental impacts related to pavement conditions.

3.8 Acknowledgements

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CHAPITRE 4

LIFE CYCLE ENVIRONMENTAL BENEFITS OF PAVEMENT SURFACE MAINTENANCE

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4.1 Abstract

In order to achieve sustainable road networks, long-term environmental costs and benefits should be recognized and incorporated in decision making process of pavement management units. This paper provides an assessment of life-cycle environmental benefits of pavement maintenance and discusses their incorporation in Pavement Management Systems (PMS). A case study regarding a 1 km long section of an urban collector road shows that pavement surface maintenance provides environmental benefits ranging from $700,000 to $18,000,000 over a 40 year analysis period, depending on the maintenance treatment applied and the discount rate used. Preventive maintenance was found clearly more sustainable than corrective maintenance. Noise benefits represented the major component of the environmental benefits. Reversely, although pavement management practices often consider greenhouse gases, the results show that the reduction of greenhouse gases emissions due to pavement management strategies is minimal. The paper also discusses the incorporation of environmental costs in pavement management practices and highlights the importance of an appropriate discount rate, specific to environmental impacts and the need to assess the influence of the discounting method on the environmental benefits.

4.2 Résumé

Afin de développer de façon durable les réseaux routiers, les unités de gestion des chaussées commencent à incorporer dans leur processus de prise de décision les coûts et bénéfices encourus sur le long terme. Cet article a pour but d'estimer les bénéfices sur le cycle de vie des stratégies d'entretien des chaussées et de discuter de l'incorporation de tels bénéfices dans les systèmes de gestion des chaussées. Les résultats de l'étude de cas réalisée sur une collectrice en milieu urbain d'une longueur de 1 km montrent que l'entretien de la surface de roulement induit, sur 40 ans, des bénéfices environnementaux d'un montant compris entre 700,000 à 18,000,000 $ selon le type d'entretien et le taux d'escompte retenus. Il ressort plus particulièrement que l'entretien préventif est plus durable que l'entretien palliatif. De plus, les bénéfices liés au bruit représentent la majeure partie des bénéfices environnementaux alors qu'il est souvent ignoré en gestion des chaussées. Bien que souvent incluse dans la gestion des chaussées, la réduction des émissions de gaz à effet de serre se révèle être par contre minimale. Finalement, la discussion sur la prise en compte des coûts environnementaux dans la gestion des chaussées souligne particulièrement l'importance d'utiliser un taux d'escompte spécifique aux impacts environnementaux ainsi que le besoin d'évaluer l'influence de la méthode d'actualisation sur les bénéfices environnementaux.

4.3 Introduction

Pavement management systems (PMS) have been developed to assist engineers and planners with the design of maintenance programs that are cost-effective on the long term (Kulkarni and Miller, 2003). Depending on the strategy adopted, the maintenance program implies different types and patterns of pavement surface condition throughout the use phase of the pavement. These types and patterns in turn have an impact on the magnitudes of environmental nuisances related to traffic movement on the pavement. Those environmental nuisances include noise, vibration, leachate and runoff waters, air pollution, and greenhouse gases (Santero and Horvath, 2009; Zhang et al., 2010).

Yet PMS do not commonly include environmental concerns. Consequently, costs associated with the adverse impacts affecting human welfare, ecosystems, buildings and crops are constantly disregarded in pavement management despite the fact that they are anyway incurred by society. Sustainability having gained attention in the last two decades, several researchers recently included environmental impact indicators when evaluating or comparing pavement maintenance treatments and materials (e.g. Chan et al., 2011; Yu and Lu, 2012). Some other researchers have developed new tools to help pavement management units broaden their scope and include environmental impacts in their decision making process (e.g. Huang, Bird and Heidrich, 2009; Nathman, McNeil and Van Dam, 2009; Wang et al., 2012). However, in most cases, environmental impacts incorporated in these PMS do not include the impacts occurring during the use phase of the pavement life cycle (Gosse, Smith and Clarens, 2013; Santero, Masanet and Horvath, 2011b). This deficiency is detrimental to sustainability for two reasons. First, as the use phase is the longest phase of the pavement life cycle, corresponding environmental impacts are expected to be significant and cannot be overlooked (Chan, Keoleian and Gabler, 2008; Gosse, Smith and Clarens, 2013; Santero, Masanet and Horvath, 2011b). Second, the sustainability concept includes the intergenerational equity principle (Padilla, 2002) that implies to take into account the long-term effects such as the environmental impacts occurring throughout the use phase.

Being widely used for the assessment of the long-term economic cost-effectiveness of maintenance alternatives (Walls and Smith, 1998), life cycle cost analysis (LCCA) is an appropriate tool to incorporate long-term environmental costs and benefits. Some recent studies have started incorporating the use phase environmental impacts in pavement management by using LCCA (see Lidicker et al., 2013; Zhang, Keoleian and Lepech, 2013). However, until now, no attempt has been made to quantify the environmental benefits of pavement surface maintenance over the pavement life-cycle and no tool has been designed to perform this quantification. Pellecuer, Assaf and St-Jacques (under revision) developed the Pavement Environmental Impact Model (PEIM) to assess the annual cost of the environmental impacts associated with pavement condition which is useful to establish the life-cycle environmental benefit of pavement surface maintenance. Providing at least an order of magnitude of this benefit is essential to justify, promote and ensure the sustainability of road networks by securing more funding to road maintenance. It would also help quantify the environmental consequences of decisions concerning the choice of pavement management strategies.

The objective of this study is to appraise the life cycle environmental benefits of pavement maintenance treatments. PEIM was used in combination with LCCA principles to compute annual and life cycle environmental costs for three pavement management strategies. The road section chosen for the case study was an urban collector road section. We hypothesized that this road section type allows the assessment of significant environmental benefits as it is characterized by high population density and high traffic level. This paper also discusses the limitations of this new approach and of the need for future improvements.

4.4 Methodology

In order to assess the life-cycle environmental impacts of pavement management, this paper relies on the comparison of maintenance treatments and their associated environmental benefits. In this study, the annual environmental benefit of a pavement maintenance strategy was calculated as the difference between the environmental costs associated with a "do nothing" base scenario versus the environmental costs associated with the maintenance treatment in question. PEIM provided the annual costs of environmental impacts associated with the maintenance treatment. Then the life cycle environmental benefit of the maintenance treatment was calculated according to LCCA.

4.4.1 Model description

PEIM estimates the annual costs from environmental impacts associated with pavement characteristics following the four steps procedure of the impact pathway approach. A thorough description of PEIM can be found in Pellecuer, Assaf and St-Jacques (under revision). The impact pathway approach is a bottom-up approach that determines the economic cost of adverse environmental impacts by following the pathway of nuisances from the source of emissions, to quantified environmental changes, which in turn lead to an assessment and quantification of the physical impacts on receptors, and finally to costs associated to prevent or repair those impacts (Bickel et al., 2006).

First, PEIM computes the traffic-induced air pollutant, greenhouse gases and noise emissions depending on the pavement condition. Thus, emissions of noise and of particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide and dioxide, sulfur dioxide, hydrocarbons, and nitrogen oxides are taken into account in the model. However, environmental costs associated with maintenance operations per se are out of the scope of PEIM and were not assessed in this study. The emitted noise (i.e. sound energy) is assessed with empirical functions depending on the pavement type. The amount of atmospheric emissions varies with pavement roughness.

Second, PEIM estimates the dispersion of these nuisances and the exposure level to each nuisance of nearby residents, ecosystems, buildings and crops. The noise level at the receptor takes the distance from the receptor to the road and the ground absorption into account. The dispersion of the atmospheric emissions is represented with a simple plume dispersion model.

