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Environmental Implications of Pavements: A Life Cycle View

Bin Yu
University of South Florida, yubin@mail.usf.edu

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Environmental Implications of Pavements: A Life Cycle View

by

Bin Yu

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Major Professor: Qing Lu, Ph.D.
Bo Zeng, Ph.D.
Gangaram S. Ladde, Ph.D.
Manjriker Gunaratne, Ph.D.
Qiong Zhang, Ph.D.

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DEDICATION

Still I do not feel a hundred percent sure that I am on the verge of graduation with a title of Dr. even writing this dedication. The scenario that happened three years ago emerges in my mind. I cannot fully recall the motivation and the hesitation that propels to decide to quit the job and to continue to study but with half confidence. Fortunately, my parents offered me unwavering supports, encouraging me to fly over the ocean to begin a new chapter of life, as they always do in my life. Therefore, I owe the foremost gratitude to them for bringing me to the world, nurturing and educating me, and understanding and supporting me in every significant decision. Quitting the job to continue the study was a rush decision but operated smoothly, which was fully ascribed to valuable help from my major professor, Dr. Qing Lu. He is very responsible and knowledgeable in the academics and always illuminates me in the dilemma. Under his guidance, I carry out the research work in an efficient and flexible fashion, which further enriches me the academic background and inspires me to dive deeper in the academic ocean.

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ABSTRACT

Environmental aspect of pavement, unlike its economic counterpart, is seldom considered in the theoretical study and field practices. As a highly energy and material intensive infrastructure, pavement has great potential to contribute to the environment protection, which, in root, depends on the in-depth understanding of the environmental impacts, holistically and specifically. A life cycle assessment (LCA) model is used to fulfill the goal.

This research firstly carried out extensive literature review of LCA studies on pavement to identify the major research gaps, including: incompleteness of the methodology, controversy of the functional unit, and unawareness of feedstock energy of asphalt, etc. Based on that, a comprehensive methodology to apply the LCA model in the context of pavement engineering was developed. The five-module methodology, including material module, maintenance and rehabilitation (M&R) module, construction module, congestion module, and end of life module, covers almost every stage of pavement for a life time. The unique contribution of the proposed methodology lies in the deep-going modeling of the congestion module due to construction and M&R activities and the great efforts on the usage module. Moreover, the proposed methodology is a complex structure, demanding many sub-models to enrich the model bank and therefore another three contributions are made accordingly. Specifically, the environmental damage costs (EDCs) were calculated based on the estimates of the marginal damage cost

of involved air pollutants; a function describing the relationship of pavement roughness and average vehicle speed was established; and an improved pavement M&R optimization algorithm was developed with the incorporation of EDCs.

To demonstrate how the proposed methodology can be implemented, a case study of three overlay systems, including hot mixture asphalt (HMA), Portland cement concrete (PCC), and crack, seat and overlay (CSOL), was performed. Through the case study, the PCC option and CSOL options are found to have less environmental burdens as opposed to the HMA option while the comparison between the former two is indeterminate due to the great uncertainties associated with usage module, especially pavement structure effect; and the material, congestion, and usage modules are the three major sources of energy consumptions and air pollutant emissions. Traditionally, cost evaluation of pavement does not refer to EDC while the developed M&R optimization algorithm suggests that EDC occupies a significant fraction of the total cost constitution. And the M&R algorithm leads to a reduction from 8.2 to 12.3 percent and from 5.9 to 10.2 percent in terms of total energy consumptions and costs compared to the before optimization results.

On the other aspect, pavement communities seem to prefer long life pavement because they believe small increase of pavement thickness prolongs the service life and thus leads to a smaller marginal cost while the study in Chapter 5 suggests that it may not be always true, at least in terms environmental impacts. Specially, frequently used pavement designs in the U.S. of two design lives, 20 years and 40 years, at three levels of traffic, are evaluated for their environmental impacts using the proposed methodology. It is found that only at high traffic volumes, the 40-year designs carry environmental advantages over their 20-year counterparts while the opposite is true at the low or medium traffic volumes. Unfortunately, it is not possible to determine the watershed traffic volumes due to the disturbance of many external factors.

CHAPTER 1: INTRODUCTION

1.1 Background

Pavement is a significant component of infrastructure systems, and also fundamental to economic prosperity and personal mobility. However, the American Society of Civil Engineers (ASCE) graded the pavement infrastructure as D and listed it as the top infrastructure concern in the Report Card (2009). In the U.S., an estimated $375.5 billion budget is needed over the next 5 years to maintain and improve the highway system, and 320 million tonnes of raw materials are invested annually into the construction, rehabilitation, and maintenance of pavements (ASCE 2006).

Despite large amount of investment and long history, pavement communities seem to have ambiguous recognitions about the environmental impacts of pavement systems due to various reasons. Unlike the prevalent acceptance of monetarily evaluating the pavement systems, environmental burdens have traditionally been ignored. Even in the development of the next generation pavement design system, the Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP 2004), consideration of the environmental aspect is barely touched. However, increasing fuel consumption demand, rapid raw material depletion, and urgent environmental protection requirements are driving the development of an environment-friendly pavement design, which must rely on a clear understanding of the environmental impacts of pavement systems. In a holistic view, pavement materials production, materials transportation, construction activities, maintenance and rehabilitation (M&R) schedules, and usage of pavements after opening to traffic all make their contributions. To what extent these components would impact the environment and how they can be improved to reduce environmental damages are critical questions to be answered in order to develop environment-friendly pavement systems.

1.2 Evaluation Approaches

A life cycle assessment (LCA, also known as life-cycle analysis, eco-balance, and cradle-to-grave analysis) is a technique to assess environmental impacts associated with all stages of a product or process from cradle to grave.

> *"LCA can help avoid a narrow outlook on environmental concerns by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential impacts associated with identified inputs and releases, and making a more informed decision by interpreting the results"* (U.S. Environmental Protection Agency [EPA] 2006).

The goal of LCA is to compare the full range of environmental effects assignable to products and services in order to improve design process, support policy determination and provide a sound basis for informed decisions.

Three LCA models, process-based LCA model, Economical Input-Output (ECO-IO)-based LCA model, and hybrid LCA model, are widely used among many disciplines and companies. Generally speaking, process-based LCA enjoys high data precision at a project level while suffering from incomplete system boundary torment; ECO-IO-based LCA model, contrarily, possesses complete system boundary while being lack of data precision; hybrid LCA combines the advantages of the former two LCA models but demands a more sophisticated mathematical skill. A detailed discussion of the *pros and cons* of each model is presented in Appendix 1.

LCA is not a new concept and was initiated by Coca Cola Company to explore alternative containers besides the glass bottle dating back to 1960s. LCA models have been widely applied to different disciplines. For example, Stokes and Horvath (2011) used LCA model to evaluate the urban water provisions in California (2011); Deeper and Murthy applied LCA model to assess the energy consumption and greenhouse gases (GHGs) of producing ethanol from grass straws (2011); Busset performed LCA study on the remediation processes of soils contaminated by polychlorinated biphenyl (2011). Nevertheless, application of LCA model to the pavement field has only a history of less than two decades and is still at a maturing stage with many knowledge gaps to be filled. Despite this, LCA has witnessed growing application practices and received increasing attention and significance from the pavement communities.

Other than the LCA model, environmental impact assessment (EIA) and eco-labeling are two commonly used approaches to evaluate the environmental impacts of a product or process. An EIA is an assessment of the potential positive or negative impact of a proposed project on the environment, together consisting of the environmental, social and economic aspects. EIAs are unique since they require decision makers to account for environmental values instead of requiring adherence to a predetermined environmental outcome. However, the disagreement on the use of EIA is growing because its influence on development decisions is limited and it is also criticized for falling short of its full potential (Jay et al. 2007). The eco-labeling approach builds a labeling system for various products. It evaluates the pollution or energy consumption through index scores or units of measurement, or is simply in consistent with a set of practices or minimum requirements to reduce the harm to the environment. However, assembling all environmental indicators into a single score is discouraged by the ISO and also criticized for the possibility of possessing high score while having negative environmental impacts (Humbert et al. 2007).

This research does not intend to argue for or against a certain environmental assessment approach, but rather asserts that the LCA model provides a most comprehensive and power tool to evaluate the environmental impacts of pavement with due efforts. Additionally, it should be acknowledged that an LCA model is complementary to EIA and Eco-labeling approaches (Tukker 2000; Trusty 2006).

1.3 Research Objectives

This research aims to resolve several critical issues that currently plague the LCA application and to build a systematic methodology of performing LCA in the field of pavement engineering. Five primary objectives are to be explored through the research, including:

1. Critical review of existing LCA studies relevant to the pavement or close fields.
2. Development of a systematic methodology of implementing LCA model in the context of pavement engineering.
3. Identification and resolution of some issues that are confronted by the LCA model practitioners.
4. Illustration of the application of the proposed LCA methodology by a detailed case study.
5. Inventory and evaluation of the environmental impacts of typical pavement designs of regular life (20 years) and long term (40 years) in the U.S.

The first objective intends to suggest the state-of-the-art and limitation of pavement LCA studies so as to pave the way for future research. The second objective is to raise a comprehensive methodology based on the first objective and set a standard to continue the research. Lack of commonly consented LCA methodology has tortured the LCA studies in the pavement field ever since the beginning. This dissertation strives to resolve the issue. The third objective focuses on resolving several specific challenges that are complained by pavement researchers. For this objective, it is not intended to solve the major concerns completely but to bite the problem bit by bit and make some contributions to the progress of LCA models. The third objective includes the establishment of the relationship between pavement roughness and average vehicle fleet speed to help usage module analysis, the incorporation of environmental damage cost (EDC) to make a more complete pavement cost analysis, and an M&R activities optimization algorithm with the incorporation of EDC to improve the pavement M&R schemes. The fourth objective is to firstly implement the proposed methodology to assess the environmental impacts of three commonly used overlay systems in the U.S., and to secondly exhibit a detailed procedure of how to implement the methodology so that future users can adopt or adapt it to their own cases. There is a thought among the pavement community that long life pavement designs carry economic advantages compared to the current regular pavement designs since they believe small increase of pavement thickness can prolong the pavement service life and thus lead to a smaller marginal cost (Rawool and Pyle 2008). While the thought itself has not been fully verified, the environmental considerations of pavements of 20-year and 40-year designs are unveiled and intended to be quantified to support or sway the preference of long life pavement designs, as is the goal of the last objective.

1.4 Research Approaches

The first objective is performed through extensive literature review. Based on that, a comprehensive methodology is to be established. The proposed methodology needs to be: firstly, comprehensive to incorporate as many components as possible; secondly, logically connected but differentially recognized. In other words, for the proposed methodology, the user can both understand the overall environmental impacts and the specific contributions from individual modules and components. Based on the in-depth analysis of life cycle inventories (LCIs) after performing the LCA, pertinent optimization plans can be raised to improve the pavement designs. For examples, determining a balance between maintaining pavement ride quality and fuel consumptions; optimization of pavement structural design to achieve an overall savings in a life cycle view; implementing LCA into pavement design to achieve environmentally friendly pavements.

The literature review identifies three tasks to be resolved in this research to contribute to the LCA progress. The first one is to build a model of average vehicle speed as a function of pavement roughness. Pavement management system (PeMS) will be used as data resource. The PeMS provides information such as the inventory of physical pavement features including the number of lanes, length, width, surface type, as well as condition surveys that include distress, rutting, and surface friction, etc. The provided information is to be used to build the model. The second task is to incorporate the EDC to the cost evaluation system of pavement, which needs a reliable estimation of the marginal damage cost (MDC) of certain air pollutant. A large sample size is necessary to fit a probability density function (PDF) and obtain a best guess as well as the uncertainty range of certain air pollutant through extensive literature review. The EDCs are then calculated as the sum of the products of quantity and MDC. The third task is to develop an algorithm to optimize the M&R schedule to achieve an overall cost saving. Specifically, dynamic programming, which is adopted by many previous studies in pavement field (Ravirala and Grivas 1995; Durango-Cohen 2004; Robelin and Madanat 2007), will be used. The dynamic programming algorithm itself is not novel. However, compared with previous algorithms, the intended one adds one more dimension, EDC, to make the cost evaluation more complete.

To demonstrate the proposed LCA methodology, a detailed case study will be performed, as is the target of the fourth objective. The background information of the case study is: an old Portland cement concrete (PCC) pavement has reached the end of its service life and demands rehabilitation to restore the serviceability. The existing base course is assumed to perform well and can still work without intensive maintenance activities. Three frequently adopted replacement options are used.

1. Remove and replace the existing PCC pavement with new PCC layer.
2. Remove and replace the existing pavement with hot mixture asphalt (HMA) layer.
3. Crack and seat the existing PCC pavement and then overlay with HMA layer.

The three overlay systems are to be evaluated about their environmental burdens using the proposed LCA methodology. LCIs include: fuel consumption, CO_2, CO, CH_4, N_2O, NO_x, SO_x, VOC, and PM_{10}, etc.

To assess the environmental impacts of typical pavement designs in the U.S., a series of factors, including pavement type (flexible pavement, joint plain concrete pavement [JPCP], and continuously reinforced concrete pavement [CRCP]), traffic volume (low, medium, and high volumes), design life (20 years and 40 years) will be factorized to form various pavement designs following AASHTO pavement design manuals and are verified by the MEPDG software (version 1.0), as to fulfill the last objective. Following the same procedure of the case study, the environmental impacts of various designs will be estimated and compared.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

There have been a limited number of LCA studies in the area of pavement engineering, with various LCA models being proposed. In general, each model is partitioned into different modules, which carry disparate functionalities to contribute to the final results. A module, also named as part, component, phase, or stage in various LCA studies, is the unique term to represent the functional block of LCA model in this research. The specific modules in the LCA study vary greatly and have not reached consensus among the pavement community. Different practitioners disaggregate LCA models into different modules. For example, Roudebush (1996) evaluated the environmental impacts of concrete and asphalt highway pavement systems by dividing the LCA model into ten modules, including: natural resource formation, natural resource exploration and extraction, material production, design, component production, construction, use, demolition, natural resource recycling, and disposal; Santero (2009) split the LCA model into five individual modules, including material, construction, use, maintenance, and end-of-life (EOL); Zhang (2010a) preferred to view the LCA model as six-fold, including material, construction, distribution, congestion, usage, and EOL modules.

Despite non-uniform classification, the constitutions of LCA model remain similar. Each classification can be transformed into a standard one by adding or subtracting between modules. For example, the sum of natural resource formation, natural resource exploration and extraction, material production, and the combination of demolition, natural resource recycling, and disposal by Roudebush's classification (1996) equate to the material module and EOL module by Santero (2009) and Zhang (2010a), respectively. Transportation module, in Zhang's system, is implicitly incorporated in the material module and the EOL module in Santero (2009).

One notable missing module of most LCA models is about pavement design. Based on available literature, Roudebush (1996) is the only one who considers design module of a pavement project. If encompassed within the LCA model, the design module involves the intellectual procedure of designing a pavement, including performing structural calculations, plotting blueprints, and conducting general accounting services that support the construction process. These activities are mainly confined to office buildings or sometimes need field investigations and thus produce environmental impacts including: fuel and electricity consumption, water consumption, waste generations within office and in field. However, for the energy and material-intensive projects such as pavements, those consumptions are negligible and the effect of the marginal change of design module is very limited on the final inventory. Based on the above reasoning, it is acceptable to exclude design module from LCA model.

A complete LCA model then should consist of material module, construction module, maintenance module, congestion module, usage module, and EOL module. However, most LCA models are incomplete, with focus mainly on material and construction modules while ignoring others, especially the usage module. According to the findings from research that did incorporate usage module, it would dominate analysis results or at least is a counterpart to the material module (Häkkinen and Mäkelä 1996; Zhang et al. 2010a; Santero 2009). Thus ignoring the usage module would also ignore a great portion of environmental burdens in LCA model.

2.2 Review of LCA Application to Pavement Field

Literature review is performed in this section on currently available LCA studies in pavement field. Aside from heated debate over PCC versus asphalt pavement, some novel materials or secondary materials used in pavement construction are also included, such as ultrafine/nano-titanium dioxide photocatalyst (a coating placed over PCC to trap and absorb organic and inorganic air pollutants by a photocatalytic process), glass, tire rubber mixed in the bitumen, slag, etc. Also, some bridge engineering LCA case studies are also of interest since their methodologies are beneficial and illuminative to pavement researchers.

The purpose of the review is to: firstly, understand the *status quo* of current research and figure out existing limitations; secondly, discuss the limitation and point out pathway to breakthrough; and thirdly, provide guidance to the dissertation work and recommend future research.

There are only a few LCA case studies in the pavement field, and many of which are not complete enough to incorporate all the modules introduced previously. Therefore, the review task is split into different categories to correspond to respective modules. Each literature will be fit into one category based on its focus, emphasis, or innovation. This is a subjective classification and may witness overlap for some literatures. Nevertheless, this arrangement highlights the significant module and underlines the innovation ideas behind them.

As have been pointed out by Santero (2009), many of the so-called pavement LCAs are, strictly speaking, LCIs, meaning lack of impact assessment. Even without a further impact assessment step, LCIs follow the same process as performed by the LCA models, provide valuable data for further research, and will not be differentiated from LCA models in this review.

2.1.1 Material Module

Material module deals with the process of material production, from raw material extraction to the leaving at the front gate of manufacturers, and is also called “cradle-to-gate” process. Transportation within the process is included. Material module is compressively included and viewed as one of the most significant modules in the LCA model.

Stripple (2001) presented a most detailed material module concerning cement concrete and asphalt mixture production among all peer researches, which is used by many later studies as data source. A wide range of environmental metrics, including energy consumption, various water and air pollutants, and solid waste are examined. They are tabulated in the appendix of his report.

Transparency is sufficiently assured in this study by enumerating process used in the production, even with the inclusion of slightly used materials, such as the production of zinc to galvanize the steel. The hot and cold methods are used to produce the bitumen with the mixture unchanged. The hot approach mixes warm bitumen with heated stones in the drum plant. For the cold approach, the bitumen is firstly emulsified with emulsifier to become an emulsion consisting of 65 percent bitumen and 35 percent water, and then mixed with the aggregate at a lower temperature by a mobile plant. Two advantages are associated with the cold approach: one is less energy consumption due to low mixing temperatures; the other is shorter transportation distances since the mobile plant can be placed nearby the construction site. However, the report does not refer to the possible quality issue produced by the cold approach compared with the hot one.

As a comprehensive LCA model, this Swedish report does not confine to material module alone. Construction module was modeled by aggregating the fuel consumptions and environmental burdens of construction equipments. Routine maintenance activities, such as salt gritting in winter, snow clearance, and moving and clearing of verges, were carefully examined. However, structural rehabilitation activities, such old pavements replaced by PCC overlay, HMA overlay, or CSOL, were not included. And during construction or M&R periods, congestion module of passing-by traffic was not referred. Usage module was roughly estimated about the electrical energy and material consumption used for the operation of peripheral facilities that surround the road, like lighting, hot dip galvanized steel, aluminum, diesel, etc. Carbonation of cement concrete was discussed but finally excluded because the author argued the process to be slow. EOL module was ignored under the assumption that roads had an infinite service life. One notable distinction in this study is the consideration of aspects that are not directly connected to the pavement itself, such as road markings, wild life fence, vegetation, and deicing.

Stripple investigated the environmental impacts of three pavements, one JPCP, and two HMA pavements with one using cold approach and the other using warm approach. Their structural designs are listed in Table 2.1.

Table 2.1 Structural Designs in Stripple's Study

Pavement type	Surface (mm)	Base (mm)	Sub-base (mm)
JPCP	unspecified	500	1000
HMA (hot)	unspecified	500	1000
HMA (cold)	unspecified	500	1000

The functional unit is defined as 1 km length of roadway for a 40–year analysis period. The traffic volume is 5000 vehicle per day with no further information about the traffic compositions. Under this given, the JPCP consumes considerably more energy than does either of the HMA pavements without the consideration of feedstock energy of bitumen, while the opposite is true when feedstock energy is considered. Aside from material input, the major contribution to energy consumption originates from electrical energy consumption for road lighting and traffic control. However, the energy difference is small between the hot and the cold approaches. Two emission scenarios, low emission vehicles and normal vehicles, were applied to sensitivity analysis. Low emission vehicle brings a benefit of significant reduction of the NO_x emission and almost negligible influence to other metrics, like fuel consumption, CO_2, and SO_2.

For cement concrete production, Marceau et al. (2007) conducted a concentrated LCA study commissioned by the Portland Cement Association. This report is the second update of *Environmental Life Cycle Inventory of Portland Cement Concrete*, originally published in 2000 and later updated in 2002.

In this report, the authors focused only on material module. Environmental metrics in this report include fuel, electricity, and raw material consumption, airborne emission, waterborne discharge and landfill waste. In the compilation of LCIs, production-weighted averages were adopted other than simple arithmetic averages for the reason that the environment impacts of cement and concrete are not proportional to the number of plant, but rather to the amount of production.

Three concrete products: ready mixed concrete, concrete masonry, and precast concrete, were studied. The functional unit is a unit volume of concrete produced by cement, supplementary cementitious materials (SCMs), and aggregates. System boundary is defined as the aggregation of cement and slag cement manufacture, aggregate production, transportation of fuel, cement, SCMs, and aggregates to the concrete plant, and plant operations (including truck mixer washout in the case of ready mixed concrete). Upstream pathway of Portland cement and slag cement were imported into the concrete system boundary.

For ready mix concrete, samples of various scenarios, such as with different 28-day compressive strength (20-35 MPa), with addition of fly ash (to substitute 20 and 25 percent of the cementitious materials) or with slag cement (35 and 50 percent by weight of cementitious materials), were exhaustively tabulated about their environmental metrics in the appendix. Concrete masonry unit is the dominant product of concrete masonry plants and the LCI is provided in detail. Moreover, LCIs of three precast concrete mix designs (with 28-day compressive strength to be 50 MPa, 70 MPa, and unspecified) can also be found.

In Athena Institute’s report (2006), fly ash and ground granulated blast furnace slag as well as portion of recycled asphalt pavement (RAP, 20 percent) were used in the roadway construction to reduce the environmental burdens compared with using virgin materials. RAP, in the study, is treated as free of any feedstock energy in the inventory despite it persists in the bitumen infinitely. Feedstock energy is counted in the fresh asphalt mixture but separated as individual element in the LCI plots and tables, which approximately accounts for 75 percent of the total energy. Primary energy and global warming potential figures for production of unit cement concrete and HMA are shown in the appendix.

This LCA study investigates the consumed energy and global warming emission for rigid Portland cement and flexible asphalt roadways in Canada with various scenarios of traffic volumes. Many efforts were assigned to maintain equivalent pavement designs for each alternative. These designs were further verified using the MEPDG software.

Three types of concrete and asphalt roadway systems were designed: arterial road and conventional unrestricted access highways, high column highways, and urban freeways (In Quebec and Ontario). For the Ontario freeway, the functional unit is a three-lane kilometer roadway in one direction while the others of equivalent functionality are defined as a two-lane kilometer roadway in one direction. The analysis period is 50 years. Three traffic levels are assumed: collector roads and minor highways (5000 annual average daily traffic [AADT]), arterial road and major highways (15000 AADT), and high volume highways (50000 AADT), with 10 percent of trucks for all three scenarios. Detailed information about the structural design is listed in Table 2.2.

Table 2.2 Structural Designs in Athena Institute's Study

Type	Arterial roadway/highway				High volume highways				Urban freeways			
									Quebec		Ontario	
Pavement type	PC	AC	PC	AC	PC	AC	PC	AC	PC	AC	PC	AC
Surface(mm)	200	170	190	170	225	205	215	205	240	240	260	300
Base(mm)	150	150	150	150	150	150	150	150	150	286	100	100
Sub-base (mm)	150	585	0	165	150	700	0	225	689	553	300	500

For the listed alternatives, construction module were considered but obscurely introduced. Energy consumption due to construction activities accounts for only less than one percent of the total embodied energy of materials by a rough estimate. Major maintenance activities applied to the rigid pavement include diamond grinding, load transfer restoration and placement of asphalt concrete overlay; for the asphalt pavement, only asphalt overlay strategy is planned at certain years. Minor or routine roadway maintenance activities, such as joint and crack sealing, patch repairs and curb repair et al., are omitted due to its insignificant effect and the difficulty in estimating the material requirements precisely. No other module is discussed in the report.

The report results in a favor of the cement concrete pavement as opposed to the asphalt pavement whether feedstock energy is counted or not. Specifically, asphalt pavement consumes 2.3-5.3 times the energy of cement pavement if feedstock is included and still 31-81 percent more energy if not. Transportation sensitivity analysis was performed and revealed that while sharing a minor part, transportation related energy consumption and emission increases rapidly and becomes more significant if haul distances for granular materials increase appreciably.

Material module was carefully explored in the LCA study by Zapata and Gambatese (2005). It covers the aggregate extraction, bitumen production, cement production, and steel production but ignores the raw material transportation for the assertion that energy required for transportation can vary tremendously depending on many variables including the travel distances, modes, and condition of travel surfaces. Miscellaneous data sources were cited to build the material LCIs, including Häkkinen and Mäkelä (1996), Berthiaume and Bouchard (1999), Stripple (2001), and others. The majority of data from each reference are in fair consistency except for the bitumen production which is of variation of one order of magnitude. The authors finally chose bitumen production data from Stripple (2001), which naturally leads to a similar conclusion as Stripple's.

In this peer reviewed paper, a CRCP and an asphalt pavement were evaluated in terms of energy consumption. Two LCA approaches, P-based approach and IO-based approach were briefly compared. After that, a summary of existing literatures, with focus on the comparison of their conclusions, suggests contradictory results from different studies. Finally, the authors decided to use P-based approach as the research methodology due to wide acceptance. The feedstock energy of bitumen is not considered.

The functional unit is defined as a 1 km section of a typical two-lane highway with a high volume of traffic in the U.S. The pavement structure is designed for 10 million 80 kN (18 kip) equivalent single-axle loads (ESALs), which is an estimation of 10 or more years of interstate highway traffic. The pavement structural designs are shown in Table 2.3. No maintenance activities are scheduled for the project. Construction module was modeled with data from contractor survey. No congestion, usage, EOL modules were studied.

Table 2.3 Structural Designs of Athena Institute

	Surface (mm)	Base (mm)
Asphalt	300	150
CRCP	220	150

Through the study, the authors found that the CRCP pavement requires more energy than the asphalt pavement to perform extraction of raw materials, manufacturing and construction processes. Major energy demand in the production of asphalt pavement occurs during asphalt mixing and drying of aggregates while cement material is the driving element in the energy consumption of CRCP pavements.

2.1.2 Construction and M&R Module

Construction and M&R module deals with the fuel consumption and environmental releases of construction equipments used in the construction and M&R activities. In this review, material consumption in the construction and M&R module is added to the material module, and traffic disturbance and the resulting additional fuel consumption and air emissions are estimated in the congestion module. Moreover, every time of usage depreciates the capital value and diminishes the life of construction equipment which leads to a growing fuel consumption and air emission rate. It would be better to consider the effect of these two scenarios despite that construction and M&R module plays a minor, or sometimes even negligible role in the constitutions of LCIs, according to the research by Athena Institute (2006), Chan (2007), Zhang et al. (2010a, 2010b).

Construction activities were exhaustively enumerated in the study by Weiland (2008), Weiland and Muench (2010) about three pavement replacement options for an aged PCC pavement, including: removing and replacing the aged pavement with PCC pavement (PCC option); removing the aged pavement and replacing it with HMA (HMA option); and cracking and seating the existing pavement and placing an HMA overlay (CSOL option). The structural design and maintenance schedule of the three rehabilitation options are listed in Table 2.4.

Table 2.4 Structural Designs of Weiland et al.

PCC option	HMA option	CSOL option
Rehabilitation		
330mm PCC	325mm HMA	125mm HMA
		225mm cracked and seated existing PCC
250 mm existing crushed aggregate	250 mm existing crushed aggregate	250 mm existing crushed aggregate
Existing subgrade	Existing subgrade	Existing subgrade
Maintenance		
Year 20: diamond grinding	Year 16: mill-and-fill	Year 16: mill-and-fill
Year 40: diamond grinding	Year 32: mill-and-fill	Year 32: mill-and-fill
Year 50: diamond grinding	Year 48: mill-and-fill	Year 48: mill-and-fill

The energy consumption and emission data of construction equipment were estimated by U.S. Environmental Protection Agency (EPA) NONROAD model. Environmental metrics from NONROAD output include: energy consumption, CO_2, CO, NO_x, SO_x, CH_4, particle matter ($PM_{2.5}$ and PM_{10}), SO_2, N_2O, and volatile organic compound (VOC).

Material module was estimated by data from various literatures. Asphalt concrete production was loosely translated from Stripple (2001) and cement concrete production used the data from Marceau et al. (2007). The environmental impacts of different combinations of vehicles and fuels for transportation purpose in material module were estimated by GREET model. Feedstock energy was not included which would increase 30 percent of the total energy as estimated by the authors if included. The LCA model included only material module and construction and M&R module. The user delay and resultant air emission and fuel consumption, differences in smoothness and their potential impact on usage module, noise and safety as well as other less quantifiable factors, and minor maintenances between rehabilitation actions were mentioned in the limitation section by the authors but not analyzed.

The functional unit was defined as one-lane mile of reconstructed highway for 50 years with periodic maintenances. An average of about 105,000 AADT (in each direction), that is about 3.5 million ESALs per year, was assumed. For the defined functional unit, the CSOL option consumes and emits the least energy and greenhouse gases (GHGs) compared with the PCC option and the HMA option. Material productions, specifically, PCC production and HMA production, tend to dominate energy usage and GHGs emission as well as other atmospheric items investigated, such as SO_x, CH_4, $PM_{2.5,}$ NO_x, etc.

Disparate from peer researches, this LCA study conducted an impact and data quality assessment. Impact assessment was performed on energy consumption, acidification, human health criteria air, eutrophication, and photochemical smog. Four indices were used to evaluate the data quality used in the study, including: time-related coverage (new or old), geographical coverage (site specific or from locations with different conditions), precision, completeness and representativeness of the data, and consistency and reproducibility of the method used. The data quality evaluation system is beneficial to future citation as it provides information about which data can be trusted, updated or replaced for the practitioner’s case.

M&R activities are usually predetermined by the author(s) at the beginning of the LCA model based on empirical models or maintenance manuals. The maintenance activity itself is a less energy and material demanding contributor to the LCIs but influences the congestion module appreciably. An optimized M&R schedule is desired to minimize the corresponding environmental burdens. Zhang et al. (2010b) pioneered the pavement M&R scheme optimization research with the help of LCA model, but with great potential to be improved.

In the study, a life cycle optimization model was developed to determine the optimal preservation strategy for the pavement overlay systems and to minimize the total life cycle energy consumption, GHG emissions, and cost within the analysis period. The main interest of this paper lies in the utility of dynamic programming algorithm to optimize the maintenance activities so that different objective functions, like minimizing total cost, total energy consumption, or GHG emission, are achieved.

Life cycle cost analysis (LCCA) model was combined with LCA model in this paper as another interesting contribution. The LCA-LCCA methodology, initiated by Keoleian (2006), integrates LCA and LCCA by assigning monetary index for each air pollutants. Detailed discussion of the model will be presented in the "LCA&LCCA model" section (section 2.2.8). Before optimization, the overlay preservation strategies were scheduled for the integrated LCA-LCCA model by empirical data from Michigan Department of Transportation (MDOT), which served as a control to compare with the after optimization results.

The functional unit is a 10-km freeway section with two directions that would serve for 40 years. Each direction has two 3.6 m wide lanes, a 1.2 m wide inside shoulder, and a 2.7 m wide outside shoulder. The AADT is approximately 70,000 vehicles with 8% heavy trucks. Three overlay systems are used as maintenance strategies. The thickness is 175 mm for concrete overlay unbounded from the existing pavement by 25 mm asphalt layer, 100 mm engineered cementitious composite (ECC) layer, and 190 mm HMA overlay directly placed over the existing pavement.

Congestion module was studied with great efforts but will be left to be introduced in the “Congestion Module” section (section 2.2.3). By the study, the proposed algorithm to optimize maintenance strategy demonstrates to be effective in reducing the total energy consumption, GHGs emission, and cost for the concrete, HMA, and ECC overlay systems, by a range of 5 to 30 percent, 4 to 40 percent and 0.4 to 12 percent, respectively. The cost is defined by the authors as the sum of agency cost, user cost, and EDC due to the emitted air pollutants. The study sets a zero annual traffic growth rate as the baseline case. When considering the traffic growth, the algorithm is expected to be more beneficial in environmental burden alleviation and cost saving through optimizing the maintenance activities.

However, with different objective functions, the optimum maintenance strategy varies. Specifically, cost objective favors a less frequent preservation strategy while the opposite is true for the energy/GHGs emission objectives. The baseline case reveals user cost to be dominant. However, with the employment of Monte Carlo simulation, the range of potential environmental cost is so large to overwhelm the user cost at its upper bound. Thus the authors suggested an inclusion of the EDC into pavement design and maintenance.

2.1.3 Congestion Module

Construction and M&R activities influence the passing-by vehicular operations, leading to congestion, detour, or wait in queue symptoms when vehicles drive through construction zones. The disrupted driving behavior leads to additional fuel consumption and air emission for some pollutants due to reduced speed and longer travel distance if detour is taken. The difference of the two scenarios, normal traffic operation and driving under construction and M&R periods, is calculated in congestion module as an individual contributor to the final LCIs. Only limited studies consider the congestion module in current LCA studies although they universally suggest a significant impact from congestion module at a high traffic volume.

Kendall (2004) initialized the incorporation of congestion module into LCA model in his master thesis, which propels the study a big step forward. Although being a LCA study of concrete bridge deck paving designs, this thesis covered each of the five modules and therefore built a systematic methodology of performing LCA study. Two deck paving options, the conventional steel reinforced concrete (SRCC) deck with mechanical steel expansion joints, and the SRCC deck with ECC link slabs, were evaluated in terms of their environmental metrics, including energy consumption, air emission, water pollutant, and solid waste. Several following studies used the same methodology to perform the LCA case studies, for instance, Keoleian et al (2005, a journal paper adapted from the thesis), Zhang et al. (2010a, 2010b).

The functional unit is a bridge that is 0.1 mi (160 m) long, four lanes wide (two lanes in each direction), and the deck is 9 in. (23 cm) deep and rests on steel girders supported by a steel reinforced concrete substructure for a 60-year life span. Traffic volume passing the bridge is estimated to have 35,000 cars per day in each direction. For the two deck paving candidates, their M&R activities were scheduled as: the bridge deck needs rehabilitation replacement every 30 years, deck resurfacing and joint replacement every 15 years, and minor maintenance every 5 years for the conventional joints; and deck resurfacing every 20 years, and minor maintenance every 10 years for the ECC system.

In the thesis, material module includes a wide range of materials, such as cement, gravel, fly ash, super plasticizer, PVA fiber and uses multi-source of data. The volume and energy intensity of each material are tabulated. Machinery requirement for construction events were obtained from estimation of a Michigan-based highway contractor. The resultant energy consumption and emissions based on equipment class and horsepower rating were given by U.S. EPA NONROAD model. Construction activities in this study were separated into two categories. Processes that involved demolishing and dismantling the bridge component and transporting the demolished materials were attributed to the EOL module, while the remainings belonged to the construction module.

Congestion module was performed. Traffic delay, detour, queue length under construction and M&R period were estimated using KyUCP traffic model (Rister and Graves 2002) after comparison with the other models, such as QUEWZ98 developed by the Texas Transportation Institute, CO_3 developed by Robert Carr at the University of Michigan, QuickZone developed by McTrans. The vehicle fuel consumption and emission data under disturbed status were measured by U.S. EPA MOBILE6.2 software, which provides tailpipe and evaporative air emissions on a per year basis through 2050. Fuel consumption and air emission differences between vehicular operation under construction periods and normal conditions were calculated as the tradeoff of performing construction activities, which is given in the equation.

$$Y_{total} = VMT_{queue} \times Y_{queue} + VMT_{workzone} \times Y_{workzone} + VMT_{\det our} \times Y_{\det our} - VMT_{normal} \times Y_{normal}$$

where Y_i represents the value of different environmental indicators, such as fuel usage (L/km) or emission values (g/km); VMT_i is the total miles travelled by vehicles (km or mile); i is scenario index, representing the total, waiting in queue, passing through work zone, taking detour, or operating under normal conditions.

Distribution process, that is transportation in other literatures, was treated as an individual module in the thesis. The distribution process was closely linked to the material module and EOL module. The thesis tabulated the transportation mode and distance of the materials. Additionally, the author noted that the roughness development of bridge deck wears the vehicle tires and reduces fuel economy, resulting in an increased fuel consumption, which belongs to usage module, but did not perform detailed calculation due to the lack of feasible models. EOL module was simply treated as landfill with consideration of removal and transportation of demolished deck paving layers. The same demolition process for the ECC and the conventional systems was assumed despite that the demolition process of the former one proved much more difficulty than the latter one.

In general, a systematic LCA methodology was constructed on bridge deck paving project and can be readily applied to pavement field. The study found: firstly, the ECC link slab is much environmentally friendly compared to the conventional concrete deck; and secondly, construction related traffic delay is realized to be a driving element of environmental impacts.

Sensitivity analysis of future traffic pattern was investigated by three scenarios, zero percent, one percent, two percent annual traffic growth rates. It indicates that at the 2 percent traffic growth rate, traffic related energy consumption grows 13 and 23 times of the zero percent level for the ECC and conventional systems, respectively. One point to note is that, NO_x emission witnesses a negative value in congestion module which means that the emission actually decreases during construction and M&R activities. The explanation by the author is the NO_x emission rate is higher at high speeds than low speeds and construction and M&R activities reduce the passing-through fleet speed.

Huang et al. (2009b) evaluated the additional fuel consumption and emissions by the traffic during the roadwork periods and found it to be significant. A British based LCA methodology was proposed in the paper but will be reviewed in the “LCA Model” section (section 2.2.9). A case study was applied to an asphalt pavement rehabilitation project in the U.K. Traffic condition on the road section was simulated by micro-simulation program VISSIM and then fed into the traffic emissions model. Emissions from traffic under the roadwork period and normal condition were compared.

2.1.4 Usage Module

Usage module is of great complexity as opposed to the other modules. It deals with activities occurring on pavements after the pavements are opened to traffic. There are many factors affecting usage module, which are differentiated into two major categories in this dissertation: traffic-related factors and pavement-related factors. Typical and most important traffic-related factors include: traffic volume, traffic composition, fuel economy improvement, and vehicle emission reduction technology, etc.; pavement related factors include pavement roughness development trend, pavement structure property, albedo, material leachate, noise, and heat-island effect, etc.

Usage module plays a significant role in the LCA model but is seldom touched or with no satisfactory completeness in the current available literatures. The usage module is still at a burgeoning stage and demands tremendous research efforts. For example, roughens reduces the fuel economy appreciably and models to characterize their relationship are mostly built on WesTrack project data (Epps et al.1999). However, the test data is specific to heavy trucks and not suitable to be directly used for passenger cars. Moreover, increased roughness tends to reduce the fleet speed in a general trend which increases the fuel consumption and air emission but its concrete function remains unveiled despite some concerning researches have been performed, such as Karan et al. (1976) , Bennett (1994), and Chandra (2004). These studies, however, are either outdated or foreign data-based (Chandra, 2004). Structural properties of pavements, HMA pavement versus PCC pavement, influence fuel economy at different rates for passenger cars and heavy trucks. The study by Zaniewski (1989) did not find an appreciable difference between the two pavement types for passenger cars while revealed heavy vehicles to experience a 20 percent drop in fuel economy on asphalt pavements than on concrete pavements. The study by National Research Council of Canada Centre for Surface Transportation Technology and the Canadian Portland Cement Association suggested that for a fully-loaded tractor semi-trailer, it combusts 6, 8 and 11 percent more fuel on asphalt pavements than on concrete pavements at speeds of 60, 75, and 100 km/h, respectively, on one of the test sections (Taylor et al. 2000). Beuving et al. (2004) built a theoretical approach to determine fuel consumption loss on flexible pavements. Model calculations suggested an average loss of 0.05% under normal operating conditions and were capped at 0.88%. For more discussion of the issues that plague the usage module, please read Santero (2009).

Häkkinen and Mäkelä (1996) published a research report in Finland which pioneered the application of LCA concept to the pavement field. Despite its initialization, it is actually one of the most comprehensive LCA studies due to the inclusions of usage stage, including the traffic related environmental burdens, noise generation, lighting requirement, dust formation, and carbonation of concrete pavement. Its objective is to assess the environmental impacts of concrete and asphalt pavements for a 50-year analysis period. LCIs in this study include: energy consumption, air emissions, raw material usage, and noise generation.

The functional unit in this report is 1 km of pavement bearing 20000 vehicles per day with a life span of 50 years. Two types of pavements become the target, with their structural designs shown in Table 2.5.

Table 2.5 Structural Designs of Häkkinen and Mäkelä

Asphalt pavement	SMA (50 mm)	ABK(70 mm)	ABK (120 mm)	Rock 1.9-2.5m
Concrete pavement	Concrete (220 mm)	ABK (120 mm)		Rock 1.9-2.5m

Maintenance activities were performed with two or three times grinding for concrete pavements and a Finnish or Swedish practice for asphalt pavements within the analysis period.

Under this given, environmental burdens caused by traffic during 50 years are dominating compared with pavement materials, paving activities, maintenance activities and lighting requirement. However, there is no appreciable difference for traffic related environmental metrics between the PCC and HMA pavements because the authors assumed that the measured differences in rolling resistance were insecurely small compared with other factors influencing the fuel consumption. Traffic disturbance due to M&R activities are very small in the study, possibly due to a small traffic volume. And the final result is not sensitive to the uncertainty and variation in fuel consumption caused by traffic disturbance. Lighting requirement for concrete and asphalt pavements are considered by the *Commission Internationale de l'Eclairage* (CIE, that is the International Commission on Illumination) classification. Finnish asphalt pavements are of R2 type and concrete pavement of R1, which means 2/3 higher electricity requirement for asphalt pavements than for concrete pavements. Noise generation is seldom considered in subsequent LCA models while in this study, it was transformed into land space requirement for the two pavement types to be both reduced to 55 dB. Stud tire is frequently used in Finland during winter season, thus the dust formation due to tire abrasion was considered.

For material module, the data of bitumen production, cement production, aggregate production, and transportation during the process were well described using North Eurocentric sources. Construction module was counted by including the fuel consumption and resulting emission of unspecified paving equipment. At construction periods, no congestion was calculated due to the assumption of new construction project. What-if assessments were performed on energy consumption reduction due to beneficial pavement characteristics and one fourth recycling of the asphalt pavement materials.

The research is in favor of concrete pavement in terms of energy consumption and CO_2 emission whether feedstock energy of bitumen is counted or not. A rank as paving + maintenance< materials<lighting<traffic is summarized in terms of the significance of their environmental impacts during 50 years.

Zhang et al. (2010a) developed a comprehensive methodology of performing LCA. Although dedicated to pavement overlay systems, this methodology can be used as a standard practice for other cases. The authors spent much content on the model explanation, with focus on the congestion and usage modules, which made the study distinctively superior to most previous LCA studies. Outputs of the study include: total primary energy consumption, CO, NO_x, SO_x, VOC, biological oxygen demand, chemical oxygen demand, and waterborne suspended matter.

The functional unit is a 10-km long freeway section in two directions that will function for 40 years. Each direction has two 3.6 m wide lanes, a 1.2 m wide inside shoulder, and a 2.7 m wide outside shoulder. The thickness of the three overlay systems are 175 mm for concrete overlay unbounded from the existing pavement by 25 mm asphalt layer, 100 mm ECC layer and 190 mm HMA overlay directly placed over the existing pavement. The AADT is approximating 70000 vehicles with 8% heavy trucks. Maintenance activities are implemented to the three overlay systems.

In this paper, The LCA model was divided into six modules, including: material module, distribution module, construction module, congestion module, usage module, and EOL module. The material module was calculated using data sets from various sources including the Marceau et al. (2007), the Athena Institute (2006), and the SimaPro 6.0 software. In the distribution module, the material was transported by a combination of roadway, railway and waterway with assumed distances. In the construction model, operating time of the equipment was estimated by previous construction project documents from MDOT and the production rate of each machine. The fuel consumption and air emission were outputted by U.S. EPA NONROAD model as previously used by Kendall (2004). Congestion module was estimated by the same model used by Kendall et al. (2004).

In the usage module, two influencing factors were considered: fuel economy change and road roughness change over time. For heavy trucks, a 1.5 percent annual fuel economy improvement rate was assumed while for passenger cars, fuel economy improvement was modeled by an equation proposed by Lee et al. (2002). A distress index was used to characterize the pavement deterioration trend of the concrete, HMA and ECC overlay, which is a function of international roughness index (IRI) proposed by Lee et al. (2002). A fuel economy and IRI relationship was created by the experiment data of WesTrack project (Epps et al. 1999). In this way, the additional fuel consumption due to increased IRI was determined. IRI increase has more impacts on the LCIs, like reducing fleet speed and lane capacity and causing additional friction and vertical acceleration of the vehicle body. In practice, the speed was adjusted by an equation raised by Wilde et al. (2001) in the paper; the capacity reduction was estimated by an India-based research, whose traffic conditions are significantly different from those in the U.S. To estimate the additional air emission by frictional and vertical vibrations, a constant emission rate was assumed for a typical speed of operation (90–105 km/h) of a truck (Tunnell and Brewster 2005).

The EOL module was simplified as landfill since the authors claimed that the concrete pavement is not widely recycled in the new pavement surface layer and a substitution of more than 20 percent RAP will reduce the pavement quality despite that waste asphalt pavement is widely recycled.