Third, each environmental impact incurred by each kind of receptor is assessed with a specific exposure-response relationship. Each of these relationships, which are based on epidemiological studies, describes the correlation between the exposure to a hazard and the related health effects.

Fourth, the economic valuation of environmental impacts is based on unit costs obtained from damage and repair costs when available and from willingness to pay estimates otherwise. This step is discussed in more detail below.

4.4.1.1 Inputs and outputs

PEIM relies on four modules, namely noise, emission, health and valuation modules (see Figure 4.1). These four modules require four kinds of inputs: traffic data, climatic data, receptor data, and road data. Traffic data comprise annual average daily traffic, percentage of heavy vehicle and average vehicle speed. Receptor data include the distance from the receptor to the road and the linear population density along the road section. Climate data are limited to average wind velocity and direction. Road data encompass geometric data typically available at road agencies (length of the road section as well as width and number of traffic lanes) and pavement characteristics that are usually monitored by pavement management units (pavement roughness, surface texture and structural deflection).

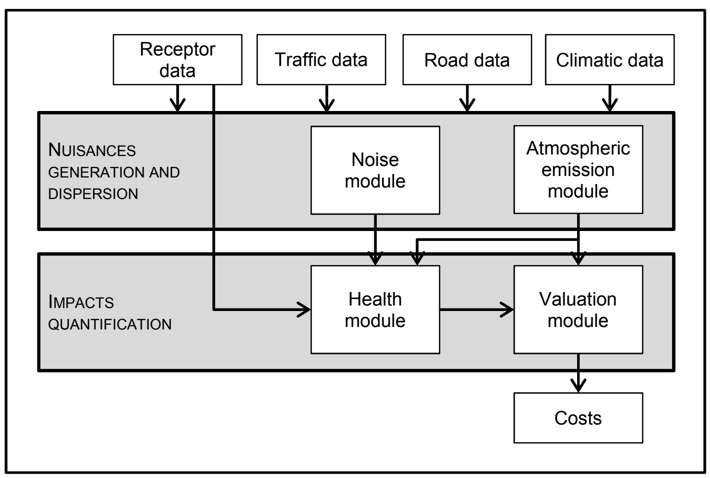

Figure 4.1 Schematic architecture of PEIM model
Adapted from Pellecuer, Assaf and St-Jacques (under revision)

PEIM provides an economic value for impacts of noise and atmospheric emissions on the pavement environment. Impacts of noise consist of effects on human health (e.g. myocardial infarction) and annoyance (e.g. loss of productivity). Impacts of atmospheric emissions encompass air pollution effects on human health (e.g. respiratory disease), on ecosystems biodiversity (e.g. loss of biodiversity) and on building facades and materials (e.g. facade degradation). Impacts of atmospheric emissions also include climate change impacts on human welfare, ecosystems, crops, buildings and infrastructures.

4.4.1.2 Economic valuation

PEIM valuation module is mainly based on damage and repair costs associated with physical impacts incurred by the receptors, such as health effects or building damages. When the economic valuation of physical impacts is difficult because of lack of scientific knowledge, PEIM uses economic values inferred by indirect methods such as hedonic pricing or contingent valuation (see Pearce, Atkinson and Mourato (2006) for details about these methods). Adapted for the Canadian context and using 2000 as the base year, PEIM computed environmental costs in $CA\$_{2000}$.

The economic value associated with health effects of both noise and atmospheric emissions corresponds to the sum of treatment costs, which are observed market costs. The economic values associated with noise annoyance are estimated based on stated preference methods, since those three impacts are hardly related to real market costs. Stated preference methods rely on surveys from which investigators infer willingness to pay and willingness to accept compensation (i.e. how much people would pay, or what payment people would expect to receive, in order to respectively avoid or accept a particular impact). A detailed presentation of these methods may be found in Pearce, Atkinson and Mourato (2006). The economic value associated with biodiversity loss due to atmospheric emissions is based on the restoration cost of the ecosystem affected by the atmospheric emissions from road traffic. The economic value associated with building damage due to atmospheric emissions is inferred from the observed cleaning and renovation expenditure. The economic value associated with carbon dioxide is based on the social cost of carbon, which is an estimate of damages caused by carbon dioxide emission or, conversely, the benefit of reducing that emission. This value depends on the climate sensitivity to carbon dioxide concentration, the level of climate damages expected at low temperatures, the level of damages at high temperatures, and the discount rate (Ackerman and Stanton, 2012).

4.4.1.3 Uncertainties

The outputs of PEIM are affected by uncertainties pertaining to gaps in scientific knowledge and to the values of model parameters. Current knowledge allows the incorporation of impacts of noise on human health, and of atmospheric emissions on human health, ecosystems, crops, buildings and infrastructure. However, the gaps in scientific knowledge prevent PEIM from incorporating the impacts of all nuisances on all receptors (e.g. impact of noise on ecosystems and impact of contaminated runoff water on crops). This results in minimization of the environmental costs computed by PEIM. Moreover, pavement roughness is the only proxy for pavement surface condition used by PEIM. Not specifically considering pavement distresses such as cracking or potholes introduces uncertainties in the assessment of environmental impacts and costs.

The values of parameters involved in health and valuation modules are uncertain by nature. To take into account this uncertainty, epidemiological studies provide low, central, and high estimates of the number of health case due to an increase in the nuisance level. Similarly, economic studies provide as well low, central, and high estimates of the unit costs for each kind of impact. PEIM uses these values to compute low, central, and high estimates of environmental costs in order to take into account the uncertainty pertaining to the value of parameters. Further details about the uncertainties affecting PEIM can be found in Pellecuer, Assaf and St-Jacques (under revision).

4.4.2 Environmental costs actualization

PMS involve the economic analysis of management alternatives to determine the most effective one on the long term (Walls and Smith, 1998). LCCA is an economic technique commonly used in pavement management that incorporates all the relevant costs and benefits occurring during the analysis period. This technique features an analysis period that should generally exceed the pavement design period in order to reflect long-term differences between maintenance alternatives (Walls and Smith, 1998). LCCA usually incorporates costs related to initial construction, maintenance and rehabilitation of pavement that are referred to as agency costs. In advanced analysis, LCCA may also incorporate social costs. Social costs consist of user costs such as car repair expenditures and environmental costs such as those related to air pollution (Zhang, Keoleian and Lepech, 2013). LCCA provides net present values of each maintenance alternatives that are considered in decision making process by discounting associated costs and benefits to present value.

Discounting raises well-known ethical problem regarding intergenerational equity and is highly controversial subject in economics (Hellweg, Hofstetter and Hungerbuhler, 2003; Quiggin, 1997). In order to circumvent this sustainability issue, economists propose two avenues, both of them supporting the principle that environmental costs and benefits should be discounted at a different rate than agency costs. The first avenue is to use a smaller discount rate that remains constant over the analysis period at a value of 0% or approaching 0% (Roumboutsos, 2010; Sáez and Requena, 2007). The second avenue involves the use of a declining discount rate over the analysis period, resulting in a hyperbolic discount factor instead of the usual exponential discount factor (Gowdy, 2004; Sáez and Requena, 2007). No consensus existing about which discounting method is appropriate to ensure the sustainability of management practices, one should perform a sensitivity analysis of environmental benefits to alternative discounting methods before incorporating those benefits into pavement management systems.