The paper found that the ECC overlay system (580 TJ) demands substantially less energy as compared with the concrete system (680 TJ) and the HMA system (2100 TJ, with feedstock energy). The life cycle energy consumption for the three systems is dominated by material production energy, traffic congestion related energy, and roughness related energy, where roughness factor consumes 23, 36, and 14 percent of the total energy of the concrete, ECC, and HMA overlay systems, respectively. And the ECC system reduces GHGs emission by 32 percent and 37 percent compared to the concrete overlay system and HMA overlay system, respectively. The same abnormal phenomenon is observed for NO_x and CO emissions in congestion module for the same reason mentioned in "Congestion Module" section (section 2.2.3). Sensitivity analysis found that future traffic increase and fuel economy improvement significantly influenced the results, with the former being negative and the latter being positive.

Treloar et al. (2004) performed a hybrid LCA model, which was fulfilled by replacing IO outputs with their corresponding process level data, to establish a methodology for assessing the environmental impacts of roadway systems. Energy consumption was the only environmental metric interested. Usage module was considered and found to be significant, but not very much relevant to the pavement itself. Specifically, the usage module was focused on the modeling of vehicles, including fuel consumption of the traffic, the embodied energy in vehicle manufacturing, and ownership cost of the vehicles. These modeling parameters have no direct connection to pavement system; nor the fuel economy of vehicle driving on different pavement structures is characterized. In this sense, this is more interesting to vehicle industry than to the pavement community.

The functional unit is a rural highway of 5 km stretch that supports 10000 vehicles per day, with 10 percent trucks. Eight different pavement structure designs, including a CRCP, an undoweled JPCP, a composite pavement, and five asphalt pavements, are listed in Table 2.6 with different service lives.

Table 2.6 Structural Designs of Treloar et al.

CRCP (102mm)	Low strength concrete (107 mm)	Analysis period: 40 years
JPCP, undoweled (186mm)	Low strength concrete (107 mm)	Analysis period: 40 years
AC (231mm)	Low strength concrete (131 mm)	Analysis period: 40 years
AC (171mm)	Low strength concrete (108 mm)	Analysis period: 40 years
AC (171mm)	Compacted earth	Analysis period: 40 years
Compacted earth	Compacted earth	Analysis period: 20 years
AC (128mm)	Low strength concrete (175mm)	Analysis period: 40 years
AC (42mm)	Low strength concrete (252 mm)	Analysis period: 20 years

Congestion module and EOL module are not within the scope of this study. In material module, the energy intensity of the materials was calculated in a hybrid way, that is, industry data of energy usage are substituted into IO model based on Australia IO tables, 1992-1993 version. The construction module was estimated using an Australian IO model without numerating the types, productivities, and energy consumption rates for the individual equipment.

M&R activity was modeled with an annual 4 percent energy requirement out of the total energy, as assumed by the authors, which brings a 1.6 times and 0.8 times increase of total energy requirement for 40 years and 20 years analysis period. This influenced the results significantly but was not evaluated about its uncertainty in the sensitivity analysis.

In general, this LCA study prioritizes the interest in determining the importance ranking of materials, construction, maintenance activities, and vehicle operation in the roadway life cycle period, but does not aim to suggest the best pavement practices out of the eight candidates. Road construction process is a small contributor to the total energy consumption while vehicle related energy, that is manufacturing energy and operational energy, is significant to the energy demand. Although a bit deviating from the pavement engineer's interest, this hybrid LCA methodology points out a feasible path to retain the accuracy of process LCA and minimize the truncation error by using IO LCA.

2.1.5 EOL Module

EOL module is seldom included in the LCA model since many authors treat the pavement with infinite life as long as M&R activities are implemented timely. Some consider the EOL module by simplifying waste materials landfilled. The Athena Institute (2006) recycled 20 percent of waste asphalt pavement in new construction project and therefore reduced the energy portion from material module appreciably. The study considered the energy consumption for old pavement demolishment and waste material transportation in the EOL module.

Horvath and Hendrickson (1998) performed an IO LCA study on pavement with EOL module briefly touched. Toxic fumes emitted from hot bituminous materials during construction period were characterized and the recyclability of the two materials was discussed in the EOL module.

As the first peer reviewed journal paper in the U.S., EIO-LCA (Economic Input-Output Life Cycle Assessment) model from Carnegie Mellon University was used to assess a HMA pavement and a CRCP pavement in the U.S. based on the 1992 Industry Benchmark IO model. Environmental outputs include fuel consumption, electricity demand, ore and fertilizer usage, and air, water, and land discharges. However, GHGs emission is missing from the inventory.

The functional unit is set as two pavement structures (CRCP of 220mm and HMA of 300mm) to withstand ten million ESALs, which is estimated roughly to be ten years of interstate highway traffic by the authors. No maintenance schedule is planned during the period. Feedstock energy is not included in the LCIs. Under the given conditions, the asphalt pavement consumes 40 percent more energy than does the concrete pavement in the material module. However, while enjoying credit in energy consumption aspect, the concrete pavement releases more air pollutants compared with the asphalt pavement in the other way. Steel used in the CRCP structure occupies a considerable portion of the discussed environmental metrics.

In the study by Park et al. (2003), the original highway was demolished and recycled for 35 percent, with the left sending to landfill as the EOL treatment. Energy consumptions of demolishing waste pavement structure and moving waste materials were considered. This is an IO LCA study to measure the environmental loads of highway systems based on the IO tables from Korean. The study includes material module and a series of Korean data for the other involved modules. In general, these data are heavily Korea based, many of which are derived from questionnaires, hard to trace their roots and thus make the study infeasible to replicate by foreign researchers.

In an overall view, the paper is not a traditional asphalt pavement versus concrete pavement comparison but a more generalized LCA methodology demonstration. The authors tested the methodology with an asphalt pavement design. Output metrics in this study include: equivalent oil consumption, SO_2, NO_x, and CO_2. One thing to note is that being the most significant metric, equivalent oil, is not strictly defined about its baseline oil type and exchange rates between different types of oil. The functional unit in the study is 1 km highway with four lanes that will last for 20 years. The highway system is not given about its traffic volume. Geometric information of the highway is listed in Table 2.7.

Table 2.7 Structural Designs of Park et al.

Surface (cm)	Base (cm)	Sub-base (cm)	Other (cm)
5	25	30	25

The study found the largest amount of energy to be consumed by the material module, following by M&R activities, and then construction module and EOL module.

2.1.6 Other Category

The literatures discussed above are classified by their most important module or innovative contribution to the specific module. Some are left to be not eligible for the classification. However, this does not mean that the left ones are of less importance or interest but just less suitable to match one certain category.

For instance, a novel concept “emergy” was used in the report by Roudebush (1996) to evaluate the environmental choice between asphalt pavement and concrete pavement. Emergy is defined as the available energy of one kind that is used up in transformations directly and indirectly to make a product or service (Odum, 1996). The unit of emergy is emjoule or emergy joule. Using emergy, sunlight, fuel, electricity, and human service can be put on a common basis by expressing each of them in the emjoules of solar energy that is required to produce them.

Uniquely, ten modules were differentiated for the LCA model in this report, including: natural resource formation, natural resource exploration and extraction, material production, design, component production, construction, use, demolition, natural resource recycling, and disposal. Despite a different partition of the methodology, the modules can be manipulated by addition or subtraction to obtain the same ones as used by others. The LCI is presented in the form of emergy. The feedstock energy is not considered.

The functional unit is a 24 feet wide and 3281 feet (one kilometer) long pavement section over a 50-year analysis period, with no information regarding traffic levels. Two pavement structures, asphalt pavement and concrete pavement, are introduced in Table 2.8.

Table 2.8 Structural Designs of Roudebush

Asphalt pavement	5 in. asphalt	14 in. aggregate course
Concrete pavement	9 in. JPCP	6 in. aggregate course

For cement pavement, a one-inch asphalt bondbreaker and nine-inch concrete overlay are placed over the original pavement surface at the end of year 25 as the rehabilitation plan; for asphalt pavement, the rehabilitation plan is scheduled as:

1. A 5 in. asphalt concrete overlay is placed at the end of year 14.
2. The original asphalt concrete pavement and overlay are demolished and removed at the end of year 25.
3. A new 5 in. asphalt concrete pavement is constructed over the original 14 in. untreated aggregate based course at the end of year 25.
4. A 5 in. asphalt concrete overlay is placed at the end of year 39.

All except usage and congestion modules were studied in the emergy form, although the author recommended future research on light requirement and fuel consumption for the two pavement structures. Emergy calculation applicable to the concrete and asphalt pavement is said to be obtained from companies, individuals, and documents. Four aspects were evaluated, including environment, fuel, goods, and service for each of the ten modules with great details presented in the appendix.

Mroueh et al. (2000) published a two-stage research report on several typical pavement structures of Finland highway systems. The first stage aims to develop a life cycle impact assessment (LCIA) procedure for the comparison and evaluation of alternative roadway constructions; the second stage assembles data from various sources to form the LCIs for the selected pavement structures. Inventories of this research include: raw materials and secondary products, energy and fuel consumption, emissions of CO_2, NO_x, SO_2, VOC, CO and PM, dust formation, compounds leaching into underground water and noise generation.

The functional unit is a 17 m wide, 5 m deep and 1 km long highway in Finland with 7000 AADT and 14 percent heavy vehicles. Various typical pavement structures in Finland are considered in the study, as listed in Table 2.9.

Table 2.9 Structural Designs of Mroueh et al.

Structural layer	Natural aggregate	Asphalt 1	Asphalt 2	Asphalt 3
surface	160 mm AC	50 mm AC	160 mm AC	160 mm AC
base	250 mm stone	150 mm stone	150 mm stone	150 stone
Sub-base	250 mm gravel	650 mm fly ash+ 2% cement	350 mm fly ash+ 2% cement	350 mm fly ash
Lower sub-base	250 mm sand	200 mm sand	200 mm sand	200 mm sand

Structural layer	Concrete 1	Concrete 2	Blast-furnace slag
surface	160mm AC	80mm AC	160 mm AC
base	100 mm crushed concrete	200 mm crushed aggregate	100 mm crushed blast-furnace slag
Sub-base	350 mm crushed concrete	200 mm crushed concrete	250 mm granulated blast-furnace slag
Lower sub-base	55 0mm sand	450 mm sand	200 mm granulated blast-furnace slag

Material module in the report was exhaustively explained with transparent sources, which quoted the results of the report by Häkkinen and Mäkelä (1996). Construction module was covered but lack of details of how the road construction was performed. One novel idea to note is: noise influence during the construction period was characterized by multiplying the sound intensity (in dB) and construction hours.

Road maintenance was assumed to take place in accordance with the common Finnish road maintenance strategy (Häkkinen and Mäkelä 1996). Each alternative experienced the same maintenance because the authors asserted that the same performance of each alternative was expected. Usage module was shallowly touched, just with the consideration of leachate of pavement materials into ground water based on the laboratory-scale leachate test results. The EOL module was treated as leaving the pavement where they were or landfill by a combination of national level and project level of transportation distances of materials.

The study proposed a single score for each alternative by an expert weighting system derived by questionnaires, which heavily weights environmental indicators such as materials and energy consumption. Also, questionnaires were distributed to two set of people, but received a non-negligible difference between the answers, which might alter the final conclusions if the alternative response score system was used. In the other systems, production and transportation of the materials for road construction have the most significant environmental burdens while in the expert weighting system, consumption of natural materials and leaching behavior of recycled materials are regarded as of great significance.

Inamura et al. (1998) proposed an IO-based hybrid LCA methodology on pavement system in Japan, including expressway construction, expressway maintenance, vehicle production, and fuel consumption by vehicle operation. The LCA model is based on IO table of Japan, 1990 version. GHG equivalent emission is the only environmental metric in the LCI.

The functional unit is selected as an inter-city toll way in the north-eastern region of Japan with a total length 679.5 km. The analysis period is 60 years. Traffic volume is said to be prepared by the Japan Highway Public Corporation (JHPC) but with no concrete information. The material module, construction module, and usage module are considered in the LCA models. The congestion module and EOL module are out of the scope of this study.

The construction cost of the expressway are obtained by the contract cost estimate in the contract year price and then converted into the base year (1990) price. Maintenance cost of the expressway is also supplied by JHPC.

The car industries are one of the basic 405 sectors in the IO table, and can be estimated about the emission per one million yen of car production. Traffic in the highway included three vehicle classes: passenger car, bus, and truck. Each vehicle class is further divided as gasoline and diesel powered with different emission rates. Based on the above information, the emission factors for the expressway construction, expressway maintenance, vehicle production, and fuel, were estimated in a unit of ton-C/million yen. The results indicate that the emission from vehicle operation plays the most important role in the life cycle emission of expressway and most of emission comes from freight transportation (truck).

A sensitivity analysis using the structural decomposition approach was developed to investigate the effect of technology change on the CO_2 emissions. While it does reduce the emission amounts considerably, the benefits by technology improvement is neutralized by the demand increase, and thus results in a net increase in CO_2 emission.

The authors further carried out comparative analysis of expressway system and high-speed railway system. The two systems have similar functions but not exactly the same. Expressway system bears freight and passenger transport while the high-speed railway serves only passenger transport. Furthermore, the two systems have different scales in construction and traffic conditions. Therefore, the passenger-km is selected as the functional unit in the comparison part. The result reveals that expressway system emits less CO_2 than the high-speed system before 30 years and the opposite is true after 30 years.

2.1.7 Secondary or Innovative Materials

Increasing energy shortage pressure and environmental protection concerns have encouraged the utility of pollution-free, recyclable engineering materials that consume less energy to manufacture. The use of secondary (recycled), instead of primary (virgin) materials helps ease the landfill pressure and reduce the rate of raw material depletion. Secondary materials are also called “resources in the wrong place” and can and should be reused or recycled. In Europe and U.S. (Pihl and Milvang-Jensen, 2001), recycled materials used in construction are classified as industrial byproducts, such as steel slag and coal fly ash; road byproducts, such as reclaimed concrete pavement (RCP) materials and RAP materials; or demolition byproducts, such as crushed concrete, tiles, and bricks. In the LCA model, EOL module deals with waste material treatment and material module considers the substitution of secondary materials to virgin materials. Besides, more materials of green properties are also employed in road construction to mitigate the environmental impacts. Several LCA studies concerning secondary materials and innovative materials are performed.

Chiu et al. (2007) evaluated the environmental impacts of using recycled materials to rehabilitate asphalt pavements by an Eco-indicator 99 index in Taiwan area. Three recycled materials (RAP, asphalt rubber and glassphalt) and the traditional HMA are compared, where glassphalt is a term used to represent HMA incorporating 10-25 percent crushed glass (Chiu and Lu 2007; Chiu and Pan 2006). The functional unit is defined as a one-lane-kilometer roadway of 5 cm thickness for a 40-year life span. The authors assumed the effects of traffic volume and pavement thickness to be the same for different alternatives in the study. No detail traffic information was provided.

The authors considered only material module, including material depletion, electricity and heat consumption, transportation fuel usage. Those components are assigned with individual Eco-indicator values. Under the same thickness and traffic influences, the service lives for conventional HMA, RAP, asphalt rubber, glassphalt are 6, 6, 9, and 5 years. However, the life expectations for the four alternatives are not clarified about the background information or supporting evidence. The authors further expanded the service life to a uniform 40 years for all four alternatives and their environmental impacts are linearly expanded to compare. Through the study, eco-burden for glassphalt is the highest with traditional HMA following, and RAP and asphalt rubber being the same and least for the 40-year life span.

Generally speaking, this study is based on Eco-indicator index but has several following issues that cripple the credibility of the research results: firstly, the life time of each alternative was determined by the authors with no supporting background information, which would significantly alter the results if slight disturbance occurs; secondly, the validity of lineally expanding the service time and corresponding eco-burdens to 40 years is not very reasonable; and thirdly, too limited module is used (only material module), which introduces tremendous completeness concern of the study.

Gschösser et al. (2011) performed a cradle-to-gate LCA study to evaluate the environmental impacts of the materials used in Swiss pavements and to mine the environmental improvement potentials of the current material production process applied in Swiss. Only impacts from raw material extraction up to finished product are taken into consideration while the construction, usage, maintenance, and EOL modules are ignored. The authors justified the treatment by assuming that different production processes of the materials do not influence the usage and the maintenance of the road. The impact categories are global warming potential (GWP), cumulative energy demand, and ecological scarcity 2006 which provides eco-points per unit of the materials. The functional unit in this study is the production of 1 m^3 of road construction material. The study analyzed several production options of road materials used in Swiss asphalt and concrete pavements.

Asphalt production data was collected from a survey covering 25 percent of Swiss asphalt production companies occupying 22 percent of the total Swiss asphalt sales. RAP is used by either warm or cold recycling, with four ranges: no share, average share, production share, and maximum amount share, each range with different portion of recycled asphalt.

Averaged levels of Swiss data were used for the production of clinker, the main ingredient of cement with a variety of north Eurocentric data. A range of 0 to 100 percent RCP was used to the bottom layer of concrete pavement at a 20 percent interval. Also, four types of cement were used with compositions as: clinker, clinker + slag sand, clinker + limestone, and clinker + oil shale.

As for the sub-base mixture, three material options were discussed in the paper, including unbound sub-base, hydraulically bound sub-base and bituminous bound sub-base. For the latter two material options, three production processes (central mixing at plant, central mixing at site, and in-situ mixing) and two recycling scenarios (primary material and secondary material) were combined.

With the analysis of the combination of each scenario for the asphalt mixture, concrete mixture, and sub-base mixture, the results suggest that a reduction of 54, 38, and 93 percent is harvested for the three mixtures of the optimum designs as compared with current practices, respectively, in terms of their environmental impacts.

To assess the uncertainty of the LCA model, a Monte Carlo simulation was performed. Simulation results suggest that the probability of the optimum design being superior to the current practice is much higher than that of the reverse, and thus there are environmental improvement potentials for the current pavement materials in Swiss roads.

Titanium Dioxide (TiO_2) ultrafine particulate has been used as a coating for concrete pavement to trap and absorb organic and inorganic air pollutants by the photocatalytic process. Hassan et al. (2009) studied the environmental impacts of the material, both negatively and positively, through the LCA model. The functional unit is not explicitly defined in the study but can be viewed as the production and usage of one unit of TiO_2. No life span or application project information was provided in the paper.

Material module and construction module were included in the LCIs. Energy consumption and air emission related to the TiO_2 manufacturing, transportation and placement over PCC pavement were considered while the supporting concrete pavement was excluded from the LCIs. Energy consumption and emission data of TiO_2 manufacturing, transportation and onsite construction used a variety sources and were further complemented with outputs of EIO-LCA model developed by the Carnegie Melon University (EIO LCA model). Although the authors provided the data information, they did not explicate the detailed usage, which makes the study hard to replicate by practitioners.

Impact assessment of the obtained LCIs was performed by Building for Environmental and Economic Sustainability (BEES) model. By assigning respective weighting values to the ten environmental impacts subjectively (the authors did not justify the selection of the weighting system or provide any supporting background information), a single score was obtained finally. The authors also considered the additional cost of installation of TiO_2 and found a 4 percent cost increase per cubic meter.

The use of TiO_2 will have a positive effect on acidification, eutrophication, critical air pollutants, and smog formation but negative effects on GWP, fossil fuel depletion, water intake, ozone depletion, and human health due to its production process. However, based on the above mentioned weighting system, TiO_2 coating system has an overall negative score of -0.70 which indicates an overall positive effect on the environment to be expected eventually.

2.1.8 LCA&LCCA Integration

LCCA is a method for assessing the total cost of facility ownership. It takes into account of all costs of acquiring, owning, and disposing of a building system. LCCA is especially useful when project alternatives that fulfill the same performance requirements, but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximizes net savings. LCCA has gradually become a common practice in the pavement field with focus on monetary aspect. On the other hand, LCA model is developing quickly with focus on environmental aspects. The idea to integrate the two approaches as one naturally emerges.

Chan (2007) performed an integrated LCA and LCCA study to identify the most cost-effective alternative out of 6 rehabilitation projects, 7 reconstruction projects, and one new construction project of asphalt and concrete pavements. The study firstly performed the LCA to derive air emission information and then evaluated the environmental metrics via monetary cost, and finally fulfilled the combination of LCA and LCCA models. Outputs of the LCA model include: raw material production, energy consumption, GHGs emission and other air pollutants.

The functional unit for the 14 alternatives is universally 4-lane-km. Specific traffic conditions for each alternative are provided but no detailed pavement design information and definite life cycle period are given. Maintenance activities for the projects are also unknown.

Material consumption of each project was calculated from the corresponding LCCA document with the environmental impacts supported by a variety of literature sources and SimaPro software. One thing to note is that, 25 percent RAP is used in asphalt project and 2 percent fly ash is used in cement concrete pavement by weight. Construction activities were estimated from project specifications. Congestion and related environmental burdens due to construction activities (no maintenance activities) were estimated with project information inputs. Basically, the holistic methodology was performed following the practice of Kendall (2004). To calculate the external cost of air pollutants, MDCs were estimated with a low and high bound through literature review.

The research is in favor of cement concrete pavement compared with asphalt pavement in terms of energy consumption if feedstock energy is considered but observes paralleled energy consumptions if not. However, there is not consistent assessment of asphalt pavement and cement pavement judged by other index. Material module dominates the energy consumption and air emission in most cases since the traffic volume is low for most of the projects.

By multiplying the MDCs with the quantities of air pollutants, EDCs were calculated. Material production is no longer the dominant factor. Instead, material transportation and construction equipment operation become the more important sources. It is primarily due to the high MDCs and amounts of certain air pollutant emissions, such as lead, PM_{10}, and NO_x, as explained by the author. Similarly to Kendall (2004), negative pollution damage cost is obtained in congestion module since reduced fleet speed during the construction period curtails the NO_x and CO emissions.

Similar to the above mentioned study, an integrated LCA and LCCA model was adopted to assess two bridge deck designs, conventional concrete bridge deck and ECC link slab design, in terms of total life cycle cost including agency cost, user cost, and EDC. The same functional unit, system boundary, and maintenance schedule were used as in the study by Kendall (2004), which will not be restated here.

The air emission was estimated via the LCA methodology previously developed by the same author. MDCs of various air missions, including PM_{10}, NO_x, SO_2, CO, lead, VOC, CO_2, NO, CH_4, were calculated from various sources in 2003 U.S. dollar. A Monte Carlo simulation was conducted to fit the probability distribution for each air pollutant to reveal the uncertainties associated with the estimated MDCs.

User cost and agency cost were estimated at the real discount of 4 percent annually while a sliding discount rate that accounts for the immediate, near, and medium future scenarios were assigned to air emission damage cost. Specifically, for the immediate future (1-5 year), a 4% discount rate was used; for the near future (6–25 year), a 3% discount rate was used; and for the medium future (26–75), a 2% discount rate was used. The author realized the significant influence of discount rate on the results and examined it by sensitivity analysis.

Life cycle cost suggests an overall less cost of the ECC link slab system over the conventional system. User cost overwhelms the total life cycle cost, which consists of agency, user, and EDCs. And EDC is notably small compared with the other two costs. Of the user cost, time loss is the major contributor which is closely related to traffic volume. Thus AADT variation sensitivity analysis was performed which suggested a plausible exponential relationship between user cost and AADT.

According to the sensitivity analysis of the discount rate, 7.2 percent of discount rate is the cross point in evaluating the cost advantage of two systems. In other words, at higher discount rates than 7.2 percent the conventional system gains a cost advantage over the ECC system.

Zhang et al. (2008) applied the integrated LCA and LCCA methodology to evaluate the environmental impacts and costs of three overlay systems, the unbounded concrete overlay system, the HMA overlay system, and the ECC overlay system. The same functional unit, system boundary, and maintenance schedule were applied as in the other study by Zhang et al. (2010b). For the LCA aspect, the same module and model were used in this study. For the LCCA aspect, the framework developed by Keoleian et al (2006) was used.

The ECC overlay system carries lower environmental burdens and life cycle costs over a 40-year service life compared to the concrete and HMA overlay systems. Material module, congestion module, and usage module (roughens effect on fuel consumption and air emissions) are identified as the most significant contributors to environmental impacts while user cost, compared with agency cost and EDC, dominates the total life cycle cost.

2.1.9 LCA Models

Unlike the widespread and commonly accepted LCCA models, such as Federal Highway Administration's (FHWA) *RealCost*, Caltrans' *Cal B/C*, FHWA's *IMPACTS*, and the *Road Construction Emissions Model* of Sacramento Metropolitan Air Quality Management District, environment oriented LCA models have not yet been maturely developed and pervasively accepted. Different studies used different LCA models, which vary significantly in functional blocks, underlying rationale, and practice procedures. These LCA models are discussed in this section for their advantages and disadvantages.

2.1.9.1 PaLATE

The Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is an excel-based LCA model of environmental and economic effects of pavements and roads developed by Professor Arpad Horvath’s group. The model uses the 1992 U.S. Department of Commerce Economic Input-Output Table as the source and is complemented by additional process-based information to create a hybrid LCA tool. PaLATE models the life cycle of a pavement through material, construction and M&R, and EOL modules while congestion and usage modules are out of the scope. Environmental outputs from the model include: energy and water consumption, GWP, NO_x, PM_{10}, SO_2, CO, Hg, Pb, hazardous waste generation, and human toxicity potential (HTP). Aside from the energy, GWP, and HTP measurements, the environmental metrics are reported as raw values rather than as environmental impacts, making PaLATE primarily an inventory tool (rather than impact assessment). PaLATE also includes a life cycle cost analysis that considers the economic implications of the decisions over the life of the pavement.

Timeliness is the most criticized point of the model due to the usage of 1992 IO table of U.S. and some outdated or less accurate process level data. Also, usage module, such as congestion, fuel consumption and air emission of vehicles on pavements, and lighting requirement, etc. is notably missing. Despite the limitation, PaLATE has been used in some LCA case studies, such as Horvath (2003), Nathman et al. (2009).

2.1.9.2 ROAD-RES

ROAD-RES (Birgisdóttir 2005) is a LCA model developed for road construction and disposal of residues covering material module, construction and M&R module, and EOL module. While does evaluate the environmental impacts and resource consumption, the model pays great attention to waste material disposal methods, namely landfill and re-utilization of waste materials in roads. Eight different impact categories: global warming, photochemical ozone formation, nutrient enrichment, acidification, stratospheric ozone depletion, human toxicity, eco-toxicity, and stored eco-toxicity are evaluated by the model.

Predictions of leaching from material and the distributions of leached constitutes into the five environmental compartments (air, soil, groundwater, fresh surface water and marine surface water) occupy considerable research efforts. A new characterization method for contamination of groundwater due to leaching of salts, characterization factors for human toxicity through groundwater due to emissions of heavy metals, and a new impact category to account for the long-term leaching were developed. Case studies using the model to assess disposal of municipal solid waste incineration (MSWI) bottom ash, and construction of secondary road with and without MSWI bottom ash were presented to demonstrate that the model is useful for making comparison between different recycling scenarios.

Generally speaking, two unique contributions are made by the model: firstly, a LCA methodology with focus on material module, construction and M&R module, and EOL module was developed; and secondly, the analysis tool on residues and water pollution was designed.

2.1.9.3 Huang’s Model

One British researcher proposed a methodology of performing LCA for the construction and maintenance of asphalt pavements based on his Ph.D. dissertation work (Huang 2007; Huang et al. 2009a). After reviewing the existing literature, five barriers were identified by the author to constrain the application of available LCA studies to British road sectors, including: relevance, adaptability, compliance, scope, and availability. In the proposed framework, eleven impact categories were used to characterize the environmental impact of asphalt pavements: depletion of material, depletions of fossil fuels, GWP, stratospheric ozone depletion, acidification, photo oxidant formation, human toxicity, eco-toxicity, eutrophication, noise, and depletion of landfill space.

Unlike the classification by other studies, the model consists of 5 worksheets: process parameters, pavement parameters, unit inventory, project inventory and characterization results. The process parameters include energy in transportation, materials production and pavement construction; the pavement parameters include pavement dimension, materials recipe, and pavement life time; the unit inventories include energy production, combustion of fossil fuel, transport vehicle operation, and construction vehicle operation; the project inventories include production process, transport process and construction process; and characterization results include global warming, acidification, photo-oxidant formation, human toxicity, eco-toxicity, and eutrophication, etc.

It is found that the system covers the material module, construction module, but overlooks the congestion module, usage module and EOL module, although a following research by the same author found significant environmental impact due to traffic congestion during construction activities (Huang et al. 2009b).

In general, the proposed framework is well defined about its goal and implements the ISO14040 series of standards into the model. And the inclusion of LCIA provides useful information to decision makers, which is frequently ignored in current research.

2.1.9.4 Santero's Model

A five-module methodology of LCA model, including material module, construction module, usage module, maintenance module, and EOL modules was developed in the dissertation by Santero (2009). The author firstly reviewed the existing literatures extensively, and identified several key points that hindered the utility of LCA in pavement field, including lack of standard functional unit, incomplete incorporation of life cycle modules, an obscure discrimination of life cycle inventory and impact analysis, dilemma in the issue of feedstock energy, and the barriers of using current available LCA studies.

Lack of commonly accepted functional unit within pavement community upon which to assess the pavements is a major drawback of the pavement LCAs which shall more be blamed for the complexity of pavements than the disorganization of pavement researchers since pavement design is heavily influenced by traffic, environmental condition, material sources, and other project-related factors. Modules of LCA model are seldom satisfactory, either missing or incomplete. Material module and construction module are the focus of nearly all the existed studies, while the congestion module, usage module, and EOL module are typically ignored, as realized by the author.

Impact assessment is apparently missing from LCA literatures. Many LCA studies are better classified as LCIs than LCAs because the impact assessment step is partially or entirely excluded. Although LCIs provide plenitude of information, they may be inadequate for decision makers to understand concrete environmental impacts.

Feedstock energy of bitumen is notoriously arguable in the practice of LCAs whose inclusion or exclusion will significantly alter the results. While feedstock energy of a product is mandated to be included by ISO 14044 standards' requirement, it is actually frequently excluded by many LCA studies in pavement field. Although embodying a significant amount of energy, bitumen is a dirty burning material and traditionally not considered as an energy source. The author raised three questions to explore in order to resolve the feedstock energy issue:

> *"1. Can bitumen be used directly as fuel in some applications? If so, what are those applications and what are their environmental implications?*
> *2. What refining processes are used to upgrade bitumen to more ubiquitous fuel? What are the energy and environmental implications of those processes?*
> *3. What are the downstream effects of using upgraded bitumen as a fuel? Does it burn cleanly and/or efficiently?"*

The utility of current pavement LCAs, as summarized by the author, is hindered by one or more of the following stymies:

1. Inconsistencies in the functional unit, life cycle modules, different environmental metrics, and feedstock energy issue among LCAs make the results of the available literature largely inconclusive.
2. Uncertainty and sensitivity analyses are not fully implemented in LCAs.
3. Regional boundaries of LCAs, whose results depend on region-specific elements, pose problems in translating results between each other.

4. Shortage of peer reviewed documents.

After critical review of current research, the dissertation raised a comprehensive methodology with six modules: design, material, construction, usage, maintenance, and EOL. The design module accounts for activities that support the conceptual development of a pavement. The material module considers the processes to produce the pavement materials. The construction module considers both onsite equipment used on the construction site and traffic delay induced during pavement construction periods. The usage module consists of carbonation, lighting, albedo, rolling resistance and runoff. The EOL module includes three scenarios: landfill, reuse, and recycling.

Based on the proposed methodology, the author continued to estimate and compare the GWP ranges of each module and associated components, and identified the module and components that offer the highest potential of GWP improvement. Concerning components include: material extraction and production, transportation, onsite equipment, traffic delay, carbonation, roadway lighting, albedo, and rolling resistance. Since assumptions are specified to each component, low and up boundaries of the GWP are calculated which vary in orders and overlap between each other. The calculation results are ranked in terms of GWP improvement priority by three levels: first level, roughness, pavement structure; second level, traffic delay, transportation, materials, and radiative forcing; and third level, roadway lighting, urban heat island; carbonation, and onsite equipment. Both ideal and worst GWP scenarios were described for each component.

A case study of long life pavement using the methodology was conducted to evaluate the environmental benefits and/or drawbacks of long-life pavements. The life span of the long life pavement is set to be 40-year and 100-year; the regular 20-year design is also selected as alternatives. In the case study, usage module and traffic delay were excluded because the author asserted that prediction of traffic pattern and usage condition for a 100-year span was barely impossible and would introduce significant amount of uncertainty.

The three pavement designs are located in three regions of California with three levels of traffic volume to account for the environmental and traffic variations. The results suggest that 40-year design takes between 28 and 45 years to recoup their initial energy investment and GWP impact, relative to the 20-year design. And the lowest crossover point for one 100-year design over one 40-year design is 93 years, with the others extending over 100 years into the future. In other words, the least year for 100-year pavement design to gain environmental advantage is 93 years as compared with 40-year design. In this way, long-life pavements may not always be the best option due to the long periods of time before the benefits are realized.

The work of Santero is conclusive and suggestive and covers a broad range of research interests. Some new concepts that are not or less studied previously, such as rolling resistance, albedo, are raised to point out future research directions. Holistically, the study is prone to macro picture depiction rather than micro issue resolution and needs more efforts to fill the research gap.

2.3 Discussion of Existing LCA Studies

The reviewed literature provides insight into the environmental performance of pavements, which mostly focused on comparison between asphalt pavements and cement concrete pavements. Each literature has certain unique contributions to the LCA work.

Till date, the overall evaluation of existing LCA studies, however, is not satisfactory, as has been summarized by Santero (2009). Despite all kinds of deficiencies or limitations, the available studies are useful to help construct a more systematic and comprehensive LCA model. Limitation as well as useful information from the available literatures are analyzed and extracted below to suggest areas for improvement.

Material module receives heated debate about data source selection which depends on material production process, geometric boundary of material location, and mode and distance of transportation, etc. While the currently available data are relatively consistent on cement production, aggregate extraction, and sand production, etc., there is orders magnitude of variations of bitumen production which would significantly alter the LCA results (Zapata and Gambatese 2005). Instead of using specific values, a range may be more appropriate to represent the environmental impacts of the materials if no accurate project level data are available. Feedstock energy of asphalt binder has long been disputed about its incorporation into the LCIs. Although mandated by the ISO, the feedstock energy is more preferred to be ignored within the pavement community due to the fact that asphalt burns as dirty energy. Approach to purify asphalt to harvest energy is an interesting and promising subject but is not within the scope of this research. Moreover, truncation error, as frequently cited as a shortcoming of P-LCA models, can be partially alleviated by the hybrid approach raised by Treloar et al. (2004).

Construction and M&R module is often found to be negligible if compared with material module, congestion module and usage module. The LCA study within the U.S. can use the EPA NONROAD model to characterize the corresponding environmental burdens, as done by Kendall (2004) and Weiland (2008). Since environmental burdens of construction and M&R module are quite small, a more convenient way of estimating by an IO-based model is also acceptable, as practiced by Treloar et al. (2004). One shortcoming of the current construction and M&R module is the missing consideration of equipment wear. Every time of usage depreciates the capital value and diminishes the life of construction equipment which leads to a growing fuel consumption and air emission rate. Average level estimations of the fuel consumption and air emissions are performed in most LCA studies. It would be better to consider the effect of these two impacts. For a simplified LCA model which does not incorporate congestion and usage module, the consideration would be even more sensible since construction and M&R module is no longer negligible, as demonstrated by Weiland et al. (2010). Cass and Mukherjee (2011) used an emission calculator tool *e-CALC* to aid quantifying the emissions of the construction equipment. The equipment inputs to *e-CALC* contain information as: make, model, year, rated horsepower, useful life hours, cumulative hours used and percentage power used, etc. Hauling equipment information like gross vehicular weight and mileage is also needed to account for the to-site transportation impact. This calculation tool does not necessary warrant a precise representation of construction and M&R work due to the demand of many assumptions, but can be viewed as a step forward compared with current practices if project data concerning the equipment can be obtained.

Moreover, as suggested by Zhang et al. (2010b), suitable M&R plans can significantly reduce the environmental impacts through optimization. In their study, although the environmental impacts were evaluated by monetary index, which is a meaningful trial because it adds one more element to the LCCA to be more complete, the MDCs of each pollutant were determined with less credibility. Although a Monte Carlo simulation was performed by Zhang et al. to account for the uncertainty range, the sample size was pretty limited which reduced the reliability of the simulation in root. Actually, the estimation of the MDC proves to be difficult and with great uncertainties. For example, the average MDC of CH_4 is 44.9€/tonne by Tol and Downing (2000) and 493.5€/tonne by Pietrapertose et al. (2010), and so on. It is hard to choose one and abandon the others. A justifiable selection or treatment of the MDC among all candidates is desired to estimate the EDC with more confidence. In this research, it is expected to estimate the MDC more precisely through collection of many samples to fit the PDF for certain pollutants. The estimation is to serve the purpose of M&R schedule optimization. An easily practiced and efficient algorithm to optimize M&R schemes in terms of least environmental impacts or other objective functions is expected.

Despite that the construction and M&R module has a limited environmental influence, its resulting congestion effects are not trivial at all when the traffic volume is high. Nevertheless, congestion module, in most LCA studies, is ignored, partially because of unawareness and partially because of modeling challenge. Huang et al. (2009) simulated the traffic pattern under maintenance periods. Chan (2007) built the congestion module in the KyUCP model to account for the abnormal traffic behaviors, like detour, speed reduction, and waiting in queue. However, their efforts are far from perfect. According to the calculation of Zhang et al. (2010a), the congestion length using the KyUCP model grows longer than 15km due to high traffic volume, which, on one hand, suggests the nature of traffic sensitivity of the congestion module, and one the other hand, reveals the inability of the model. Due to the significance of congestion module, it is urgent to develop a more robust model to better capture the effect. This research aims to do some contribution. Zhang et al. (2010a) assumed a fixed detour rate while as will be used in this research, QuickZone model calculates the detour rate depending on the traffic volume. The higher the volume is, the larger the detour rate is taken.

Usage module is of high importance and complexity and therefore deserves above average attention and effort. Zhang et al. (2010a) strived to capture the influence of pavement roughness on fuel consumption and air emissions of vehicles. In their roughness effect model, one most important feature was the relationship between pavement roughness and vehicle speed. His treatment was to use the findings by Chandra (2004). The context of Chandra's study is that vehicle drives at some 65 km/h while in the U.S., vehicle typically drives at 65 mph in the highways, and the traffic volumes of the two scenarios are appreciably different. However, the description of roughness and speed relationship is very limited and quite outdated (Karan et al. 1978). In this sense, the relationship between roughness and speed needs to be reconstructed, which is one of the tasks of this research. Santero (2009) summarized most important items of the usage module and calculated the extreme values of each component in the usage module. The range is helpful to generate a holistic picture but is less attractive to field project evaluation. Research works concerning the components in the usage module, such as heat island effect, albedo calculation, lighting requirement estimation, and leachate prediction, are needed. Also, only GWP indicator was provided while the other environmental metrics were not referred. Stripple (2001) and Häkkinen and Mäkelä (1996) also investigated partial contents of the usage module. Overall speaking, their efforts reveal the limitations of current studies and direct future research orientation. Among all factors that contribute to the usage module, pavement structure impact and roughness influence are two most important components. A reliable relationship between fuel consumption and roughness development and pavement structure is urgently desired. Both field test and finite element model simulation are necessary to build an empirical and mechanistic model.

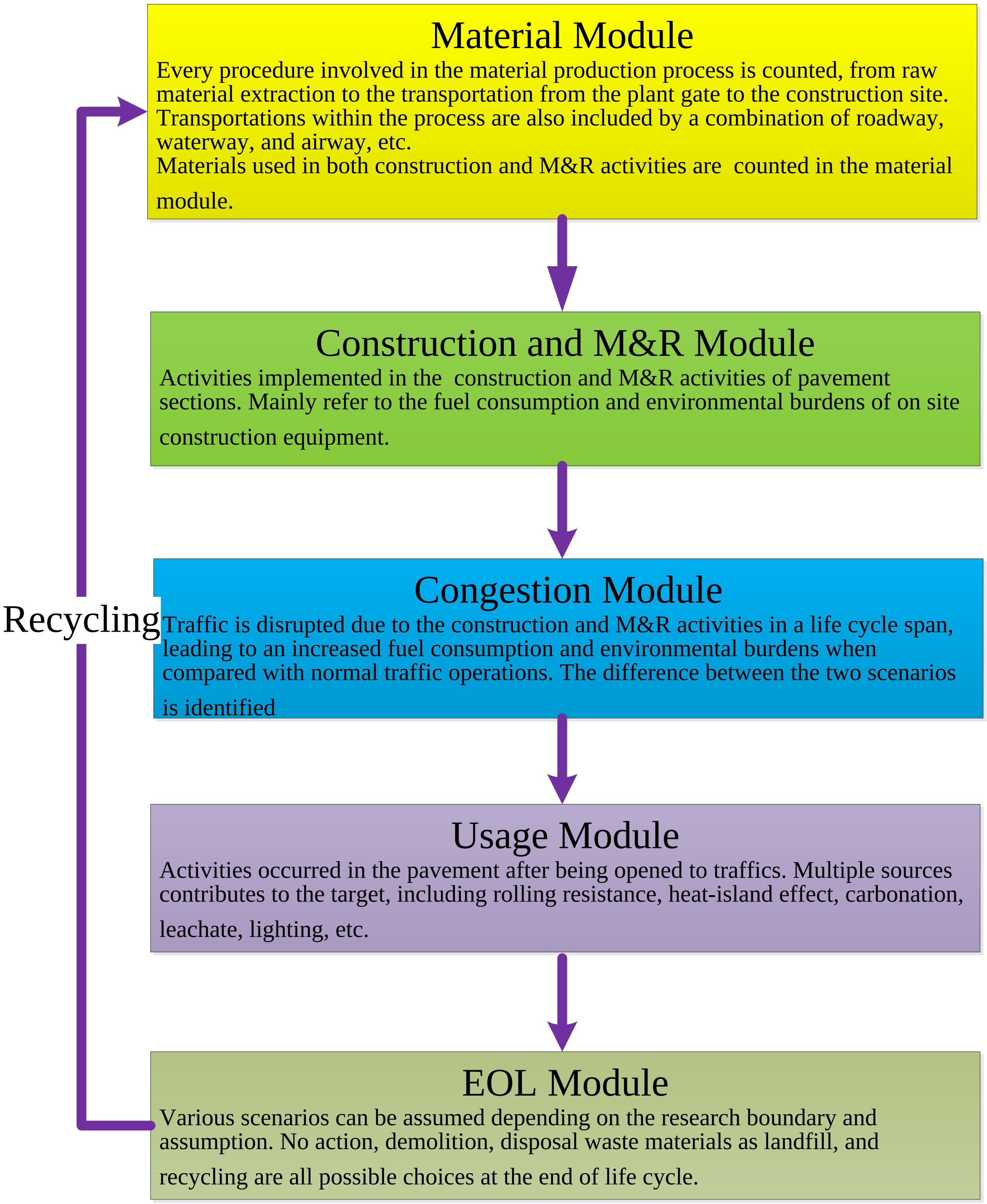
EOL module is typically ignored. ROAD-RES model by Birgisdóttir (2005) spent much content on the two waste material treatments: landfill and recycling. Athena Institute (2006) recycled 20 percent RAP to substitute virgin materials. Zhang et al. (2010a) just landfilled the demolished pavement while Stripple (2001) left the pavements where they were. By analyzing these studies, questions such as: what special equipment or process are needed and their correspond environmental impacts released to recycle waste materials; how many percentage of RAP shall be used; what is the effect of RAP on usage module of LCA model in the future, are veiled and deserve extensive explorations.

CHAPTER 3: METHODOLOGY AND THREE CONTRIBUTIONS

3.1 Methodology

As has been stated previously, a product of complicated boundary selection or intellectual disorganization of designers is not necessarily the only reason to be blamed for the lack of a comprehensive characterization of the pavement life cycle; the dearth of available data and research also appears as a primary suspect. As a complex structure, pavement fulfills its functionality subject to many external factors, including climate, traffic volume, traffic compositions, and material productions, etc. All the pre-discussed modules suffer from uncertainties. In particular, the congestion module and usage module are the two especially waiting to be unveiled and enriched. Even for those having been incorporated in the previous pavement LCA studies, the work is currently more in concept than in practice. In general, the limited understandings of some modules and corresponding supplementary models impede the comprehensive evaluation of pavements in terms of environmental impact. However, it is still urgently needed for a systematic pavement focused methodology using the LCA model, even without a hundred percent quantitative knowledge of each module. With such a methodology, a more holistic and accurate estimation can be expected.

Based on the literature view in Chapter 2, a five-module methodology is constructed, with details outlined in Fig.3.1.



Material Module

Every procedure involved in the material production process is counted, from raw material extraction to the transportation from the plant gate to the construction site. Transportations within the process are also included by a combination of roadway, waterway, and airway, etc.

Materials used in both construction and M&R activities are counted in the material module.

Construction and M&R Module

Activities implemented in the construction and M&R activities of pavement sections. Mainly refer to the fuel consumption and environmental burdens of on site construction equipment.

Congestion Module

Traffic is disrupted due to the construction and M&R activities in a life cycle span, leading to an increased fuel consumption and environmental burdens when compared with normal traffic operations. The difference between the two scenarios is identified

Usage Module

Activities occurred in the pavement after being opened to traffics. Multiple sources contributes to the target, including rolling resistance, heat-island effect, carbonation, leachate, lighting, etc.