Equation 4.1 shows how the net present value is calculated for a maintenance alternative.

$$NPV_N = \sum_{i=0 \ldots N} \frac{B_i - C_i}{\left(1 + \frac{DR_i}{100}\right)^i} \tag{4.1}$$

where NPV_N is the net present value of a management alternative over a N year analysis period (in \$); B_i and C_i are the total benefit and cost of a management alternative at year i (in

\$); DR_i is the annual discount rate at year i (in %). The factor $\frac{1}{\left(1+\frac{DR_i}{100}\right)^i}$ is referred to as the discount factor (Pearce, Atkinson and Mourato, 2006).

4.4.3 Case study

Based on the practices of the Quebec Ministry of Transportation (MTQ), pavement condition is characterized by roughness, rutting and cracking performance indexes. This case study focused on maintenance triggered by threshold pavement roughness levels that have been shown to significantly influence environmental nuisances generation (Pellecuer, Assaf and St-Jacques, under revision). The pavement structure was assumed to remain acceptable over the analysis period. The rutting and cracking were considered to require no maintenance treatment except when they affected pavement roughness. The value of the roughness performance index ranges from 0 to 100, 0 corresponding to the worst condition and 100 corresponding to the best (MTQ, 2013).

Based on MTQ practices, the usual length of analysis period ranges from 40 to 50 years and the usual discount rate is equal to 6.5% (MTQ, 2013). To get an insight of the relative environmental benefits of different management strategies, the analysis period does not need to be long. Therefore, the analysis period was limited to 40 years in this study.

4.4.3.1 Case description

To run PEIM, data identified in the previous section are needed. For the case study, a collector road section located in a densely populated urban area was selected. The linear density of population was set to 260 people per kilometer and the traffic volume was equal to 5,000 vehicles/day. However, the length of the analysis period implies that traffic volume cannot be reasonably considered as constant over the period. The growth of the traffic volume supported by the road during the analysis period was calculated based on the report of SAAQ (2012). The traffic volume on this road section was equal to 5,000 vehicles/day at the first year and then increased almost linearly up to a value of 8,479 vehicles/day at year 40, with an average annual growth rate of 1.3%. Other traffic data include the average vehicle speed and the percentage of heavy vehicles that were considered to be constant over the analysis period and were 50 km/h and 5%, respectively.

Characteristics of the road section represent an urban collector in the City of Montreal, Quebec. The road section has two traffic lanes each 3.5 m wide and two parking lanes each 2.5 m wide. The house rows were located 2 m away from the road right-of-way. The road section was a one kilometer long asphalt pavement at the beginning of its service life. The pavement showed minor deflection, had a mean profile depth equal to 0.85 mm and a roughness performance index equal to 100 after construction. The traffic supported by the pavement was assumed to be light enough to maintain the deflection of the pavement at its initial value. The roughness performance index (0-100 percentage scale) decreased with pavement surface age at a rate of 2.23 percentage point per year.

Finally, the wind direction was assumed to be orthogonal to the street and the wind velocity was assumed to be equal to 1m/s.

4.4.3.2 Pavement maintenance scenarios

For given pavement structure, functional class, and traffic level, the relationship between pavement age and roughness performance index (RPI) can be estimated with deterioration models from MTQ (personal communication, 2013). For our simulation scenario, i.e. an urban collector road carrying an annual average daily traffic of more than 5,000 vehicles and paved with a new dense-graded asphalt concrete, RPI is estimated with

$$RPI = 100 - \propto * age \tag{4.2}$$

where $\propto$ is the deterioration rate.

This case study included one base and three alternative maintenance scenarios. In order to evaluate the environmental benefit of the alternative maintenance scenarios, the base scenario consisted in letting deteriorate without any maintenance operation. The alternative maintenance scenarios corresponded to different maintenance treatments. Table 4.1 shows the deterioration rate and other characteristics of the four scenarios.

Table 4.1 Characteristics of pavement maintenance scenarios

Scenario	**Maintenance trigger level**	**Maintenance treatment**	**Treatment cost ($/1000 m^2)**	**RPI improvement**	**RPI deterioration rate**
Base	-	-	-	-	2.23
Corrective A	RPI under 33	Mill and overlay	15,000	100	2.90
Corrective B	RPI under 58	Mill and overlay	15,000	100	2.90
Preventive	Pavement surface age is 10	Seal coat	5,000	20	2.23

Note: RPI is roughness performance index

The first two alternative maintenance scenarios are based on common MTQ practices. MTQ maintenance programing is based on corrective maintenance operations performed after a deficiency occurs in the pavement. MTQ uses two performance index thresholds of 58 and 33 for minor and major deficiencies associated to pavement roughness, respectively. Characteristics of both corrective maintenance scenarios used in this study were almost identical. The maintenance operations associated with both scenarios consist of a mill and overlay treatment that costs $15,000 per 1,000 m^2 and improves RPI up to a value of 100. Following the maintenance operations, the pavement deteriorates at a rate of 2.90 RPI per year. The only difference between both corrective scenarios was the maintenance trigger value, which was set at 33 for corrective scenario A, and at 58 for corrective scenario B (see Table 4.1).

The last alternative maintenance scenario relied on a preventive maintenance treatment introduced by the authors. That scenario used a seal coat every ten year, regardless of pavement surface condition. According to MTQ, this treatment costs approximately $5,000 per 1,000 m^2 and improves roughness performance index by 20 per treatment. After the maintenance operation, the performance index decreases at the same rate as the rate before the treatment (i.e., a rate of 2.23 per year).

Figure 4.2 shows the variation of the roughness performance index resulting from the maintenance treatments of the base and alternative maintenance scenarios. Over the analysis period, the base scenario used no treatment. The corrective scenario A required one treatment at year 33, the corrective scenario B required two treatments at years 21 and 37, and the preventive scenario required three treatments at years 11, 21 and 31.

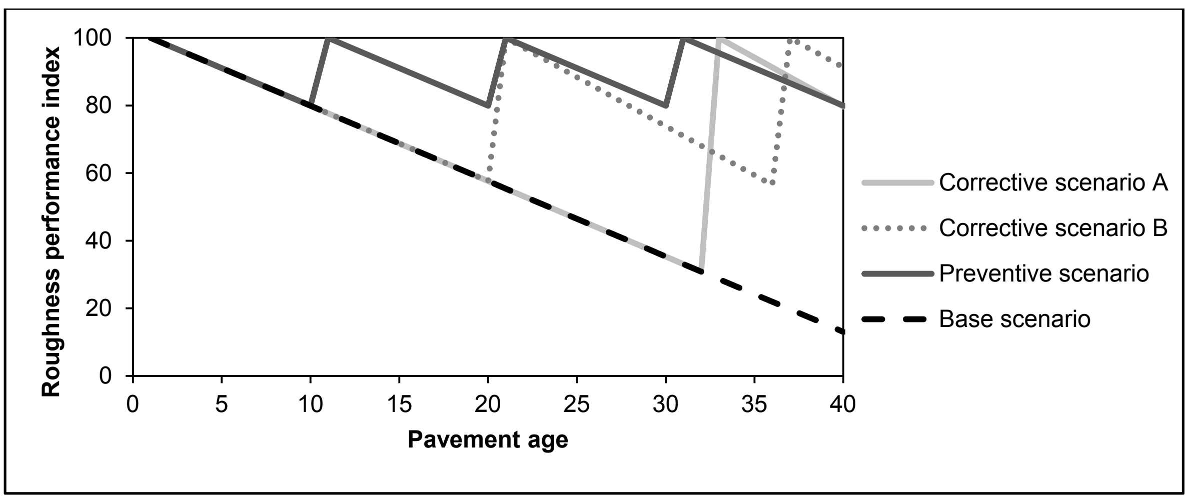

Figure 4.2 Roughness performance index of base and alternative maintenance scenarios over the analysis period

4.5 Results

In the economic analyses, namely the LCCA, a discount rate is applied to costs and benefits occurring at different points of time to make them comparable to each other (Hellweg, Hofstetter and Hungerbuhler, 2003). Such a discount rate can be defined as the interest rate at which society is willing to lend money for public projects. The discount rate thus takes to in consideration the growth rate of consumption and the rate of time preference that accounts for people's impatience (Pearce, Atkinson and Mourato, 2006). Applying a discount rate prevents from comparing the intrinsic value of costs and benefits occurring at different times. This study provides annual environmental benefits in constant dollars in order to compare the variation of environmental benefits throughout the analysis period. For the total environmental benefits, both non-discounting and discounting approaches were used to highlight the effect of discounting.