EOL Module

Various scenarios can be assumed depending on the research boundary and assumption. No action, demolition, disposal waste materials as landfill, and recycling are all possible choices at the end of life cycle.

Figure 3.1 Schematic Flowchart of the Methodology of Pavement LCA Model

Design module is not included in the framework for the same reason explained previously. The material module carries similar definitions and functionalities of peer studies, and M&R activities in the proposed methodology are implicitly incorporated in the construction activities to form a construction and M&R module, which specifically characterizes the environmental impacts of on-site construction equipment during construction and M&R activities.

Unlike previous treatment, congestion module is separated as an individual one to characterize the environmental impacts of vehicle fleet operations under construction and M&R activities. The differences of vehicular fuel consumption and relevant air emissions under normal traffic condition and construction and M&R periods are calculated. The justifications of the separation are: firstly, congestion module is frequently ignored by many former researches; secondly, when considered in the model, congestion module causes significant environmental impacts in urban area (Huang et al. 2009b) or in bridge and highway systems when the traffic volume is high (Treloar et al. 2004; Zapata and Gambatese 2005; Zhang et al. 2010a), and thirdly, modeling congestion module proves to be difficult and far from perfect in the current stage. Thus it is necessary to better capture the environmental impacts from congestion module and an equal status is therefore assigned as do the other four modules.

Usage module, compared with previous ones, is greatly enriched, including a variety of items. The usage module is influenced by many factors which can be split into two categories: one is traffic related, such as traffic volume, fuel economy, traffic growth rate; the other is pavement related, such as roughness, pavement structure, albedo, and carbonation, etc. Many assumptions are introduced to carry out the calculations of usage modules and thus great uncertainties are also introduced. Sensitivity analysis about significant parameters and assumptions are vital to assure grounded conclusions or suggestions.

Other than simply landfill or leaving the pavement structure where they are, EOL module in the proposed methodology has more options, such as recycling. Energy consumption and environmental burdens to dismantle and transport the old pavement structure and those for pre-processing the waste pavement materials before they can be used are considered.

Compared with previous methodologies, the proposed one is comprehensive, which highlights the significant research focus and explores most of the modules with in-depth efforts. Using the proposed methodology, comprehensive and detailed environmental evaluations of pavements can be realized.

3.2 Environmental Damage Cost

This section aims to provide data for estimating the EDC of pavement structure. Two issues are to be solved: the first is to discuss a suitable selection of discount rate and its power over the cost analysis; and the second is to determine relative accurate and reliable MDC of specific air pollutant.

3.2.1 Discount Rate Discussion

Discount rate is an elementary concept in the economics and has been widely used in the LCCA models. It accounts for the relation of investing money today and equivalent money tomorrow so that the investment is subjected to time effect. Traditionally, cost analysis includes agency cost and user cost in pavement engineering. Agency cost mainly refers to the investment in constructing and maintaining the pavement, and user cost refers to the aggregation of user delay cost, vehicle operating cost, and risk of traffic accident (Wilde et al. 2001). Apparently, EDC due to the air pollutants, waterborne pollutants, solid waste, and noise, etc., is notably missing. The reason may be that pavement engineers have not yet accustomed to the consideration of environmental impacts as well as the difficulty in accurately estimating the EDC of certain pollutants.

Tentative considerations of assessing EDC have been tried by Kendall et al. (2008) and Zhang et al. (2008, 2010b), as introduced in the "LCA&LCCA Integration" section in Chapter 2. However, their methods suffer from two shortcomings: firstly, their MDC sample size is relatively small and outdated, and based on which, a Monte Carlo simulation is performed to estimate the uncertainty range; and secondly, their estimation method is less transparent and reasonable because sometimes, simple arithmetic average is used out of various sources, such as peer reviewed paper, working paper, and report, etc. To improve their model, two questions shall be answered: firstly, what discount rate shall be used; and secondly, how to determine more reliable MDC of certain air pollutants.

For the first question, economists pioneer the research with great controversies. They wonder how much money is needed to mitigate the current global climate change to avoid the disaster in the future. The central point of the question lies in the discount rate selection which will significantly alter the economic expectation for a long time range. Then why it is necessary to discount? The first reason is that air emissions have long lives in the atmosphere. Emission today contributes to the concentration of air pollutants long into the future. The second reason is that climate system has significant inertia. The impact of the emission is felt substantial period of time later. For example, even an immediate emission stop of GHGs will not benefit our generation since prior emissions continue to have effect in the climate systems. In other words, emission toady hurts people tomorrow and reduction in emissions today helps future people (Posner 2004).

What is the power of discount rate then? A demonstration example is given by Sunstein and Weisbach (2008). Suppose as a result of climate change, a loss of $1 trillion dollars in one hundred years is expected. If Stern's discount rate of 1.4 percent (Stern 2007) and Nordhaus's discount rate of 5.5 percent (2007) are used, the results are tremendously diverged. The former scenario will result in a cost within 100 years nearly 53 times as high as the latter scenario. If the harm occurs 200 years later, the Stern's approach will overwhelm the Nordhaus's approach by a factor of 2800. A different selection of the discount rate will lead to a different policy decision. A stringent policy of controlling GHGs emission is urgently needed in Stern's view while a moderate action shall be implemented in Nordhaus' view.

It is not the intention of this research to propose a suitable discount rate in terms of pure rate of time preference, the product of the elasticity of the marginal utility of consumption and the per capita growth rate of consumption (Ramsey 1928). Instead, it is desired to know how to select a suitable discount rate to make the calculation more realistic. Traditionally, exponential discounting is used, with a form of:

$$f(D) = e^{-kt} \tag{3.1}$$

where $f(D)$ is the discount factor that multiplies the value of reward, t is the delay in reward, and k is a parameter governing the degree of discounting. The practices of Stern and Nordhaus use exponential discounting. With exponential discounting, the valuation falls by a constant factor per unit time. However, studies have shown that the constant discount rate assumption is systematically violated (Frederick et al. 2002). In this sense, a hyperbolic discounting method is used (Green and Myeerson 1996; Farmer and Geanakoplos 2009), with a form of:

$$f(D) = \frac{1}{1+kt} \tag{3.2}$$

where all the parameters have the same meanings as those in Eq. 3.1. In the hyperbolic discounting, valuation falls quickly initially, but then at a slower rate for longer time interval. Hyperbolic discounting has been observed in humans and animals societies.

Weitzman (1998) argued that the "lowest possible" interest rate should be used for discounting the far-distant future part of any investment project, such as measures to mitigate the possible effects of global climate change, through mathematic proof. And a gamma discounting rate was proposed to discount the global warming by Weitzman (2001) based on an extensive questionnaire involving 2160 economists world widely. In his paper, "approximate recommended" sliding scale discount rates was presented. Specifically, for the immediate future (within years 1 to 5 hence); the discount rate is 4 percent; for the near future (within years 6 to 25 hence), the discount rate is 3 percent; for the medium future (within years 26 to 75 hence); the discount rate is 2 percent; for the distant future (within years 76 to 300 hence); the discount rate is 1 percent ; for the far-distant future (within years more than 300 hence); the discount rate is 0 percent. In Zhang et al. (2008, 2010b), the sliding scale discount rates were used to estimate the EDC.

3.2.2 Marginal Damage Cost Estimations

In the following content, it is desired to estimate the MDC of certain air pollutants following Tol's method (Tol 2005), with slight modification. Based on extensive literature review, four methods are used to calculate the MDC. First, simple average is calculated with equal weight for different literature. For those studies that report alternative estimates, the weights according to the preference expressed by the original author(s) are distributed but with a sum of one, as is the second method. Third, a subjective quality weighting system is used, which consists of five criterions:

> *"Is the study peer reviewed? Is the study based on an independent impact assessment? Is the study based on dynamic climate change scenario? Is the study based on economic scenarios? Does the study estimate the MDCs (rather than average damage costs)? The maximum score is five, the minimum is zero."*

Here, the age effect is also added to the estimation, with 0.1 points per year since 1995 (In Tol's practice, 0.1 points was added per year since 1990). Fourth, the same weighting system is used but only applied to peer reviewed studies. Some studies report standard deviations, confidence intervals or the entire probability densities, which will be used directly in the simulation. Some studies, however, only report a "best guess" and are therefore assumed as normally distributed, with the standard deviation equal to the mean. For studies reporting a confidence interval, a combined exponential and negative exponential distribution is used, with the middle of interval to be the best guess if not reported. This treatment seems subjective. However, compared with the previous practice used in the pavement LCA model, three advantages are realized: firstly, the sample size is enlarged by an extensive literature review; secondly, the estimation result is based on quality evaluating instead of simple arithmetic mean: estimation from high quality paper will receive high score, and vice versa; and thirdly, a probability density distribution can be obtained. Key pollutants, including several criteria pollutants specified by the U.S. EPA, three primary GHGs, and VOC, are waiting to be estimated about their MDCs.

3.2.2.1 Carbon Dioxide (CO_2)

Tol (2005) has performed the MDC estimations out of 103 samples from 28 studies following his proposed methodology. Since the estimation is relatively new and greatly comprehensive, the results will be used in this research to perform the CO_2 damage cost calculation. Key findings of the study are listed in Table 3.1.

Table 3.1 Probability Characteristics of the MDCs of CO_2 Emission ($/tC)

$/tonne, 2005 price	Mean	5%	10%	Median	90%	95%
Composite	93	-10	-2	14	165	350
Author weight	90	-8	-2	10	119	300
Quality weight	129	-11	-2	16	220	635
Peer reviewed only	50	-9	-2	14	125	245

As can be seen, studies that are peer reviewed have lower estimate and smaller uncertainties. The author also stated that *the MDCs of* CO_2 *are unlikely to exceed $50/tC, and probably much smaller*.

3.2.2.2 Methane (CH_4)

Following the modified method of Tol (2005), an extensive literature review is performed on the MDC of CH_4, which is evaluated by different weighting systems. Their results are summarized in Table 3.2. Before using the data, they are all converted to the unit of dollar/tonne at the 2010 price.

Table 3.2 Characteristics of the MDCs Estimates of CH_4

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
COWI (2000)		53-237 €/tonne (1993)	1/3	N	Y	N	N	Y
	2223€/tonne (1995)		1/3					
	86€/tonne (1993)		1/3					
Tollesfen (2009)	25€/tonne (2009)		1/8	Y	N	Y	Y	Y
	72€/tonne (2009)		1/8					

Table 3.2 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Tollesfen (2009)	156€/tonne (2009)		1/8					
	240€/tonne (2009)		1/8					
	750€/tonne (2009)		1/8					
	1500€/tonne(2009)		1/8					
		906-1656 €/tonne (2009)	1/8					
		990-1740 €/tonne (2009)	1/8					
ExternE (1997)		386-741 €/tonne (1997)	1/2	N	Y	Y	N	Y
		370-710 €/tonne (1997)	1/2					
EIA (1995)	220$/ton (1989)		1	N	N	N	N	N
MIRA (2011)	420 €/tonne (2011)		1	N	N	N	N	N
West (2006)	240 $/tonne (2006)		1	Y	Y	Y	N	N
Schilberg (1989)	0.19 $/lb (1989)		1	N	N	N	N	N
MA DPU (1990)	0.11 $/lb (1989)		1	N	N	N	N	N
Tol and Downing (2000)	44.9€/tonne (2000)	1.9-2579 €/tonne(2000)	1	N	Y	N	N	Y
Defra (2004)		158-630 £/tonne(2003)	1	N	Y	N	N	Y
Kandlikar (1995; 1996)		114-456 £/tonne(2003)	1	Y	Y	Y	N	Y
Fankhauser (1995)		190-760 £/tonne(2003)	1	N	Y	N	N	Y
Hammitt (1996)		105-418 £/tonne(2003)	1	Y	N	Y	N	Y
Pietrapertosa et al. (2010)	493.5€/tonne (2010)		1	Y	N	Y	Y	Y
Chernick and Caverhill (1991)	0.11 $/lb (1989)		1	Y	N	N	N	N

Note: C. Est., central estimate; Unc. R, uncertainty range; AW, author weight; PR, peer reviewed; New, independent impact assessment, Dyn, Dynamic climate change; Eco, economic scenario. The abbreviations keep the same meanings for the following contents.

Fig. 3.2 simulates the 25 PDFs. It also contains a composite PDF. The composite PDF is based on the “vote counting”. Each entry of Table 3.2 gives a vote, corresponding to the relative probability.

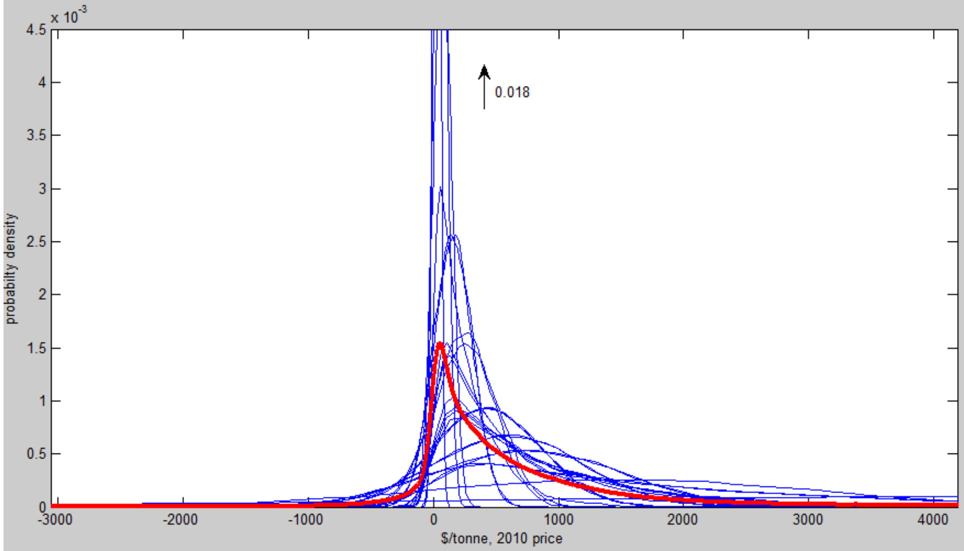


Figure 3.2 PDFs of the 25 Estimates of the MDCs of CH_4 Emissions and the Composite PDF (bold)

Fig. 3.3 displays the author weight PDF, quality weight PDF as well as the composite PDF if only peer reviewed studies are considered. Fig. 3.4 displays the corresponding cumulative density functions (CDFs).

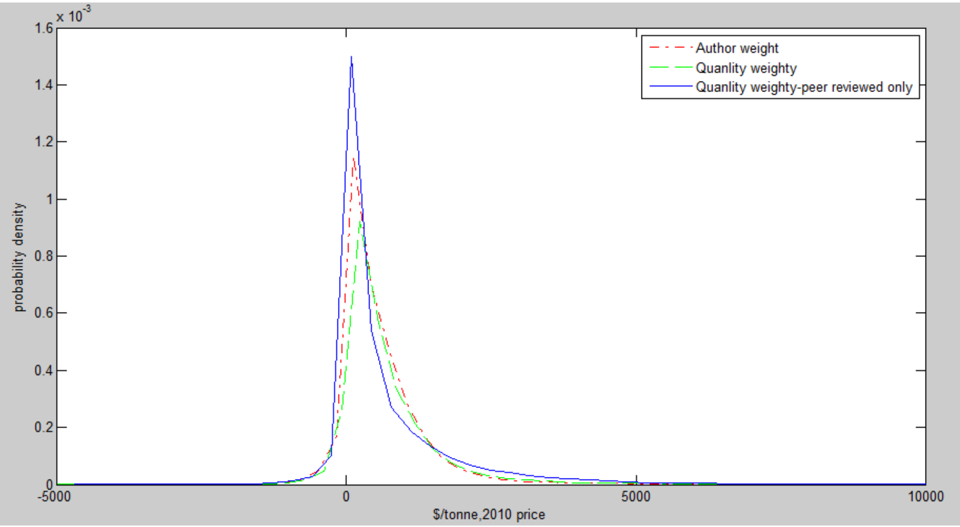


Figure 3.3 PDFs of the MDCs of CH_4 Emissions for the Three Scenarios

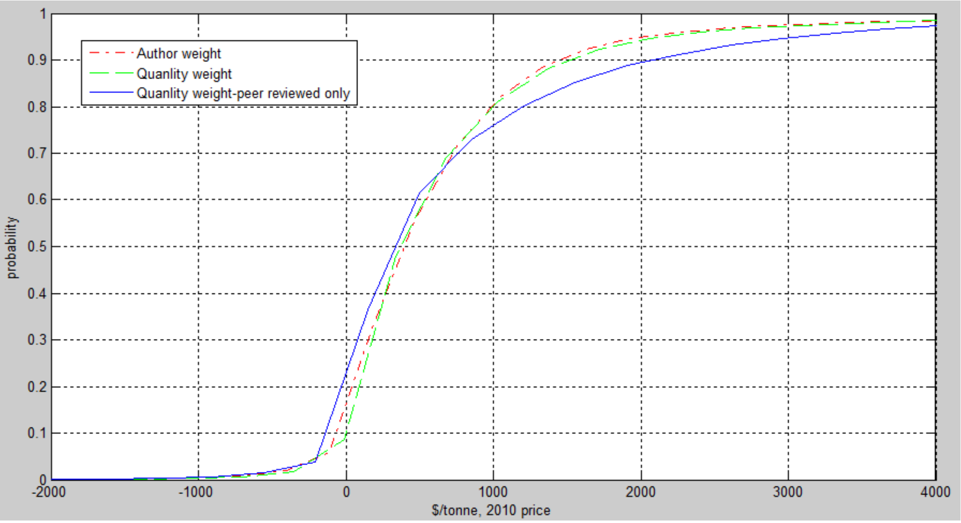


Figure 3.4 CDFs of the MDCs of CH_4 for the Three Scenarios

Table 3.3 shows some characteristics of the uncertainties. As can be seen, the author weight simulation has the most narrow uncertainty range and the differences between the other three are significant in the upper bound. Also, the available peer reviewed literatures are limited. In this sense, the best guess for the MDC of CH_4 is probably 625$/tonne.

Table 3.3 Probability Characteristics of the MDCs of CH_4 Emissions ($/tonne)

$/tonne, 2010 price	Mean	5%	10%	Median	90%	95%
Composite	764	-128	-15	350	1888	3099
Author weight	625	-151	2	387	1424	1993
Quality weight	636	-70	12	361	1496	2151
Peer reviewed only	722	-131	-12	302	2060	3070

3.2.2.3 Nitrous Oxide (N_2O)

Similarly, an extensive literature review is performed on the MDC of N_2O, with the results summarized in Table 3.4. Before using the data, they are all converted to the unit of dollar/tonne at the 2010 price.

Table 3.4 Characteristics of the MDCs Estimates of N_2O

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
COWI (2000)	1469€/tonne (1993)		1	N	Y	N	N	Y
ExternE (1997)		7097-24006 €/tonne(1997)	1/2	N	Y	Y	N	Y
		6800-23000 €/tonne(1995)	1/2					
Pietrapertosa et al. (2010)	7285€/tonne (2010)		1	Y	N	Y	Y	Y
EIA (1995)	3960$/ton (1989)		1	N	N	N	N	N
MIRA (2011)	6200€/tonne (2011)		1	N	N	N	N	N
Schilberg (1989)	1.85 $/lb (1989)		1	N	N	N	N	N
MA DPU (1990)	1.98 $/lb (1989)		1	N	N	N	N	N
Chernick and Caverhill (1991)	1.98 $/lb (1989)		1	Y	N	N	N	N
Tol and downing (2000)	748€/tonne (2000)	24.3-5242.1 €/tonne(2000)	1	N	Y	N	N	Y

Fig. 3.5 simulates the 10 PDFs of N_2O. It also contains a composite PDF. The composite PDF is based on “vote counting”. Each entry of Table 3.4 gives a vote, corresponding to the relative probability.

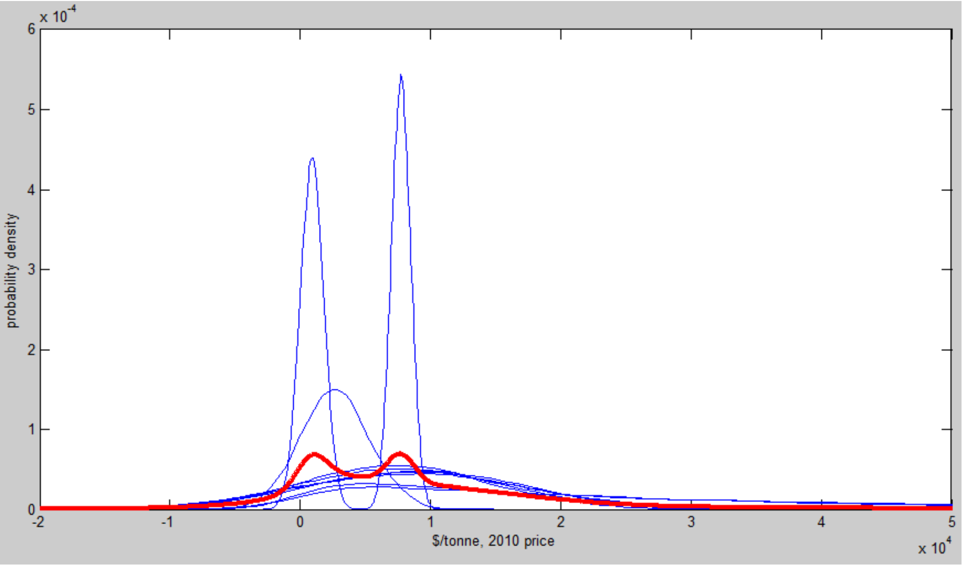


Figure 3.5 PDFs of the 10 Estimates of the MDs of N_2O Emissions and the Composite PDF (bold)

Fig. 3.6 displays the author weight PDF, quality weight PDF as well as the composite PDF if only peer reviewed studies are considered. Fig. 3.7 displays the corresponding CDFs.