4.5.1 Environmental benefits throughout the analysis period

Figure 4.3 presents the central value of the annual environmental benefits related to pavement condition for the three alternative maintenance scenarios. The figure does not display the first ten years of the analysis period because the benefits were null for this period for all three scenarios.

In general, the three alternative maintenance scenarios provided constantly increasing benefits with pavement age. Corrective scenario A provided no benefit until the first treatment occurring at year 33 and then provided an annual benefit of more than $800,000. Similarly, corrective scenario B provided an annual benefit of about $500,000 between years 21 and 36 and of about $1,000,000 thereafter. Preventive scenario provided an annual benefit of more than $200,000 between years 12 and 20, of about $500,000 between years 21 and 30, and of around $800,000 thereafter.

This last scenario presented an exception for year 11 with an annual benefit of more than $3,200,000. This relatively high value was due to a threshold effect in noise impact assessment. Based on Staatsen et al. (2004), the health effects due to noise did not include hospital admissions unless the noise level is above 70 dBA. Because of the deterioration of the pavement surface and because the traffic growth, the noise level exceeded 70 dBA at year 11 for the base scenario. On the other hand, the noise level exceeded this threshold only at year 12 for the preventive scenario due to the early treatment applied. This delay of one year caused a delay between the occurrence of the hospital admissions in the base scenario and in the preventive scenario that in turn caused the exceptional benefit of preventive scenario for year 11.

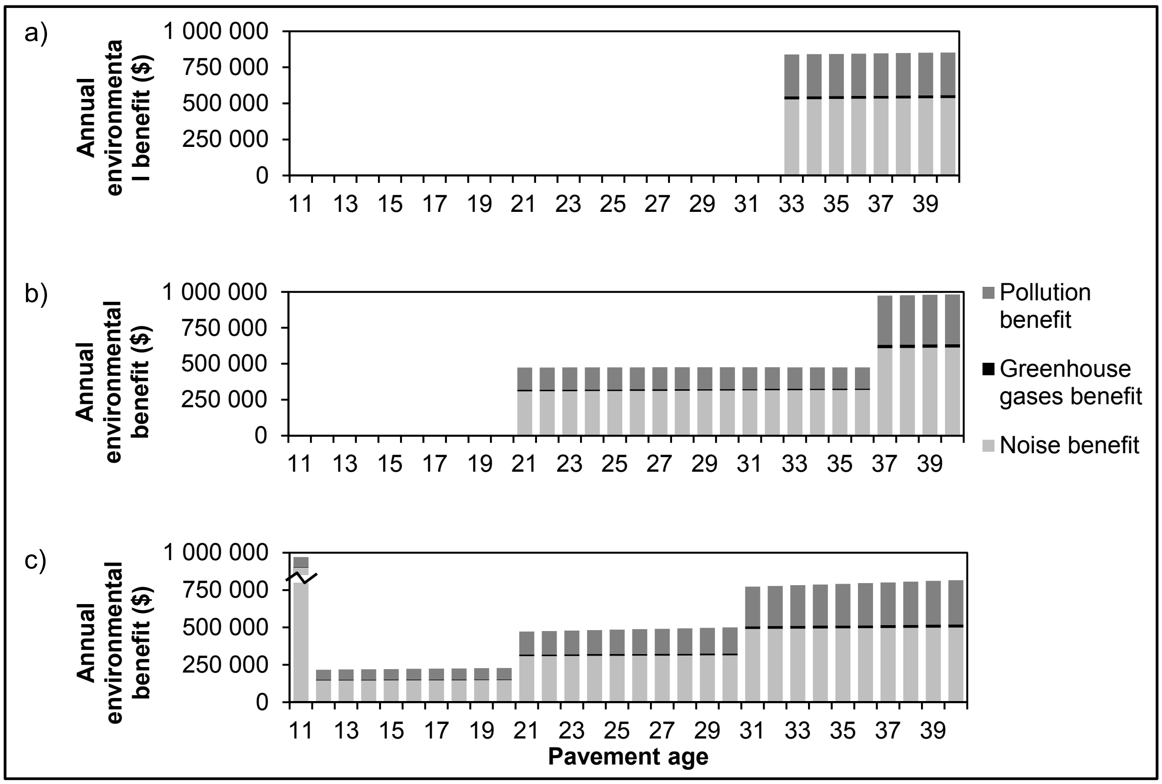

Figure 4.3 Annual environmental benefits of (a) corrective scenario A, (b) corrective scenario B and (c) preventive scenario

Because both corrective scenarios provided the same roughness performance index than the base scenario at year 11, the same noise costs were expected for that year in corrective scenarios and in base scenario. Thus, the peak in environmental benefit observed in preventive scenario did not exist for both correctives scenarios.

The reason for the increasing benefits in each scenario was twofold. First, the major part of the increasing benefit is due to the application of a maintenance treatment. The change in pavement condition due to the maintenance treatments resulted in improvement of the pavement roughness that in turn resulted in reduced environmental impacts. This condition change produced the visible steps in graphs presented in Figure 4.3. For example, pavement maintenance based on the preventive scenario resulted in an increase in environmental benefit at year 21 (from $223,000 to $473,000) that is maintained to approximately the same value until the year 31. Second, the traffic volume growth tended to accentuate the environmental benefits resulting from maintenance. The environmental benefit from maintenance is indeed all the more important as the maintenance impacts more vehicles. This effect is particularly significant concerning environmental benefits related to air pollution. For example, although the difference in roughness performance index between preventive and base scenarios was the same at year 21 and year 29, the environmental benefit for preventive scenario was lower at year 21 ($473,000) than at year 29 ($497,000) because of the traffic volume growth over this period. The annual increase of benefits associated with the traffic growth is particularly noticeable in Figure 4.3 for the last 10 years of the preventive scenario. An exception arose during years 30 to 36 for corrective scenario B. During this period, a slight decrease in environmental benefits occurred because the decrease of the benefit related to the roughness performance index was exceeding the increase of benefit related to the traffic volume growth.

Figure 4.3 also shows that most of the environmental benefit provided by pavement surface maintenance is related to noise (around 64%) and air pollution (around 34%). Only 2% of the environmental benefit of pavement surface maintenance is associated with the impact of greenhouse gases. Those percentages remained similar, irrespective of the scenarios and the analysis period. Exception was year 11 of the preventive scenario for which, as explained above, a threshold effect in noise impact assessment is experienced, causing noise to represent almost 98% of the environmental benefit for that year.

4.5.2 Life cycle environmental benefits

Figure 4.4 presents, for the three alternative maintenance scenarios, the total environmental benefits over the analysis period computed with two different discount rates. The error bars indicate the low and high estimates of the total environmental benefits. Based on the MTQ treatment costs (see Table 4.1), the non-discounted life cycle cost associated with each alternative maintenance scenario ranged from $180,000 for corrective scenario A and preventive scenario to $360,000 for corrective scenario B. These life cycle costs did not include operation cost associated with the maintenance of the pavement structure condition since it was assumed that no such maintenance was required.