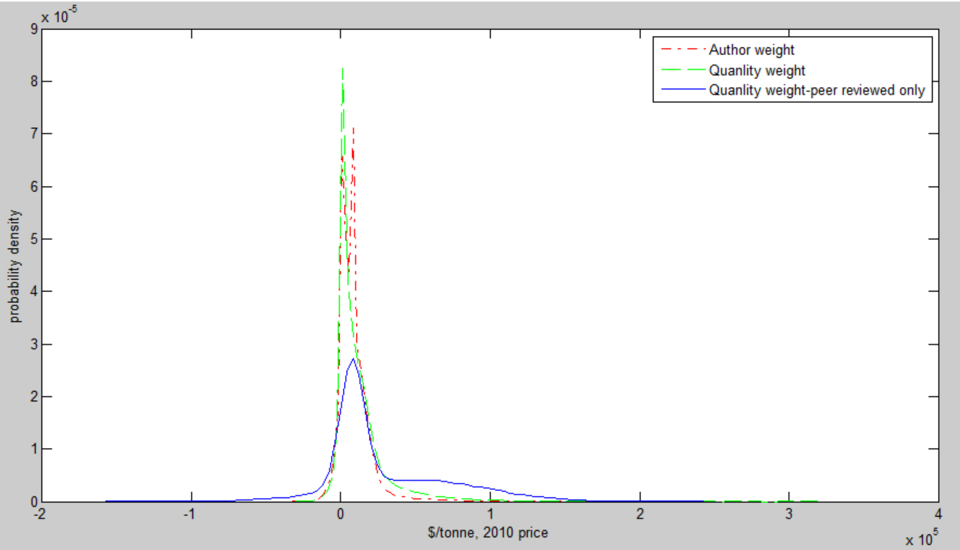


Figure 3.6 PDFs of the MDCs of N_2O Emissions for the Three Scenarios

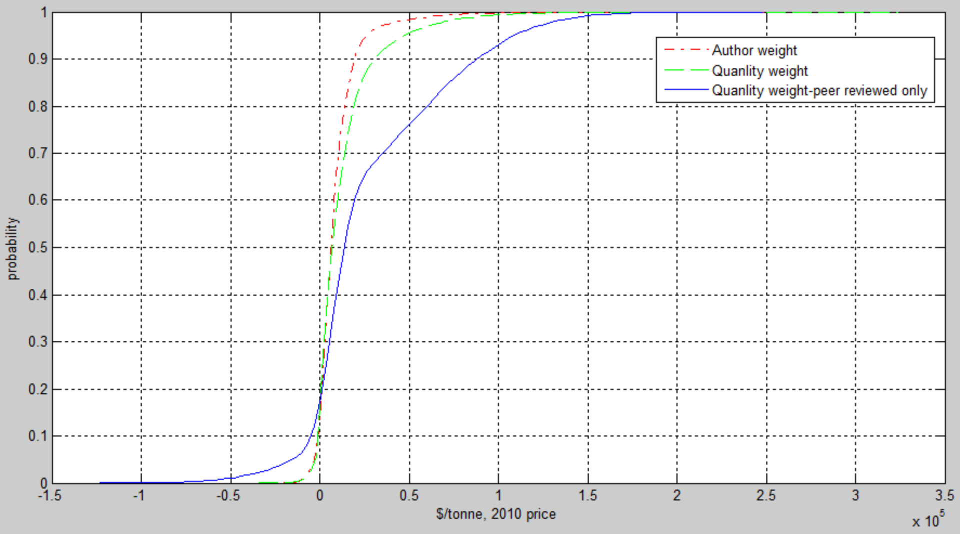


Figure 3.7 CDFs of the MDCs of N_2O for the Three Scenarios

Table 3.5 shows some characteristics of the uncertainties. As can be seen, the peer reviewed method has the most narrow uncertainty range. However, there are only two literatures that are peer reviewed. And the differences between the other three simulations are significant. It is hard to choose the estimation result. The possible best guess for N_2O may be 12341$/tonne because this estimation comes from all the literatures which are evaluated about their qualities.

Table 3.5 Probability Characteristics of the MDCs of N_2O Emissions ($/tonne)

$/tonne, 2010 price	Mean	5%	10%	Median	90%	95%
Composite	10347	-2459	-199	7280	22900	35547
Author weight	8721	-2813	-414	6927	19424	25873
Quality weight	12341	-1983	-108	6802	30539	47700
Peer reviewed only	28046	-1410	-412	1340	8899	10973

3.2.2.4 Volatile Organic Compound (VOC)

VOC is estimated about its MDC through a broad literature review, following the same way as above, with the results in Table 3.6. Before using the data, they are all converted to the unit of dollar/tonne at the 2010 price.

Table 3.6 Characteristics of the MDCs Estimates of VOC

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
COWI (2000)	1351 €/tonne (1993)		1/2	N	Y	N	N	Y
	700 €/tonne (1998)		1/6					
	253 €/tonne (1998)		1/6					
	1400 €/tonne (1998)		1/6					
Tollesfen (2009)	950€/tonne (2009)		1/6	Y	N	Y	Y	Y
	1400€/tonne (2009)		1/6					
	135 (2009 €/tonne)		1/6					
	270€/tonne (2009)		1/6					
		10851220 €/tonne(2009)	1/6					
		1535-1670 €/tonne(2009)	1/6					
Matthews and Lave (2000)	1600$/tonne (1992)	160-4400 $/tonne(1992)	1	Y	N	N	N	Y

Table 3.6 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Pietrapertosa et al. (2010)	639 €/tonne (2001)		1/3	Y	N	Y	Y	Y
	670 €/tonne (2005)		1/3					
	712 €/tonne (2010)		1/3					
Netcen (2002)	2100€/tonne (2000)		1/2	N	N	N	N	N
	1500€/tonne (2000)		1/10					
	1000€/tonne (2000)		1/10					
	1900€/tonne (2000)		1/10					
	1700€/tonne (2000)		1/10					
	2600€/tonne (2000)		1/10					
CAFE (2005)	950 €/tonne (2005)		1/8	N	Y	Y	Y	N
	1400€/tonne (2005)		1/8					
	2100€/tonne (2005)		1/8					
	2800€/tonne (2005)		1/8					
	780 € /tonne (2005)		1/8					
	1100€/tonne (2005)		1/8					
	1730€/tonne (2005)		1/8					
	2300€/tonne (2005)		1/8					
EIA (1995)	5300$/ton (1989)		1/5	N	N	N	N	N
	4236$/ton (1992)		1/5					
	5900$/ton (1992)		1/5					
	1190$/ton (1992)		1/5					
	1012$/ton (1992)		1/5					

Table 3.6 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
MIRA (2011)	7500 € /ton (2009)		1	N	N	N	N	N
VTPI (2007)	14419 $/ton (2002)		1/4	N	Y	N	N	N
VTPI (2007)	11823 $/ton (2002)		1/4					
	8963 $/ton (2002)		1/4					
	7350 $/ton (2002)		1/4					
Defra (2004)		263-665 £/tonne(2003)	1/2	N	Y	N	N	Y
	1000£/tonne (2003)	500-1500 £/tonne(2003)	1/2					

Fig.3.8 simulates the 40 PDFs of VOC. It also contains a composite PDF. The composite PDF is based on “vote counting”. Each entry of Table 3.6 gives a vote, corresponding to the relative probability.

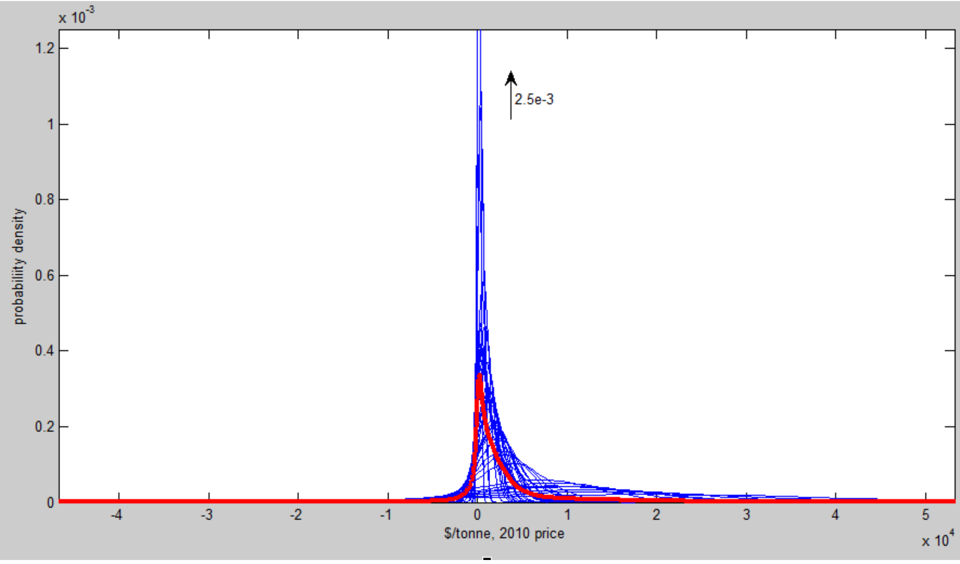


Figure 3.8 PDFs of the 40 Estimates of the MDCs of VOC Emissions and the Composite PDF (bold)

Fig. 3.9 displays the author weight PDF, quality weight PDF as well as the composite PDF if only peer reviewed studies are considered. Fig.3.10 displays the corresponding CDFs.

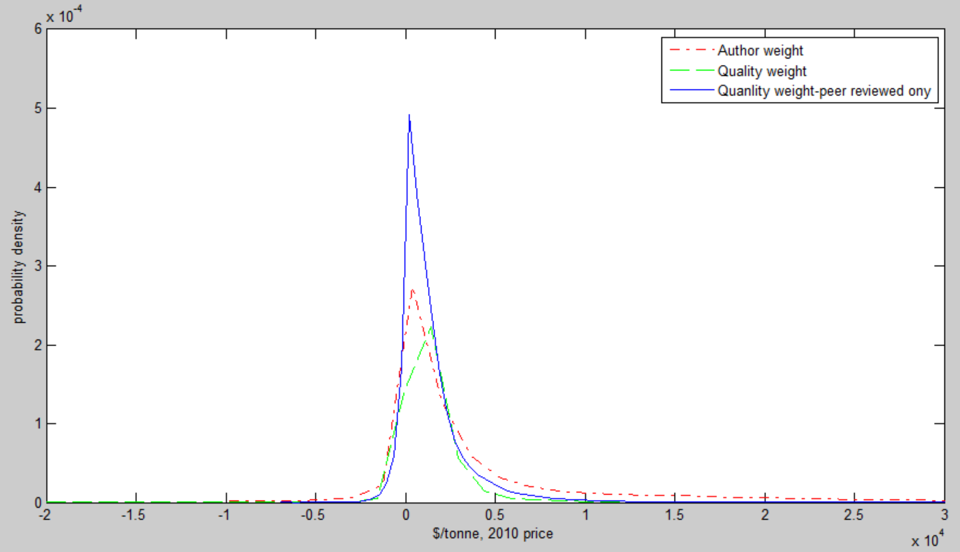


Figure 3.9 PDFs of the MDCs of VOC Emissions for the Three Scenarios

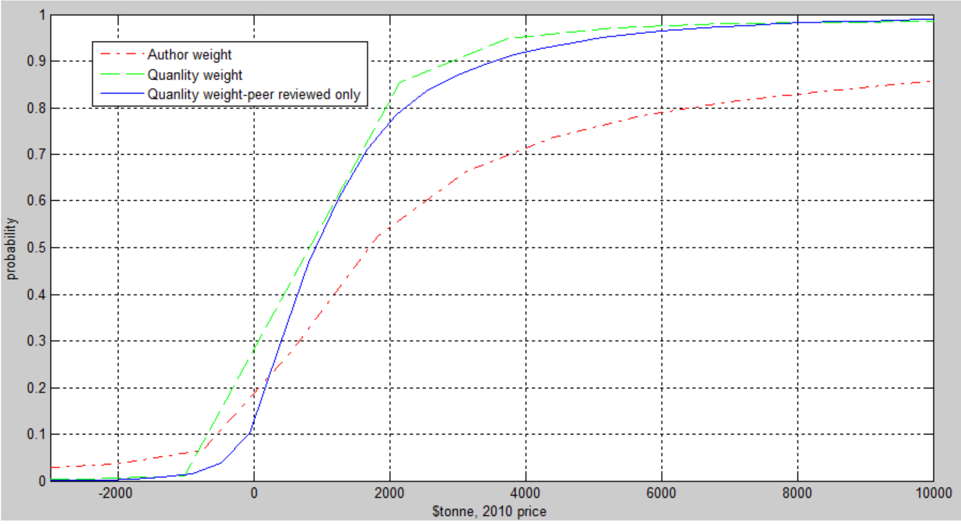


Figure 3.10 CDFs of the MDCs of VOC for the Three Scenarios

Table 3.7 shows some characteristics of the uncertainties. As can be seen, the peer reviewed simulation and quality weight has similar and the most narrow uncertainty range. There are only three literatures that are peer reviewed. The possible best guess for the MDC of VOC is 1303$/tonne.

Table 3.7 Probability Characteristics of the MDCs of VOC Emissions ($/tonne)

$/tonne, 2010 price	Mean	5%	10%	Median	90%	95%
Composite	3483	-1132	-210	1420	10360	17550
Author weight	4271	-1203	-145	1652	14119	21013
Quality weight	1303	20	76	702	2661	3796
Peer reviewed only	1445	-388	-37	900	3546	5129

3.2.2.5 Nitrogen Oxide (NO_x)

The MDCs of NO_x are collected through an extensive literature review, with their results summarized in Table 3.8. Before using the data, they are all converted to the unit of dollar/tonne at the 2010 price.

Table 3.8 Characteristics of the MDCs Estimates of NO_x

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Banzhaf et al. (1996)		7-24$/ton (1993)	1/6	Y	N	Y	N	Y
		32-76$/ton (1993)	1/6					
		83-177$/ton (1993)	1/6					
		6-56$/ton (1993)	1/6					
		53-118$/ton (1993)	1/6					
		127-518$/ton (1993)	1/6					
COWI (2000)	6017 €/tonne (1995)		1/5	N	Y	N	N	Y
	18050 €/tonne (1998)		1/5					
	18340 €/tonne (1996)		1/5					
	6000 €/tonne (1995)		1/5					
		2500-4300 €/tonne(1993)	1/5					
Tollesfen (2009)	4400 €/tonne (2009)		1/2	Y	N	Y	Y	Y
	6600 €/tonne (2009)		1/2					
Matthews and Lave (2000)	2800$/tonne (1992)	220-9500 $/tonne (1992)	1	Y	N	N	N	Y
Pietrapertosa et al. (2010)	6602 €/tonne (2001)		1/6	Y	N	Y	Y	Y

Table 3.8 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Netcen (2002)	4200 €/tonne (2000)		1/2	N	N	N	N	N
	4800€/tonne (2000)		1/10					
	2100 €/tonne (2000)		1/10					
	5400 €/tonne (2000)		1/10					
	6200 €/tonne (2000)		1/10					
	3100 €/tonne (2000)		1/10					
Sáez and Linares (1999)	16800 €/tonne (1995)		1/14	N	Y	N	N	N
		11536-12296 €/tonne(1995)	1/14					
		3280-4728 €/tonne(1995)	1/14					
		852-1388 €/tonne(1995)	1/14					
		1080-1800 €/tonne(1995)	1/14					
		10945-15100 €/tonne(1995)	1/14					
		1240-7798 €/tonne(1995)	1/14					
		2750-3000 €/tonne(1995)	1/14					
		4600-13567 €/tonne(1995)	1/14					
		5480-6085 €/tonne(1995)	1/14					
		5975-6562 €/tonne(1995)	1/14					
		4651-12056 €/tonne(1995)	1/14					
		1957-2340 €/tonne(1995)	1/14					
		5736-9612 €/tonne(1995)	1/14					
Rezek and Campbell(2007)	1056$/ton (2007)	211-2986 $/ton(2007)	1/2	Y	Y	N	N	Y
	920$/ton (2007)	668-1274 $/ton(2007)	1/2					
CAFE (2005)	4400 €/tonne (2005)		1/8	N	Y	Y	Y	N

Table 3.8 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MD C
CAFE (2005)	4400 €/tonne (2005)		1/8	N	Y	Y	Y	N
	6600 €/tonne (2005)		1/8					
	8200€/tonne (2005)		1/8					
	12000€/tonne (2005)		1/8					
	2500 €/tonne (2005)		1/8					
	3800 €/tonne (2005)		1/8					
	4700 €/tonne (2005)		1/8					
	6900 €/tonne (2005)		1/8					
EIA (1995)	6500$/ton (1989)		1/7	N	N	N	N	N
	9120$/ton (1992)		1/7					
	7200$/ton (1992)		1/7					
	850$/ton (1992)		1/7					
	7480$/ton (1992)		1/7					
	1897$/ton (1992)		1/7					
	3500$/ton (1992)		1/7					
ORNL (1995)	31448$/ton (1992)		1/4	N	N	N	N	N
	31448$/ton (1992)		1/4					
	9120$/ton (1992)		1/4					
	7467$/ton (1992)		1/4					
VTT Energy (1997)	1310€/tonne (1997)		4/9	N	Y	Y	N	Y
	856€/tonne (1997)		5/18					
	1388€/tonne (1997)		5/36					
	1500€/tonne (1997)		5/36					

Table 3.8 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Zvingilaite (2011)	5870 €/tonne (2011)		1	Y	N	N	N	Y
Andersen (2008)	6850 €/tonne (2004)		1/3	Y	Y	N	N	Y
	6160 €/t (2001)		1/3					
	6160 €/t (2002)		1/3					
Holmgren and Amiri (2007)	2450 €/ton (2007)		1	Y	Y	N	N	N
EPRI (1987)	0.07 $/lb (1989)	0.02-0.23 $/lb (1989)	1	N	N	N	N	N
Hohmeyer (1988)		0.292-1.555 $/lb (1989)	1	N	N	N	N	N
Chernick and Caverhill (1991)	1.58 $/lb (1989)		1	Y	N	N	N	N
Schilberg (1989)	1.35 $/lb (1989)		1/3	N	N	N	N	N
	9.4 $/lb (1989)		1/3					
	12.25 $/lb (1989)		1/3					
CEC staff (1989)	5.8 $/lb (1989)		1	N	N	N	N	N
Kwon and Yun (1999)	147 kwon/ton (S.D.=115.5K)	0-442.2k won/ton	1	Y	Y	N	N	Y
VTPI (2007)	15419 $/ton (2002)		1/4	N	Y	N	N	N
	8789 $/ton (2002)		1/4					
	11209 $/ton (2002)		1/4					
	6389 $/ton (2002)		1/4					
Defra (2004)		154-977 £/tonne(2003)	1/2	N	Y	N	N	Y
	7550 £/tonne (2003)	1500-29000 £/tonne(2003)	1/2					

Fig.3.11 simulates the 84 PDFs of NO_x. It also contains a composite PDF. The composite PDF is based on “vote counting”. Each entry of Table 3.8 gives a vote, corresponding to the relative probability.

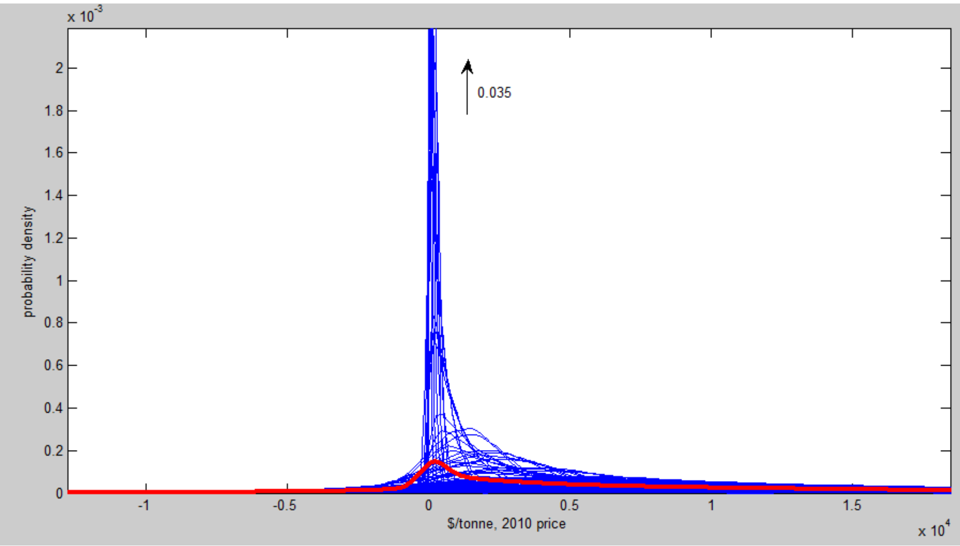


Figure 3.11 PDFs of the 84 Estimates of the MDCs of NO_x Emissions and the Composite PDF (bold)

Fig. 3.12 displays the author weight PDF, quality weight PDF as well as the composite PDF if only peer reviewed studies are considered. Fig.3.13 displays the corresponding CDFs.

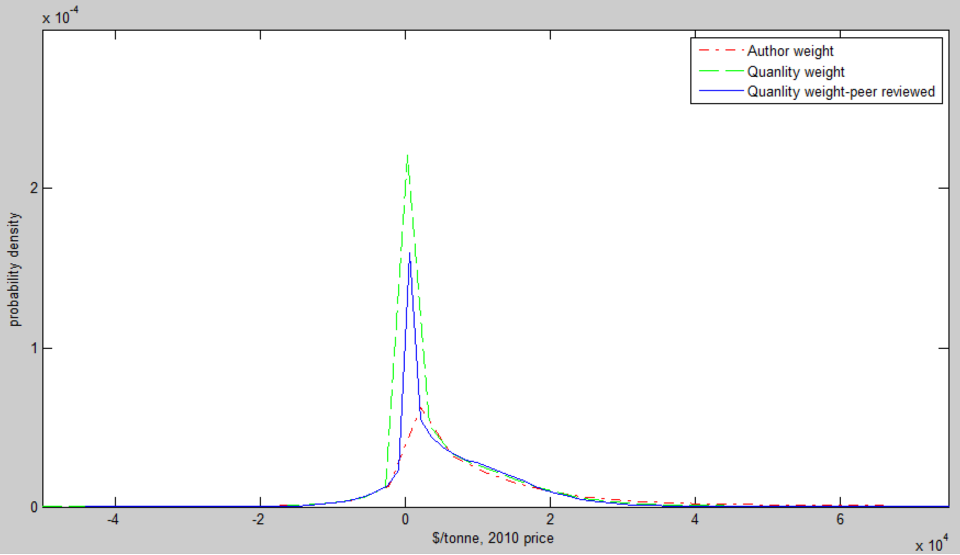


Figure 3.12 PDFs of the MDCs of NO_x Emissions for the Three Scenarios

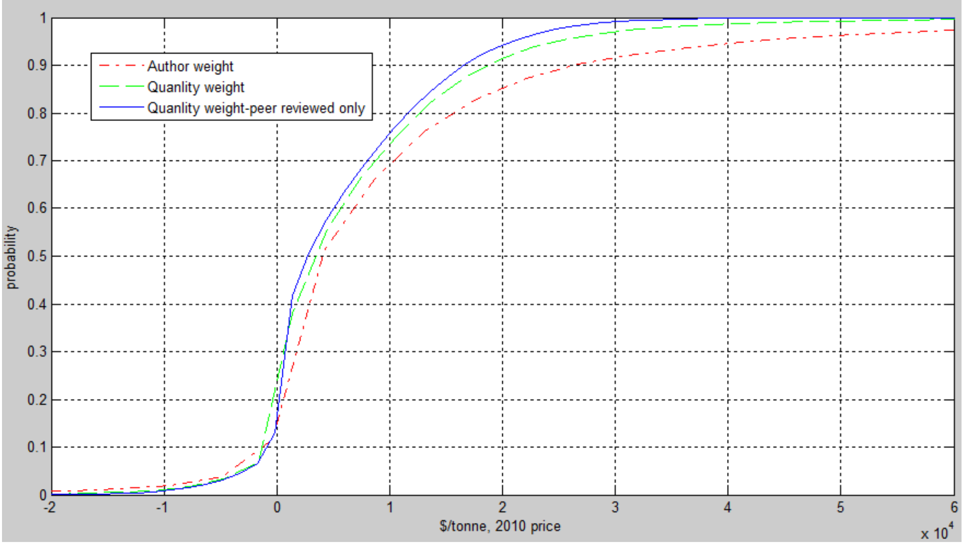


Figure 3.13 CDFs of the MDCs of NO_x for the Three Scenarios

Table 3.9 shows some characteristics of the uncertainty. As can be seen, the peer reviewed simulation has the most narrow uncertainty range. And the differences between the peer reviewed simulations and the quality weight simulations are not substantial while quite big compared with the other two simulation results. The possible best guess for the MDC of NO_x is 5511$/tonne.