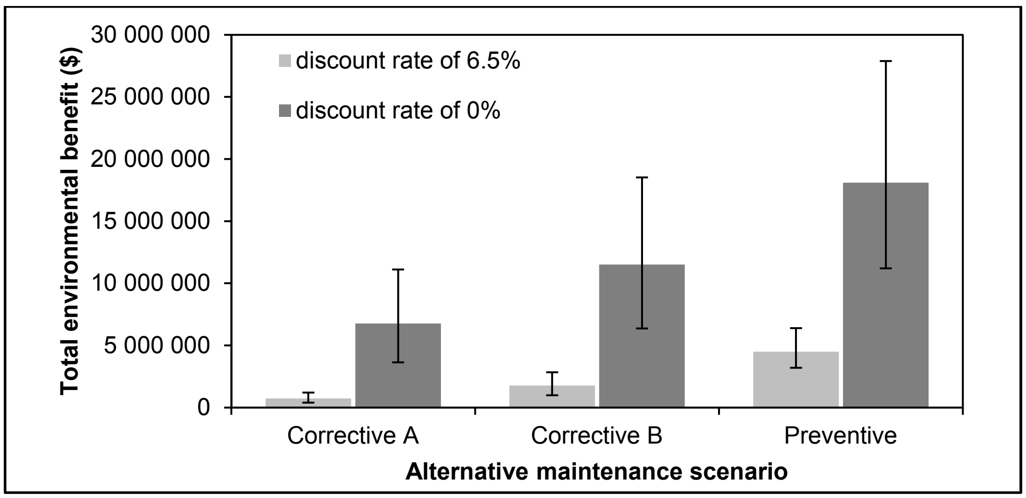

Figure 4.4 Total environmental benefits of corrective and preventive scenarios at discount rates of 0 and 6.5%

Central estimate values of total environmental benefit ranged from $6,800,000 for corrective scenario A to $18,100,000 for preventive maintenance when zero discount rate was applied, and from $700,000 to $4,500,000 when a discount rate of 6.5% was applied. Pavements with poorer condition causing environmental impacts of greater magnitude, the differences in benefits between the scenarios were consistent with their respective roughness performance index (RPI). The RPI was relatively low for the corrective scenario A, intermediate for the corrective scenario B and high for the preventive scenario. This was reflected in the benefit that was low for the corrective scenario A, intermediate for the corrective scenario B and high for the preventive scenario

On the other hand, regardless of the scenario, the significant difference in benefits between non-discounted and discounted results was due to the fact that most of the annual benefits occurred at the end of the analysis period (see Figure 4.3). For instance, discounting resulted in total benefit of corrective scenario A being reduced by one order of magnitude. Discounting also affected the percentage of life cycle environmental benefits associated with each environmental impact. For instance, benefits of preventive scenario associated with noise represented 69% and 77% of the amount of the total environmental benefit for non-discounted and discounted results, respectively.

Uncertainties pertaining to the assessment of the impacts by PEIM affected benefit estimates. The uncertainties were almost linearly linked with the magnitude of the environmental impact and thus with the associated benefits. Low and high estimates of the environmental benefits of alternative maintenance scenarios reflected those uncertainties. The preventive scenario, which provided the largest benefits, is the most affected (in absolute terms) by uncertainties and had low and high non-discounted benefit estimates of $11,200,000 and $27,900,000, respectively. On the contrary, low and high discounted estimates of the benefit of corrective scenario A were equal to $3,600,000 and $11,100,000, respectively.

4.6 Discussion

The first analysis of the relation between pavement condition and use phase environmental benefits confirms the finding of Yu and Lu (2012) that pavement maintenance provides environmental benefits as the pavement surface remains in good condition. In this urban case study, environmental benefits of pavement maintenance were found all the more important on the long term than alternative maintenance scenarios provided a RPI profile that was significantly better than RPI profile of the base scenario. A closer look at the type of environmental benefits due to preventive pavement maintenance indicated that those environmental benefits reflected air pollution, greenhouse gases as well as noise benefits at the same time. This finding is consistent with the fact that high pavement roughness causes more fuel consumption (Chatti and Zaabar, 2012), and thus more atmospheric emissions such as air pollutants (Yu and Lu, 2012) and greenhouse gases (Wang et al., 2012), and that aging pavements cause more noise (Bendtsen, Lu and Kohler, 2009).

Even if the impact pathways are different for each nuisance, the annual environmental benefits associated to each nuisance remained constant throughout the analysis period in the context of this urban case study. Regardless of the alternative maintenance scenario, this urban case study suggests that annual environmental benefits of pavement maintenance are mainly related to noise mitigation. This finding is interesting since noise is rarely considered in the recent papers related to incorporating environmental impacts in PMS (see Gosse, Smith and Clarens, 2013; Nathman, McNeil and Van Dam, 2009; Yu and Lu, 2012; Zhang, Keoleian and Lepech, 2013). On the contrary, greenhouse gases were found in this urban case study to represent only about 2% of the total environmental benefit. Currently, the greenhouse gases are often used as one of the, if not the only, main environment nuisances in pavement management (Chan et al., 2011; Gosse, Smith and Clarens, 2013; Lidicker et al., 2013; Wang et al., 2012; Yu and Lu, 2012; Zhang, Keoleian and Lepech, 2013).

The analysis of the life cycle benefits in this urban case study indicates that different management strategies provide different total environmental benefits on the long-term. Environmental benefits were notably higher when the pavement roughness was maintained minimal, i.e. when the roughness performance index remained close to 100. Therefore, pavement management strategies, oriented towards the planning and execution of frequent treatments, appear to yield greater life cycle environmental benefits in a urban context. This result reinforces and expands the conclusions from Chan et al. (2011) that applying preventive treatments is part of sustainable practices since it reduces environmental impacts due to improved pavement condition.

Moreover, the life cycle environmental benefit related to the use phase in the urban context of this case study always exceeded the life cycle cost related to pavement surface maintenance, regardless of the pavement maintenance option. With the use phase being the most influential in the pavement life cycle (Santero, Masanet and Horvath, 2011b), this finding suggests that preventive pavement maintenance may always be cost-effective when including environmental benefits in the PMS. However, this finding needs to be confirmed by including agency and environmental costs related to construction and maintenance operations (e.g. crack sealing and patching) that were not accounted for in this study. The analysis should also be expanded to consider various conditions found in urban and also rural roads.

The low and high estimates from PEIM indicate that uncertainties pertaining to the assessment of the environmental impacts affected the estimates of the annual and total environmental benefits. Uncertainties usually result from poor data quality, inaccuracy of PEIM model parameterization and deficiency in impact pathways development (Pellecuer, Assaf and St-Jacques, under revision). In the case study, uncertainties were due to deficiency in impact pathways development because of lacks and gaps in scientific knowledge. The lack of scientific knowledge affects the impact pathway reliability at three levels: the nuisances generation and dispersion, the health impact quantification and the impact valuation. First, there is evidence that noise generation is affected by pavement texture, for instance (Ahammed and Tighe, 2010; Anfosso Lédée and Do, 2002). However, PEIM noise generation module is based on an empirical model (Pellecuer, Assaf and St-Jacques, under revision) rather than on a relationship between pavement texture variation and emitted noise level variation because no such mechanistic relationship has been formulated yet. Second, the lack of proper understanding of health impacts is also an example of uncertainties affecting environmental benefit estimates. The threshold effect that caused a high benefit at year 11 of the preventive scenario raises the question about the accuracy of the scientific knowledge accuracy related to the impact pathway for noise. Based on the literature, PEIM considers that noise health effects occur when the noise level exceeds 70 dBA. However, noise health effects start occurring below this threshold and gradually increase (Althaus, de Haan and Scholz, 2009; Babisch, 2002). Third, the valuation methods used to give an economic value to certain environmental impacts is another example of the uncertainty affecting the environmental benefits assessed in this study. Costs related to noise annoyance or ecosystems are mainly based on willingness to pay methods (see Pearce, Atkinson and Mourato, 2006 for explanation of these methods). These costs are somewhat uncertain because the data from which the economic values are inferred are derived from surveys, and, therefore, are less reliable than observed market costs (Bickel et al., 2006).