Table 3.9 Probability Characteristics of the MDCs of NO_x Emissions ($/tonne)

$/tonne, 2010 price	Mean	5%	10%	Median	90%	95%
Composite	10458	-3508	-156	4866	28147	43560
Author weight	9552	-3315	-106	3869	26217	42072
Quality weight	6566	-2871	-194	3234	18611	24595
Peer reviewed only	5511	-2839	-108	2742	16576	20772

3.2.2.6 Carbon Monoxide (CO)

The MDC of CO is estimated through an extensive literature review, with their results summarized in Table 3.10. Before using the data, they are all converted to the unit of dollar/tonne at the 2010 price.

Table 3.10 Characteristics of the MDCs Estimates of CO

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Banzhaf et al. (1996)		0.2-0.39 $/ton(1993)	1/3	Y	N	Y	N	Y
		0.72-1.26 $/ton (1993)	1/3					
		1.0-2.14 $/ton (1993)	1/3					
COWI (2000)	2.07 €/tonne (1995)		1/2	N	Y	N	N	Y
	7 €/tonne (1998)		1/2					
Tollesfen (2009)	18 €/tonne (2009)		1/6	Y	N	Y	Y	Y
	28 €/tonne (2009)		1/6					
	78 €/tonne (2009)		1/6					
	156 €/tonne (2009)		1/6					
		96-174 €/tonne(2009)	1/6					
		106-184 €/tonne(2009)	1/6					
Matthews and Lave (2000)	520$/tonne (1992)	1-1050 $/tonne(1992)	1	Y	N	N	N	Y
EIA (1995)	870$/ton (1989)		1/6	N	N	N	N	N
	960$/ton (1992)		1/6					
	1012$/ton (1992)		1/6					
	9300$/ton (1989)		1/12					
	2200$/ton (1989)		1/12					
	1100$/ton (1989)		1/12					
	3200$/ton (1989)		1/12					
	5000$/ton (1989)		1/12					
	2900$/ton (1989)		1/12					
Koomey and Krause (1997)	4.65$/lb(1989)		1/6	N	N	N	N	N
	1.1$/lb(1989)		1/6					
	0.55$/lb(1989)		1/6					
	1.6$/lb(1989)		1/6					
	2.5$/lb(1989)		1/6					
	1.45$/lb(1989)		1/6					

Table 3.10 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Chernick and Caverhill (1991)	0.43 $/lb (1989)		1	Y	N	N	N	N
VTPI (2007)	435 $/ton (2002)		1	N	Y	N	N	N
Defra (2004)	2£/tonne (2003)		1	N	Y	N	N	Y

Fig. 3.14 simulates the 30 PDFs of CO. Fig.3.15 displays the PDFs for the three scenarios. And Fig. 3.16 displays the corresponding CDFs.

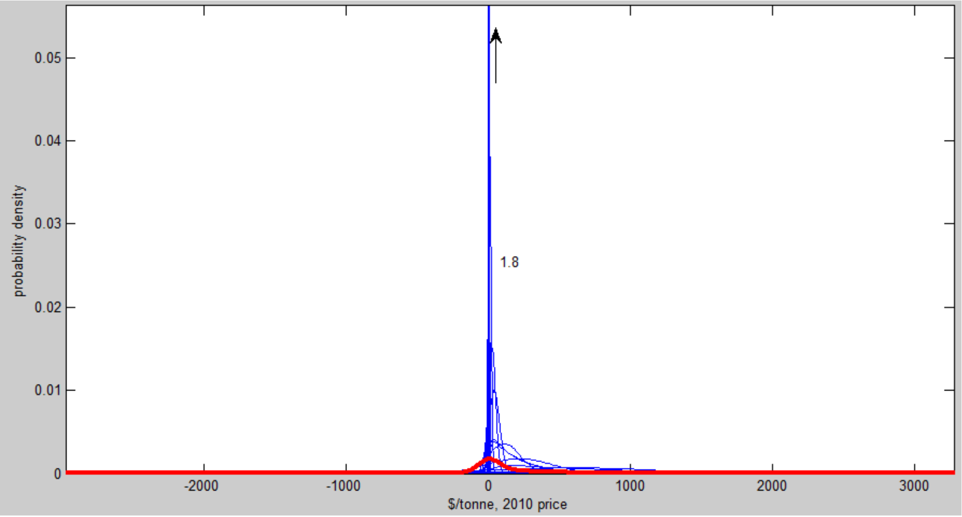


Figure 3.14 PDFs of the 30 Estimates of the MDCs of CO Emissions and the Composite PDF (bold)

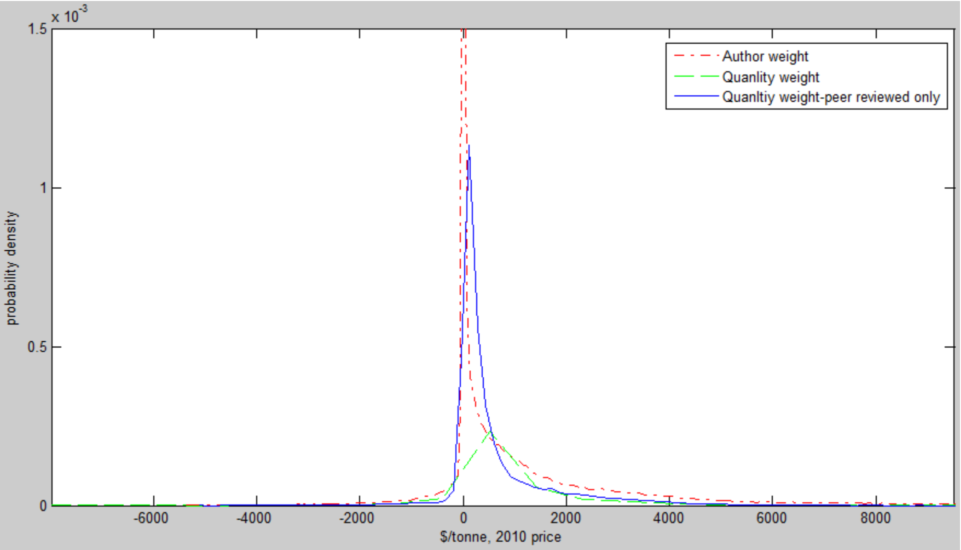


Figure 3.15 PDFs of the MDCs of CO Emissions for the Three Scenarios

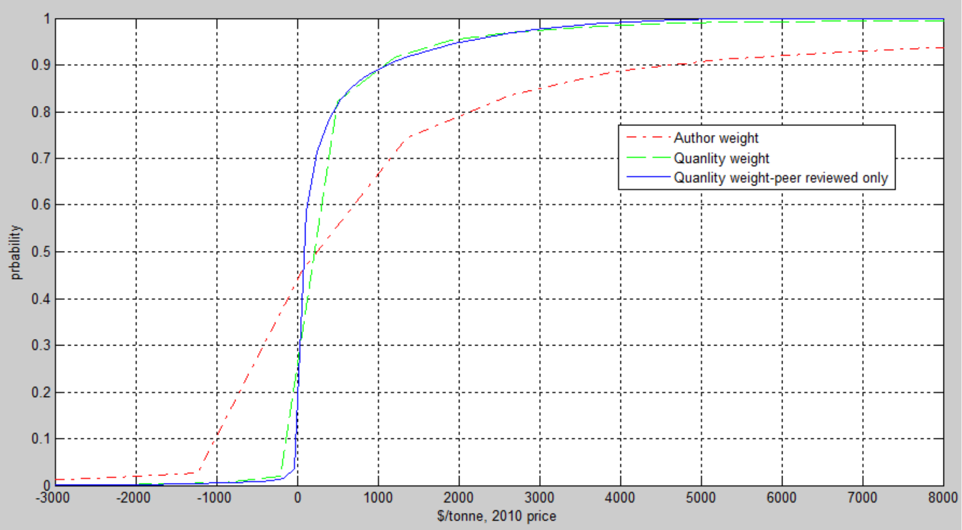


Figure 3.16 CDFs of the MDCs of CO for the Three Scenarios

Table 3.11 shows some characteristics of the uncertainties. As can be seen, the quality weight simulation has the most narrow uncertainty range. And the differences between the quality weight simulation and the peer reviewed weight simulation are not substantial while quite big compared with the other two simulation results. The possible best guess for the MDC of CO is 354$/tonne.

Table 3.11 Probability Characteristics of the MDCs of CO Emissions ($/tonne)

$/tonne, 2010 price	Mean	5%	10%	Median	90%	95%
Composite	3398	-1194	-21	349	11370	18510
Author weight	1736	-3234	-18	1236	4477	9771
Quality weight	368	-102	0	16	1023	1817
Peer reviewed only	354	-11	1	59	1122	2066

3.2.2.7 Particle Matter (PM<10 micron)

The MDC of PM_{10} is estimated through an extensive literature review, with their results summarized in Table 3.12. Before using the data, they are all converted to the unit of dollar/tonne at the 2010 price.

Table 3.12 Characteristics of the MDCs Estimates of PM$_{10}$

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Banzhaf et al. (1996)		530-806$/ton (1993)	1/3	Y	N	Y	N	Y
		1873-2720 $/ton (1993)	1/3					
		4206-6054 $/ton (1993)	1/3					
COWI (2000)	13600 €/tonne (1995)		1/4	N	Y	N	N	Y
	28700 €/tonne (1998)		1/4					
	20500€/tonne (1998)		1/4					
		9500-12800 €/tonne (1998)	1/4					
Matthews and Lave (2000)	4300$/tonne (1992)	950-16200 $/tonne (1992)	1	Y	N	N	N	Y
Pietrapertosa et al. (2010)	650 €/tonne (2001)		1/6	Y	N	Y	Y	Y
	696€/tonne (2005)		1/6					
	757 €/tonne (2010)		1/6					
	1730 €/tonne (2001)		1/6					
	1851€/tonne (2005)		1/6					
	2014 €/tonne (2010)		1/6					
EIA (1995)	4000$/ton (1989)		1/13	N	N	N	N	N
	4608$/ton (1992)		1/13					
	4400$/ton (1992)		1/13					
	1274$/ton (1989)		1/13					
	4598$/ton (1989)		1/13					
	333$/ton (1989)		1/13					
	6804 $/ton (1989)		1/13					
	2624 $/ton (1989)		1/13					
	4608 $/ton (1989)		1/13					
	23760 $/ton (1989)		1/13					
	6920 $/ton (1989)		1/13					
	7020 $/ton (1989)		1/13					
	556 $/ton (1989)		1/13					
VTT Energy (1997)	1555€/tonne (1997)		4/9	N	Y	Y	N	Y

Table 3.12 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
VTT Energy (1997)	1340€/tonne (1997)		5/18					
	2611€/tonne (1997)		5/18					
Holmgren and Amiri (2007)	3750 €/ton (2007)		1	Y	Y	N	N	N
Hohmeyer (1988)		0.233-1.244 $/lb (1989)	1	N	N	N	N	N
CEC staff (1989)	3.9 $/lb (1989)		1	N	N	N	N	N
MA DPU (1990)	2.0 $/lb (1989)			N	N	N	N	N
Kwon and Yun (1999)	15482k won/ton (S.D.=15300K)	0-53377k won/ton	1	Y	Y	N	N	Y
Chernick and Caverhill (1991)	4.22 $/lb (1989)		1/5	Y	N	N	N	N
	0.43 $/lb (1989)		1/5					
	2.0 $/lb (1989)		1/5					
	0.16 $/lb (1989)		1/5					
	1.19 $/lb (1989)		1/5					
VTPI (2007)	5346 $/ton (2002)		1/4	N	Y	N	N	N
	2620 $/ton (2002)		1/4					
	7391 $/ton (2002)		1/4					
	3622 $/ton (2002)		1/4					
Defra (2004)		161-1025 £/tonne (2003)	1/3	N	Y	N	N	Y
		6119-39245 £/tonne (2003)	1/3					
	35000 £/tonne (2003)	1800-226700 £/tonne (2003)	1/3					

Fig. 3.17 simulates the 47 PDFs of PM_{10}. It also contains a composite PDF. The composite PDF is based on “vote counting”. Each entry of Table 3.12 gives a vote, corresponding to the relative probability. Fig. 3.18 displays the author weight PDF, quality weight PDF as well as the composite PDF if only peer reviewed studies are considered. Fig. 3.19 displays the corresponding CDFs.

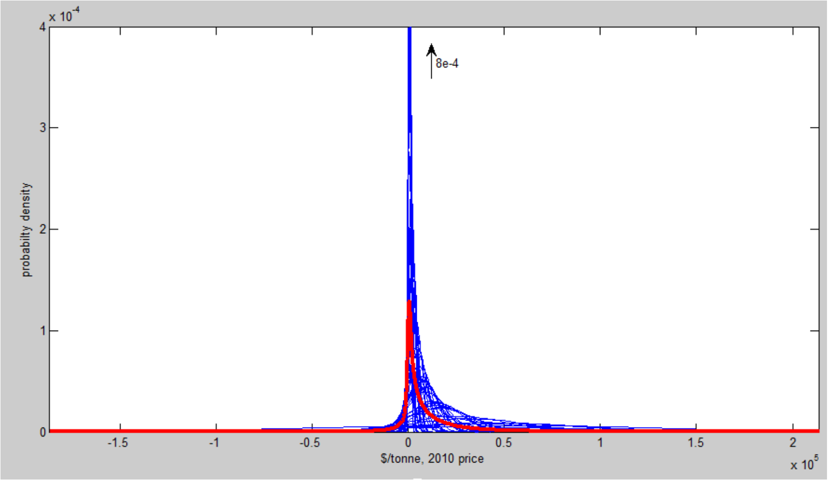


Figure 3.17 PDFs of the 47 Estimates of the MDCs of PM_{10} Emissions and the Composite PDF (bold)

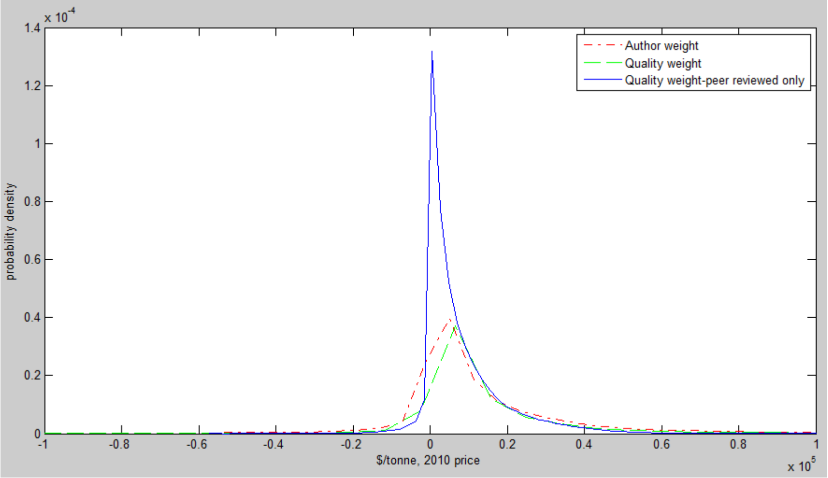


Figure 3.18 PDFs of the MDCs of PM_{10} Emissions for the Three Scenarios

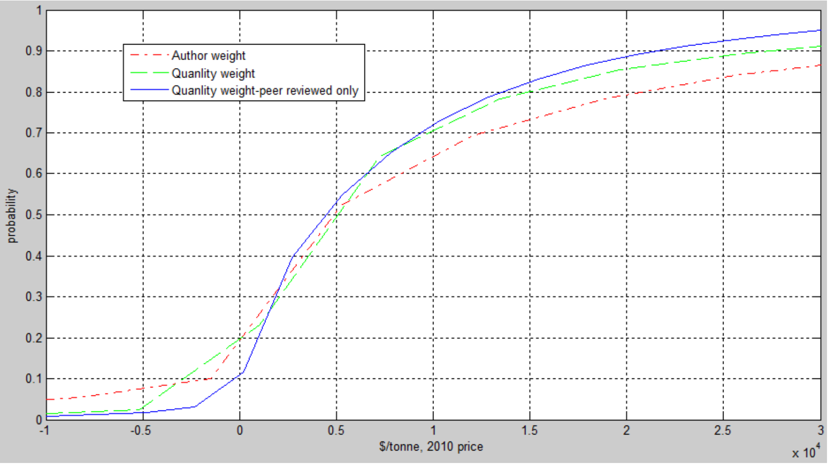


Figure 3.19 CDFs of the MDCs of PM_{10} for the Three Scenarios

Table 3.13 shows some characteristics of the uncertainties. As can be seen, the peer reviewed simulation has the most narrow uncertainty range. And the differences between the quality weight simulation and the other three simulations are substantial. The possible best guess for the MDC of PM_{10} is 7851 $/tonne.

Table 3.13 Probability Characteristics of the MDCs of PM_{10} Emissions (\$/tonne)

\$/tonne, 2010 price	Mean	5%	10%	Median	90%	95%
Composite	10933	-4695	-856	3870	32029	54516
Author weight	11409	-9504	-1453	4631	36898	60578
Quality weight	10169	-1194	119	4027	26977	42400
Peer reviewed only	7851	-693	183	4321	21575	29885

3.2.2.8 Sulfur Oxide (SO_x)

The MDC of SO_x is estimated through an extensive literature review, with their results summarized in Table 3.14. Before using the data, they are all converted to the unit of dollar/tonne at the 2010 price.

Table 3.14 Characteristics of the MDCs Estimates of SO_x

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Banzhaf et al. (1996)		9-24\$/ton (1993)	1/3	Y	N	Y	N	Y
		43-104\$/ton (1993)	1/3					
		106-178\$/ton (1993)	1/3					
COWI (2000)	12200 €/tonne (1998)		1/4	N	Y	N	N	Y
	7300 €/tonne (1996)		1/4					
	2100€/tonne (1995)		1/4					
		3100-7300 €/tonne(1993)	1/4					
Tollesfen (2009)	5600 €/tonne (2009)		1/2	Y	N	Y	Y	Y
	8700 €/tonne (2009)		1/2					

Table 3.14 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Netcen (2002)		3072-27930 €/tonne (1997)	1/2	N	N	N	N	N
		3300-30000 €/tonne (2000)	1/2					
Matthews and Lave (2000)	2000$/tonne (1992)	770-4700 $/tonne (1992)	1	Y	N	N	N	Y
Pietrapertosa et al. (2010)	6556 €/tonne (2001)		1/6	Y	N	Y	Y	Y
	7019€/tonne (2005)		1/6					
	7629 €/tonne (2010)		1/6					
	7434 €/tonne (2001)		1/6					
	7947€/tonne (2005)		1/6					
	8640 €/tonne (2010)		1/6					
Sáez and Linares (1999)	9000 €/tonne (1995)		1/14	N	Y	N	N	N
		11388-12141 €/tonne (1995)	1/14					
		2990-4216 €/tonne (1995)	1/14					
		1027-1486 €/tonne (1995)	1/14					
		7500-15300 €/tonne (1995)	1/14					
		1800-13688€/tonne (1995)	1/14					
		1978-7832 €/tonne (1995)	1/14					
		2800-5300 €/tonne (1995)	1/14					

Table 3.14 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
		5700-12000 €/tonne (1995)	1/14					
		6205-7581 €/tonne (1995)	1/14					
		4960-5424 €/tonne (1995)	1/14					
		4219-9583 €/tonne (1995)	1/14					
		2357-2810 €/tonne (1995)	1/14					
		6207-10025 €/tonne (1995)	1/14					
Rezek and Campbell (2007)	145.4$/ton	10-1682$/ton	1/8	Y	Y	N	N	Y
	89.49$/ton		1/8					
	134$/ton	9-1547$/ton	1/8					
	82$/ton	-64-223$/ton	1/8					
	470$/ton	32-5438$/ton	1/4					
	289$/ton	191-404$/ton	1/4					
CAFE (2005)	5600 €/tonne (2005)		1/8	N	Y	Y	Y	N
	8700 €/tonne (2005)		1/8					
	11000€/tonne (2005)		1/8					
	16000€/tonne (2005)		1/8					
	3700 €/tonne (2005)		1/8					
	5700 €/tonne (2005)		1/8					
	7300 €/tonne (2005)		1/8					
	11000 €/tonne (2005)		1/8					
EIA (1995)	1500$/ton (1989)		1/7	N	N	N	N	N
	4486$/ton (1992)		1/7					

Table 3.14 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
EIA (1995)	150$/ton (1992)		1/7					
	1716$/ton (1992)		1/7					
	1437$/ton (1992)		1/7					
	23490$/ton (1992)		1/7					
	4486 $/ton (1992)		1/7					
VTT Energy (1997)	1486€/tonne (1997)		4/9	N	Y	Y	N	Y
	1027€/tonne (1997)		5/18					
	1606€/tonne (1997)		5/18					
Zvingilaite (2011)	9100 €/t		1	Y	N	N	N	Y
Andersen (2008)	10070 €/t (2004)		1/3	Y	Y	N	N	Y
	15480 €/t (2001)		1/3					
	15600 €/t (2002)		1/3					
Holmgren and Amiri (2007)	2950 €/ton (2007)		1	Y	Y	N	N	N
EPRI (1987)	0.48 $/lb (1989)	0.21-0.85 $/lb (1989)	1/2	N	N	N	N	N
	1.27 $/lb (1989)	0.48-2.31 $/lb (1989)	1/2					
Hohmeyer (1988)		0.233-1.244 $/lb (1989)	1	N	N	N	N	N
Chernick and Caverhill (1991)	6.23 $/lb (1989)		1/5	Y	N	N	N	N
	0.54 $/lb (1989)		1/5					
	0.75 $/lb (1989)		1/5					
	0.41 $/lb (1989)		1/5					
	2.03 $/lb (1989)		1/5					
Kwon and Yun (1999)	311k won/ton (S.D.=234K)	0-1428k won/ton	1	Y	Y	N	N	Y
Tol and downing (2000)	-9800€/tonne	-35800-0	1	N	Y	N	N	Y

Table 3.14 (Continued)

Source	C.Est.	Unc. R	AW	PR	New	Dyn	Eco	MDC
Defra (2004)		643-2941 (pound/tonne, 2003)	1/2	N	Y	N	N	Y
	7590 £/tonne (2003)	1700-16000 £/tonne(2003)	1/2					
Schilberg (1989)	0.5 $/lb (1989)		1/3	N	N	N	N	N
	0.9$/lb (1989)		1/3					
	9.15 $/lb (1989)		1/3					
CEC staff (1989)	5.75 $/lb (1989)		1	N	N	N	N	N

Fig. 3.20 simulates the 47 PDFs of SO_x. It also contains a composite PDF. The composite PDF is based on “vote counting”. Each entry of Table 3.14 gives a vote, corresponding to the relative probability.