Despite these uncertainties, the orders of magnitude of the environmental benefits related to each pavement maintenance treatment remain reliable within area of application of PEIM. Moreover, these orders of magnitude are proven to be useful in the comparison of the life cycle environmental impacts of alternative management strategies. Moreover, most of the environmental costs computed by PEIM are market costs (medication cost for example) for which uncertainty is minimal. Therefore, the uncertainty associated with environmental costs is mainly due to the lack of scientific knowledge about processes at stake in nuisance generation and dispersion as well as in exposure- response relationship. Further research will improve the understanding of the processes at stake in impact pathways and reduce the uncertainty associated to current lacks in scientific knowledge.

In LCCA, benefits and costs are discounted in order to take into account the time preference principle (Hellweg, Hofstetter and Hungerbuhler, 2003). However, applying a 6.5% discount rate considerably diminish the importance of future environmental benefits even if these anticipated benefits are the same order of magnitude as those occurring in a near future. Comparing the discounted and non-discounted total environmental benefits show that discounting dramatically minimizes the total environmental benefit of pavement maintenance treatments on the pavement life cycle. This is in accordance with the conclusions of Hellweg, Hofstetter and Hungerbuhler (2003) that discounting long-term impacts may influence the total environmental benefit of any scenario more than all other factors. This highlights the need to perform a sensitivity analysis of environmental benefits to discounting method in order to ensure the sustainability principle of intergenerational equity.

4.7 Conclusion

In order to ensure a sustainable development of road network, pavement management practices tend to expand the boundary of their life cycle cost analyses to include environmental concerns. In this context, this study assessed the life cycle environmental benefits of three pavement management strategies applied to a one kilometer long road section located in a densely populated urban area.

Results show that the pavement surface maintenance provided notable environmental benefits ranging from $700,000 to $18,100,000 over a 40 year analysis period, depending on the type of maintenance treatment and the discount rate. Life cycle environmental benefits assessed in this study included air pollution, greenhouse gases and noise at the same time. However, noise surprisingly represented the major part of the environmental benefits whereas noise is often not included as environmental cost in the pavement management. Although pavement management practices often take into account greenhouse gases, the reduction of greenhouse gases emissions due to pavement maintenance treatments was relatively small. On the other hand, among the alternative maintenance treatments, preventive maintenance was shown to be more effective to the mitigation of environmental impacts on the long term than corrective maintenance treatments. This finding confirms confirm that preventive maintenance treatments are more sustainable.

4.8 Acknowledgements

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CONCLUSION

Les administrations routières, afin de préserver l'état du réseau routier prennent des décisions de gestion qui influent sur les caractéristiques des chaussées en général et sur l'évolution de l'état du revêtement en particulier. À leur tour, les caractéristiques des chaussées et l'état du revêtement ont une influence significative sur les impacts environnementaux de la circulation routière qui affectent non seulement les riverains, mais également la société dans son ensemble. Il est désormais clairement établi que, dans une perspective de développement durable, les administrations routières doivent intégrer ces impacts environnementaux afin de s'assurer que les choix de gestion sont optimaux, non aux seuls yeux de l'administration elle-même, mais bien plutôt du point de vue de la société dans son ensemble. Cependant, à l'heure actuelle, les pratiques de gestion des chaussées tardent à incorporer de tels impacts.

Récemment, s'inspirant des avancées dans d'autres domaines que la gestion des chaussées, la recherche scientifique propose de plus en plus d'outils pour intégrer les impacts environnementaux dans la gestion des chaussées. Toutefois, plusieurs obstacles empêchent ces outils d'être utiles aux gestionnaires des réseaux routiers. Premièrement, la confusion autour de la définition de ce qu'est l'environnement des chaussées et, conséquemment, de ce que sont les impacts environnementaux, empêche d'établir clairement comment intégrer ces impacts dans les systèmes de gestion des chaussées. Deuxièmement, les rares outils développés pour la gestion des chaussées s'inspirent sans les adapter des outils déjà existants dans d'autres domaines et se focalisent sur les impacts médiatisés, tels que les changements climatiques. Ces outils ne sont donc pas en mesure de proposer une quantification exhaustive des impacts environnementaux. Finalement, l'intégration des impacts environnementaux dans les outils habituels de la gestion des chaussées est rarement assurée. Leur quantification donne souvent lieu à la production de nouvelles données qui se superposent à celles déjà examinées par les gestionnaires, complexifiant d'autant la recherche d'une solution de gestion optimale.

Dans ce contexte, l'objectif de la thèse était de fournir un outil novateur destiné aux gestionnaires des chaussées qui permet une intégration efficace des impacts environnementaux dans leurs processus de prise de décision. Cette intégration permet ultimement aux gestionnaires d'élargir leur champ de compétence et de prendre des décisions qui sont optimales d'un point de vue sociétal, et non plus seulement technique.

La première phase du projet de recherche avait pour but d'établir les pratiques actuelles en gestion des chaussées, et de recenser les pratiques d'intégration des impacts environnementaux dans d'autres domaines que la gestion des chaussées. L'analyse de ces pratiques a permis de dresser un bilan des déficiences actuelles et de mettre en évidence la meilleure approche pour l'intégration des impacts environnementaux dans la gestion des chaussées.

La deuxième phase a consisté en le recensement des nuisances environnementales liées aux caractéristiques des chaussées ainsi qu'en l'analyse des mécanismes d'impact. Elle a abouti au développement d'un modèle conceptuel organisant tous les impacts environnementaux liés aux caractéristiques des chaussées. En s'appuyant sur les principes du cheminement d'impact, ce modèle conceptuel fournit une vue d'ensemble des processus d'impact de la gestion des chaussées sur l'environnement. De plus, il démontre la faisabilité de l'évaluation économique des impacts environnementaux dans le but de les intégrer dans les systèmes de gestion des chaussées.

La troisième phase du projet de recherche avait pour objectif de fournir d'un outil pratique, destiné aux gestionnaires des chaussées, basé sur le modèle conceptuel de la deuxième phase. Le développement de cet outil, le PEIM (Pavement Environmental Impact Model), consiste en la formulation de nouveaux modèles et en l'adaptation de modèles existants. En accord avec les principes du cheminement d'impact, ces modèles permettent : 1) d'estimer l'émission des nuisances environnementales en fonction des caractéristiques des chaussées; 2) de calculer la dispersion de ces nuisances environnementales dans l'espace; 3) de quantifier les impacts sanitaires liés à la concentration de la nuisance là où se trouve le récepteur de la nuisance ou bien à la dose de nuisance absorbée par le récepteur; et 4) d'assigner une valeur économique aux impacts environnementaux (sanitaires et autres). Grâce à la collaboration du ministère des Transports du Québec, le PEIM a été paramétré pour être utilisé dans la province de Québec. Pour un tronçon de chaussée particulier, la sortie principale de l'outil correspond donc au coût annuel environnemental pour les conditions québécoises. Une analyse de sensibilité ainsi qu'une comparaison avec des résultats publiés ont validé le PEIM.

La quatrième phase du projet s'est attachée à démontrer la pertinence de l'intégration des impacts environnementaux dans la gestion des chaussées. La quantification économique des impacts environnementaux advenant sur le cycle de vie de la chaussée sont ainsi calculés pour différentes alternatives de gestion des chaussées dans le cadre d'une étude de cas. Il est ainsi démontré que cette quantification permet de participer à la justification des choix des stratégies d'entretien du revêtement des chaussées, menant ainsi à des pratiques qui minimisent les impacts sur l'environnement et participent par conséquent à leur durabilité.

En résumé, le projet de recherche présenté dans le cadre de cette thèse a contribué à l'avancée des connaissances scientifiques ainsi qu'au développement de méthodes appliquées au domaine de la gestion des chaussées. Pour la première fois, le système de l'environnement des chaussées a été clairement établi et tous les impacts environnementaux dus à la circulation routière ont été reliés aux caractéristiques des chaussées. Par ailleurs, un outil novateur, soit le PEIM, a été développé afin de quantifier les émissions de nuisances environnementales ainsi que les principaux impacts environnementaux qui en découlent. Ainsi, le PEIM permet l'intégration des coûts environnementaux dans les outils économiques usuels de la gestion des chaussées tels que l'analyse des coûts sur le cycle de vie. Finalement, dans son ensemble, le projet démontre à la fois la faisabilité pratique de l'incorporation des impacts environnementaux dans les systèmes de gestion des chaussées et la nécessité de cette incorporation pour poursuivre un développement durable.

Parallèlement à ces contributions, plusieurs résultats issus des trois articles constituant la thèse méritent d'être mentionnés. Tout d'abord, concernant les aspects méthodologiques, les conclusions suivantes ressortent du projet de recherche :

1) à l'aide de la méthode du cheminement d'impact, les principaux impacts environnementaux peuvent être quantifiés en termes économiques dans le but d'être intégrés dans les outils économiques de gestion des chaussées;
2) afin de calculer le coût environnemental d'une alternative de gestion, il est important de bien étudier la sensibilité du coût au taux d'actualisation. Par ailleurs, ce taux d'actualisation doit être spécifique aux impacts environnementaux et, dans un contexte de développement durable, le plus proche possible de zéro;
3) les incertitudes liées aux manques de connaissance scientifique n'empêchent pas de disposer d'ordres de grandeur des coûts environnementaux fiables.

De plus, dans les limites des études de cas effectuées, les faits suivants ont été établis :

1) les stratégies d'entretien préventif permettent de lutter plus efficacement contre les impacts environnementaux que les stratégies d'entretien correctif;
2) le bruit est la nuisance environnementale due à la circulation routière qui est la plus importante d'un point de vue économique, constituant environ 55 pour cent du total des coûts environnementaux. Le bruit représente de plus la nuisance dont le coût peut être le plus facilement limité par une gestion des chaussées appropriée;
3) au contraire, bien que représentant la nuisance environnementale la plus fréquemment prise en compte dans les études scientifiques sur la gestion des chaussées, les gaz à effet de serre induisent des coûts sur lesquels les choix de gestion n'ont pas d'influence notable. Seulement deux pour cent du gain environnemental attribuable à un changement de stratégie de gestion est dû à une diminution de l'émission des gaz à effet de serre;
4) le coût environnemental annuel des nuisances dues à la circulation routière peut varier, en milieu urbain dense, entre 900 000 et 2 000 000 dollars par kilomètre pour une chaussée revêtue en enrobé bitumineux dont l'âge varie entre 0 et 20 ans;
5) en milieu urbain dense, la gestion des chaussées peut permettre l'obtention d'un bénéfice environnemental compris entre 700 000 et 18 100 000 dollars par kilomètre sur une

période d'analyse de 40 ans, selon la stratégie d'entretien et le taux d'actualisation utilisés.

Finalement, le développement du PEIM soulève plusieurs questions qui pourraient faire l'objet de nouveaux projets de recherche, parmi lesquelles deux semblent primordiales. Premièrement, certains modèles de quantification des impacts et certaines valeurs économiques utilisés dans le PEIM sont porteurs d'une incertitude due aux manques de connaissance scientifique. Cette incertitude se reflète dans les résultats obtenus de l'outil qui ne peut fournir d'estimation précise des coûts environnementaux. Même si cette incertitude ne nuit pas à la détermination de l'ordre de grandeur du coût des impacts environnementaux, elle empêche pour le moment l'utilisation du PEIM pour évaluer et comparer de façon fine les alternatives de gestion impliquant des coûts environnementaux similaires. Dans le but d'étendre le domaine d'application potentiel du PEIM, il apparaît donc crucial de limiter cette incertitude en améliorant nos connaissances et notre compréhension des mécanismes d'impact. Deuxièmement, le PEIM est limité aux impacts environnementaux liés à la circulation routière qui ont donc lieu pendant la phase d'utilisation de la chaussée. Les impacts environnementaux advenant durant les autres phases du cycle de vie de la chaussée occasionnent des coûts qui sont vraisemblablement d'une importance moindre. Toutefois, il serait intéressant d'intégrer dans le PEIM ces impacts afin 1) de valider qu'ils ne représentent qu'une part minime du coût environnemental total de la gestion des chaussées et 2) de permettre la comparaison d'alternatives de gestion qui n'engendrent pas de différence en terme de caractéristiques de la chaussée.

ANNEXE I

PARAMÈTRES DU MODÈLE PEIM

Table-A I-1 Model parameters for fuel consumption

Vehicle class	b11	b12	b13	Nw	CR1	M	Kcr2	a0	a1	a2	a3	α
Motorcycle	20.35	0.11636	0.07934	2	1.3	0.20	1.00	0.50	0.02	0.10	0	0.12
Small car	22.94	0.10323	0.12487	4	1.0	1.90	0.50	0.50	0.02	0.10	0	0.65
Medium car	22.94	0.10323	0.12487	4	1.0	1.90	0.50	0.50	0.02	0.10	0	0.65
Large car	22.94	0.10323	0.12487	4	1.0	1.90	0.50	0.50	0.02	0.10	0	0.65
Light delivery car	25.90	0.09143	0.09796	4	1.0	2.54	0.67	0.57	0.04	0.04	1.34	0.65
Light good vehicle	25.90	0.09143	0.09796	4	1.0	2.54	0.67	0.57	0.04	0.04	1.34	0.65
Four-wheel drive	25.90	0.09143	0.09796	4	1.0	2.50	0.58	0.50	0.02	0.10	0	0.65
Light truck	29.60	0.08000	0.07500	4	1.0	4.50	0.99	0.57	0.04	0.04	1.34	0.70
Medium truck	29.60	0.08000	0.11250	6	1.3	6.50	0.99	0.57	0.04	0.04	1.34	0.80
Heavy truck	38.85	0.06095	0.10884	10	1.3	13.00	1.10	0.57	0.04	0.04	1.34	0.90
Articulated truck	38.85	0.06095	0.19592	18	1.3	13.6	1.10	0.57	0.04	0.04	1.34	0.90
Mini bus	25.90	0.09143	0.09796	4	1.0	2.16	0.67	0.50	0.02	0.10	0	0.48
Light bus	29.60	0.08000	0.07500	4	1.0	2.50	0.99	0.50	0.02	0.10	0	0.48
Medium bus	38.85	0.06095	0.06531	6	1.3	4.50	0.99	0.57	0.04	0.04	1.34	0.70
Heavy bus	38.85	0.06095	0.10884	10	1.3	13.00	1.10	0.57	0.04	0.04	1.34	0.80
Coach	38.85	0.06095	0.10884	10	1.3	13.60	1.10	0.57	0.04	0.04	1.34	0.90

Note: values for motorcycle are taken from Bennett et Greenwood (2001); all other values are taken from Chatti et Zaabar (2012).

Table-A I-2 Model parameters for atmospheric emission

Vehicle class	CPF_{HC}	CPF_{CO}	CPF_{NO_X}	CPF_{SO_2}	CPF_{Pb}	CPF_{PM}
Motorcycle	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Small car	0.86454	0.86454	0.83311	1.00000	1.00000	1.00000
Medium car	0.85639	0.85639	0.82666	1.00000	1.00000	1.00000
Large car	0.85639	0.85639	0.82666	1.00000	1.00000	1.00000
Light delivery car	0.89675	0.89675	0.86369	1.00000	1.00000	1.00000
Light good vehicle	0.89675	0.89675	0.86369	1.00000	1.00000	1.00000
Four-wheel drive	0.93113	0.93113	0.87169	1.00000	1.00000	0.86641
Light truck	1.02273	1.02273	0.92301	1.00000	1.00000	0.96094
Medium truck	1.03200	1.03200	0.93544	1.00000	1.00000	0.97750
Heavy truck	1.04426	1.04426	0.97778	1.00000	1.00000	1.01536
Articulated truck	1.04483	1.04483	0.98937	1.00000	1.00000	1.02072
Mini bus	0.96722	0.96722	0.93339	1.00000	1.00000	1.00000
Light bus	0.96880	0.96880	0.88656	1.00000	1.00000	0.89813
Medium bus	1.02677	1.02677	0.92786	1.00000	1.00000	0.96769
Heavy bus	1.04294	1.04294	0.96631	1.00000	1.00000	1.00793
Coach	1.04306	1.04306	0.96704	1.00000	1.00000	1.00847

Note: values for motorcycle are taken from Bennett et Greenwood (2001);
all other values are taken from Chatti et Zaabar (2012).

Table-A I-3 Percentage of vehicle classes in the annual average daily traffic (adapted from Société de l'assurance automobile du Québec (SAAQ 2012))

Vehicle class	***a***
Motorcycle	3,572
Small car	10,949
Medium car	38,324
Large car	5,539
Light delivery car	11,016
Light good vehicle	15,775
Four-wheel drive	7,403
Light truck	6,835
Medium truck	0,178
Heavy truck	0,227
Articulated truck	0,063
Mini bus	0,03
Light bus	0,04
Medium bus	0,043
Heavy bus	0,002
Coach	0,002

Table-A I-4 Model parameters for concentration-response function

Health outcome	$CRF_{PM_{2.5}}$			$CRF_{PM_{10}}$		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Mortality	0.06542	0.12281	0.18033	0.00044	0.04123	0.05749
Respiratory hospital admission	-	-	-	0.00100	0.04287	0.06280
Cardiac hospital admission	0.18699	0.24242	0.30070	0	0.13043	0.18033
Respiratory emergency visit	-	-	-	0.00100	0.04287	0.06280
Cardiac emergency visit	0.18699	0.24242	0.30070	0.06542	0.13043	0.18033
Restricted activity day	0,79200	0.90200	1.01300	0.04000	0.06000	0.09000
Asthma symptom day (total) per asthmatic	-	-	-	0.02000	0.03000	0.27000
Acute respiratory symptom day	-	-	-	0.00002	0.18300	0.27400
Bronchitis case (adult)	-	-	-	3.06000	6.12000	9.18000
Bronchitis case (child)	-	-	-	0.00002	0.00169	0.00238

Note: - denotes no available data; values are taken from Feng et Yang (2012); Kunzli et al. (2000); Lepeule et al. (2012); Molemaker, Widerberg et Kok (2012); Ostro (1994); Wordley, Walters et Ayres (1997); low estimates are the lowest of the low estimates among the available data; central estimates are the highest estimates of the central estimates among the available data; high estimates are the highest of the high estimates among the available data.

Table-A I-5 Model parameters for health outcome quantification (adapted from Bouchard and Smargiassi (2008))

Health outcome	***N***
Mortality	0.01034
Respiratory hospital admission	0.00164
Cardiac hospital admission	0.02282
Respiratory emergency visit	0.00822
Cardiac emergency visit	0.03003
Restricted activity day	1
Asthma symptom day (total) per asthmatic	60
Acute respiratory symptom day	1
Bronchitis case (adult)	1
Bronchitis case (child)	1

Table-A I-6 Model parameters for health outcome valuation

Health outcome	UV		
	Low	**Central**	**High**
Mortality	5949471.81	12394732.93	16361047.47
Respiratory hospital admission	2740.80	3893.57	4635.21
Cardiac hospital admission	2740.80	4820.62	5933.06
Respiratory emergency visit	918.17	2970.40	3282.30
Cardiac emergency visit	3059.24	4078.98	5191.43
Restricted activity day	12.051	249.03	312.19
Asthma symptom day (total) per asthmatic	10.20	88.42	178.22
Acute respiratory symptom day	10.40	72.18	90.23
Bronchitis case (adult)	180698.14	395063.84	690619.12
Bronchitis case (child)	222.78	460.41	683.19

Note: values are adjusted from Bickel et al. (2006); Hurley et al. (2005); Molemaker, Widerberg et Kok (2012); Sawyer, Stiebert et Welburn (2007); Stieb et al. (2002); low estimates are the lowest of the low estimates among the available data; central estimates are the highest estimates of the central estimates among the available data; and high estimates are the highest of the high estimates among the available data.

Table-A I-7 Model parameters for biodiversity loss valuation (adjusted from van Essen et al., 2011)

Emission	$UVBL$		
	Low	**Central**	**High**
NO_x	299.04	1121.38	2242.76
SO_2	74.76	224.28	448.55

Table-A I-8 Model parameters for daily traffic distribution
(Quebec Ministry of Transportation (MTQ), personal communication, 2013)

Hour	**Percentage of daily traffic**
0-1	1.00
1-2	0.50
2-3	0.50
3-4	0.50
4-5	0.50
5-6	1.00
6-7	3.50
7-8	7.50
8-9	9.00
9-10	5.50
10-11	5.00
11-12	5.50
12-13	5.50
13-14	5.50
14-15	6.50
15-16	8.00
16-17	9.00
17-18	6.50
18-19	5.00
19-20	4.00
20-21	3.00
21-22	2.75
22-23	2.75
23-24	1.50

Table-A I-9 Model parameters for health outcome quantification and valuation

Health outcome (per 1000 adults exposed)		a	b	UV		
				Low	**Central**	**High**
Myocardial infarction	years of life lost	0.084	5.25	2269867.46	2299960.40	2424631.15
	days in hospital	0.504	31.5	37525.78	44682.76	47390.80
Angina pectoris	days in hospital	0.168	10.5	19142.26	22939.07	24204.67
Hypertension	days in hospital	0.063	4.5	1902.31	2228.42	2391.47
Sleep disturbance	cases	0.62	43.2	975.54	975.54	1024.32

Note: a and b values are taken from Staatsen et al. (2004); UV values are adjusted from Bickel et al. (2006).

Table-A I-10 Model parameters for annoyance quantification and valuation

Annoyance level	a	b	c	L	UV
Little annoyed	-0.0006235	0.05509	0.6693	32	56.59
Annoyed	0.0001795	0.02110	0.5353	37	130.013
Highly annoyed	0.0009868	-0.01436	0.5118	42	130.013

Note: a, b, c, and L values are taken from Miedema et Oudshoorn (2001);
UV values are adjusted from Navrud et al. (2006).

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