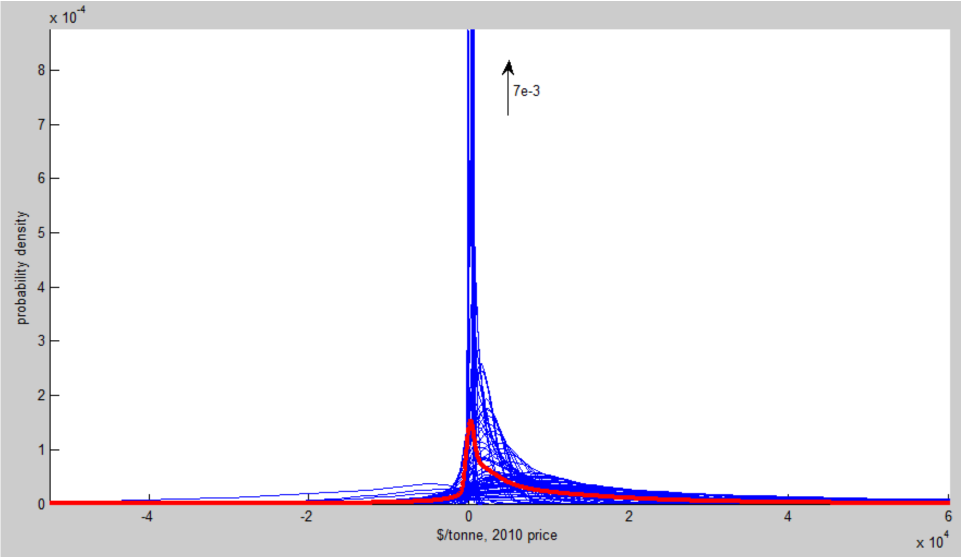


Figure 3.20 PDFs of the 77 Estimates of the MDCs of SOx Emissions and the Composite PDF (bold)

Fig. 3.21 displays the author weight PDF, quality weight PDF as well as the composite PDF if only peer reviewed studies are considered. Fig.3.22 displays the corresponding CDFs.

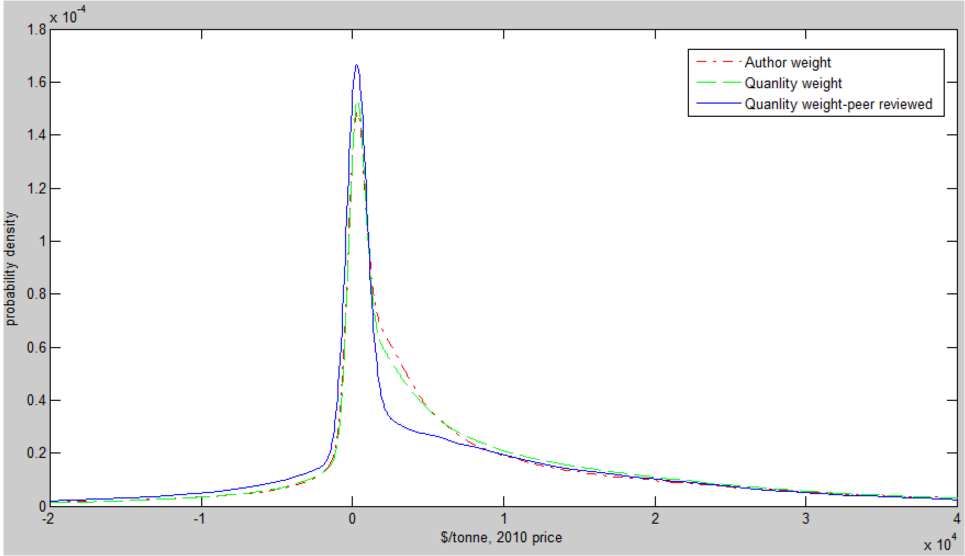


Figure 3.21 PDFs of the MDCs of SO_x Emissions for the Three Scenarios

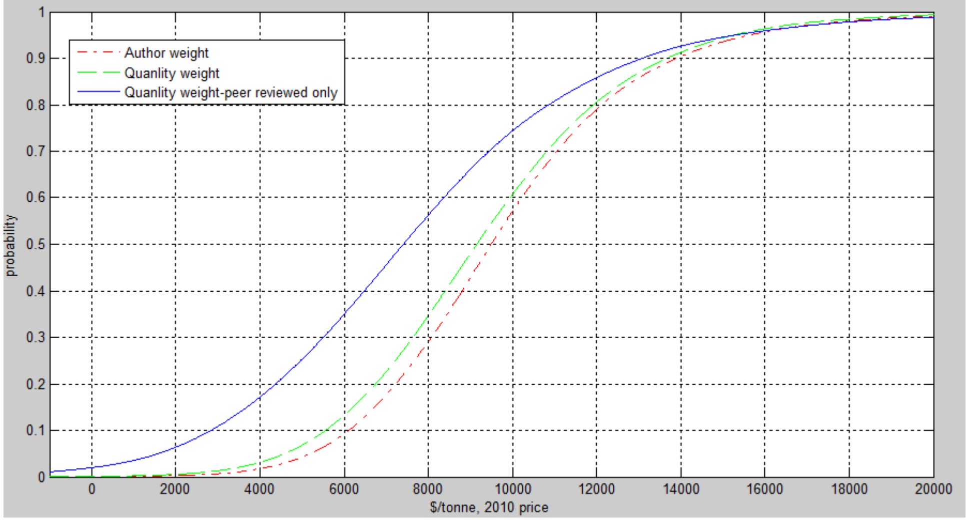


Figure 3.22 CDFs of the MDCs of SO_x for the Three Scenarios

Table 3.15 shows some characteristics of the uncertainties. As can be seen, the composite simulation has the most narrow uncertainty range. The possible best guess for the MDC of SO_x is 9695 $/tonne.

Table 3.15 Probability Characteristics of the MDCs of SO_x Emissions ($/tonne)

$/tonne, 2010 price	Mean	5%	10%	Median	90%	95%
Composite	9707	-4290	-220	4383	28372	41025
Author weight	10065	-8954	-1588	3757	32099	47754
Quality weight	9695	-8397	-1582	4164	29847	42920
Peer reviewed only	12233	-14644	-5237	2873	31758	52944

3.2.2.9 Summary

This subsection estimates the MDCs for various air pollutants through an extensive literature review. Based on the simulation, the mean value, PDF and CDF of certain air pollutants are obtained which can be used for calculating the EDC. In general, there are great uncertainties associated with the estimations. However, in most cases, estimations from simulations with quality weight systems, either quality weight or quality weight-peer reviewed only, have smaller uncertainty ranges compared with those of the other simulation approaches, which follows the experience of Tol (2005). The simulation results are mainly chosen from the quality weight systems. The estimation results are summarized in Table 3.16.

Table 3.16 MDCs of Various Air Pollutants ($/tonne)

Item	Mean	5%	10%	90%	95%	Sample size
CO_2	50	-9	-2	125	245	103
CH_4	625	-151	2	387	1424	25
N_2O	12341	-1983	-108	6802	30539	10
VOC	1303	20	76	702	2661	40
NO_x	5511	-2839	-108	2742	16576	84
CO	354	-11	1	59	1122	30
PM_{10}	7851	-693	183	4321	21575	47
SO_x	9695	-8397	-1582	29847	42920	77

3.3 Relationship of Pavement Roughness and Vehicle Speed

3.3.1 Background

Vehicle operating speed is a significant parameter that reflects the level of service of highways. Many factors influence actual vehicle operating speed. These factors are grouped by their characteristics, including: driver characteristics, vehicle characteristics, roadway characteristics, traffic conditions, and environmental conditions. As summarized by Karan et al. (1976), driver characteristics include age, occupation, gender as well as length or purpose of trips, and presence or absence of passengers; vehicle characteristics include engine size and power, type, age, and weight, etc.; roadway characteristics account for factors such as geographic location, sight distance, lateral clearance, gradient, type of surface, and others; traffic conditions include traffic volume and density, composition, access control, and passing maneuvers; environmental conditions mainly consist of two factors, time of day and climatic condition.

The importance of determining the relationship between vehicle speed and the above mentioned variables has long been recognized and relevant efforts are continuously devoted. However, observations on the involved parameters clearly suggest the markedly missing consideration of the effect of pavement surface condition, that is, roughness, on the vehicle speed. In performing LCA, it is unavoidable to use this function. In LCA model, estimating the additional fuel consumption from vehicles riding on deteriorated pavements compared to that from vehicles on ideally smooth pavements relies on precise interpretation of the relationship between vehicle speed and roughness. In the previous LCA studies (Zhang et al. 2010) that considered the effect of deteriorated pavement surface, conclusions from India-based study (Chandra 2004) was used, where the roughness ranges from 127 to 444 in/mi (2 to 7 m/km) and vehicles ride at speeds of 25-40 mph (40-64 km/h). The traffic scenario is phenomenally disparate from those in the U.S., and in this sense, the conclusions are not suitable to be directly applied to U.S. context.

Aside from Chandra's study (2004), other studies concerning the relationship between pavement roughness and vehicle speed are pretty limited and quite outdated. Karan et al. (1976) presented a good example of the problem through statistical modeling. However, the authors used a small sample size. Furthermore, although the authors found a significant effect of roughness on speed and presented four models for prediction, the coefficients in the models are inconsistent. Du Plessis et al. (1989) probed the problem to calibrate the speed prediction model in the highway design and maintenance standards model (HDM-III). A set of regression models were developed but finally all rejected due to the fact that the road type has a greater impact on speed than the roughness. However, Paterson and Watanatada (1985) found that at an IRI level less than 380 in/mi (6m/km), travel speed is relatively insensitive to roughness. Similarly, Symonds et al. (1996) suggested that travel speed is not affected by pavement roughness if IRI is less than 291 in/mi (4.6m/km). Recently, Kalembo et al. (2012) performed a study aiming at revealing the correlation between CO_2 emission and the pavement roughness. They found that a slight decrease in the mean speed from roads in poor conditions compared to roads in either fair or good condition. However, their study has only a sample size of 12 pavement sections and the t-test results indicated that at the 95 percent confidence level, the mean relative speeds (average speed/speed limit) from poor IRI roads are not statistically different those from the good IRI roads. Besides, there are several other studies predicting the vehicle speed reduction in terms of IRI for passenger cars, as listed in Table 3.17 (Bennett 1994).

Table 3.17 Effect of Roughness on Passenger Car Speed from Various Studies

Country	Reference	Decrease in Speed (km/h) per Increase in IRI (m/km)
Brazil	GEIPOT (1982)	2.00
Caribbean	Morosiuk and Abaynayaka (1982)	0.62
India	CRRI (1982)	2.57
Kenya	Watanatada (1981)	0.64

As can be seen, most studies are quite outdated. It is inappropriate to use the results directly due to disparate traffic operation scenarios, improvement of vehicle technology, and increase of number of highway lanes, etc. Therefore, it is desired to develop a model that satisfies the U.S. traffic environment and can be conveniently applied to enrich the LCA model bank.

3.3.2 Data Source

In this study, the PeMS of Caltrans is used as data source, which provides information such as the inventory of physical pavement features including the number of lanes, length, width, surface type, as well as traffic conditions including vehicle volume, vehicle speed, and volume-capacity ratio (VCR), etc. The roughness data in terms of IRI are also supplied by Caltrans and University of California Pavement Research Center, which cover a variety of highways in California from 2000 to 2008.The traffic conditions are taken directly from PeMS, including live average traffic speed, lane capacity, and traffic flow volume, etc. The traffic data are extracted from the first week of July and September to avoid the rainy season in California. Unfortunately, the speed data does not carry vehicle information, that is, it is impossible to differentia different types of vehicles and their compositions so vehicle type will not appear in the model as an independent variable.

The selection of pavement sections is random while satisfying the following three requirements: firstly, to incorporate enough sample size and geometric elements, specifically, including different pavement types and number of lanes; secondly, to avoid the interruption by non-roughness parameters as much as possible, that is, the selected pavement sections strive to be free from the impacts of curvature, gradient, and intersections; and thirdly, to have a widely distributed roughness structure. The information of the selected pavement sections is listed in Table 3.18.

Table 3.18 Physical Information of the Selected Pavement Sections

Route Num.	Pavement Type	Post Mile	Direction	No. of Lanes	Years of IRI Data	Speed Limit (mph)
I-880	F	2.55	SB	3	2002-2006, 2008	65
I-680	F	9.61	SB	3	2002-2006, 2008	65
I-10	R	0.93	EB	3	2000-2006, 2008	70
I-5	R	119.15	NB	3	2000-2006, 2008	70
I-5	R	510.34	SB	3	2001-2005, 2008	70
I-5	F	182.44	NB	4	2000-2006, 2008	70
I-5	F	16.69	SB	4	2002-2004, 2006, 2008	70
US-101	F	444.72	NB	4	2002-2006, 2006, 2008	65
US-101	F	372.6	SB	4	2003, 2006, 2008	65
I-880	F	14.81	SB	4	2002-2004, 2006, 2008	65
I-80	F	87.42	WB	4	2002-2004, 2006, 2008	65
I-5	R	46.95	SB	4	2000-2004, 2006, 2008	70
I-5	R	136.02	SB	4	2000-2004, 2006, 2008	70
I-5	R	148.04	NB	4	2000-2004, 2006, 2008	70
I-5	R	194.62	NB	4	2000-2003, 2006, 2008	70
I-80	R	87.42	WB	4	2000-2004, 2006, 2008	65
I-80	R	98.4	EB	4	2003, 2004, 2006, 2008	65
I-80	R	98.4	WB	4	2003, 2004, 2006, 2008	65
I-5	F	98.00	SB	5	2002-2004, 2006, 2008	70
US-101	F	21.48	SB	5	2001-2004, 2006, 2008	65
I-5	F	89.45	NB	5	2002-2004, 2006, 2008	70
I-5	F	100.29	SB	5	2002-2004, 2006, 2008	70
I-5	R	82.59	SB	5	2002, 2006, 2008	70
I-5	R	89.45	SB	5	2002-2004, 2006, 2008	70
I-5	R	34.19	SB	5	2000-2004, 2006, 2008	70
I-10	R	37.64	EB	5	2000-2004, 2006, 2008	70
I-15	R	17.72	NB	5	2000-2004, 2006, 2008	70
I-15	R	27.70	SB	5	2002-2004, 2006, 2008	70
I-5	F	96.69	SB	6	2002, 2005, 2006, 2008	70
I-5	F	106.79	SB	6	2002-2004, 2006, 2008	70
I-15	R	13.44	NB	6	2000-2004, 2006, 2008	65
I-5	R	92.00	SB	6	2002-2004, 2006, 2008	70

Note: The IRIs for the selected mileages are calculated for one-mile average; EB, SB, WB, and NB represent east bound, south bound, west bound, and north bound; F and R represent flexible and rigid pavements, respectively; 2007 data are not available.

3.3.3 Preliminary Data Analysis

As seen in Table 3.18, there are 32 individual pavement sections, each of which possesses a set of IRI data. In total, there are 191 set of IRI data. A roughness evaluation system in terms of IRI used by Caltrans is employed to assess the collected IRI data. The typical ride quality scale defined by the Caltrans specification is used (CalTrans 2004). Specifically, excellent is of IRI from 0 to 75 in/mi; good is of IRI from 76 to 125 in/mi; fair is of IRI from 126 to 175 in/mi; poor is of IRI from 176 to 200 in/mi; and unacceptable is of IRI greater than 200 in/mi;

For the selected pavement sections, the corresponding IRI distribution is plotted to give a general picture of the data structure, as shown in Fig.3.23.

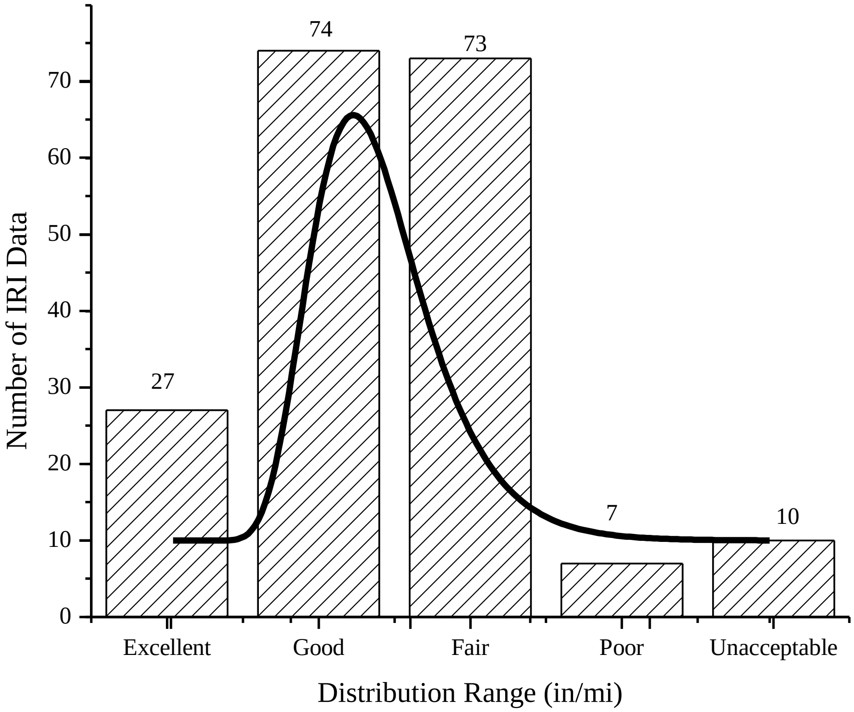


Figure 3.23 IRI Distribution and Fitting Curve of the Selected Pavement Sections

As can be seen in Fig.3.23, the distribution of the IRI data is a bit right skewed. The IRI data mainly locate in the good and fair range while what locate within the poor and unacceptable range are relatively less. This is because the agency typically does not allow the pavements to deteriorate to an unacceptable status. A more in-depth analysis about the IRI data is performed, as shown in Fig.3.24.

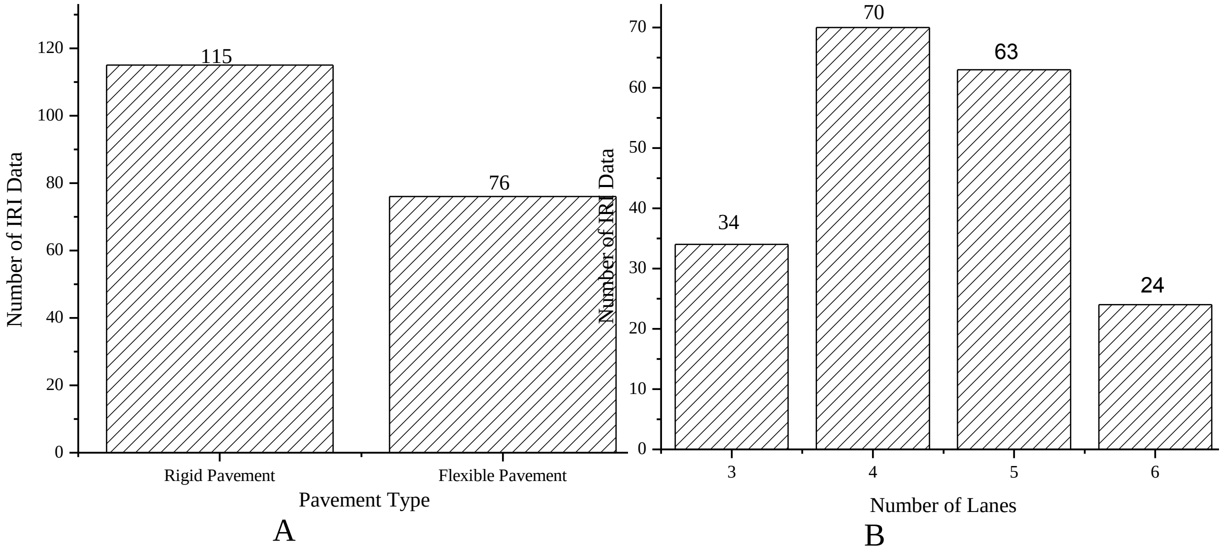


Figure 3.24 IRI Distribution in Terms of Pavement Type and Number of Lanes

The histograms of the IRI data for different pavement types and numbers of lanes are shown in Fig.3.24. As can be seen, the IRI data contain more samples from rigid pavements than from flexible ones and are mainly taken from pavement sections with four or five lanes. This is quite different from the scenarios of previous studies, whose samples were extracted from two-lane pavements.

In this study, the candidate independent variables are IRI, pavement type, number of lanes, VCR and the dependent variable is the average vehicle speed. For the independent variable, only values falling within the range from 50 mph to 80 mph are used to exclude the influences from any other factors, such as congestion, traffic accidents, bad weather, and over speeding, etc. Intuitively, it is expected that drivers tend to slow down when driving on rougher pavements.

3.3.4 Regression Analysis

When using field data or observations of in-service pavements for modeling, one major statistical issue, unobserved heterogeneity, may jeopardize the credibility and applicability of the developed model if it is not properly addressed. Unobserved heterogeneity is one instance where correlation between observables and unobservables are expected. Generally speaking, unobserved heterogeneity refers to differences across sections and/or time that may not be appropriately reflected in the available explanatory variables of a classical linear regression model as follows:

$$y_{it} = \boldsymbol{\beta}^{'}\mathbf{X}_{it} + u_{it} \quad i = 1,\ldots n;\ t = 1,\ldots T \tag{3.3}$$

where i refers to pavement section; t refers to time period; $\boldsymbol{\beta}$ is a vector of parameters to be estimated; $\mathbf{X}_{it}$ is a vector of explanatory variables; and u_{it} is a disturbance term.

The IRI data are panel structured since they contain both cross section data and time series data. However, the roughness developing trend is not of interest in this study but the relationship between speed change and roughness change on a specific road is. Thus it is assumed that time serial unobserved factors have no influence. The desired regression model suffers only from cross sectional unobserved heterogeneity.

Two approaches can be employed to capture the unobserved heterogeneity: fixed-effect model and random-effect model. The fixed-effect model examines cross-sectional and/or time-serial differences in the intercept term. If both cross-sectional and time-serial differences are examined, the model is called two-way fixed-effect model; if only cross-sectional or time serial difference is examined, it is called one-way fixed-effect model. Parameters of fixed-effect model can be estimated by ordinary least-squares regression. For the problem of interest, the one-way fixed-effect model is written as:

$$y_{it} = u_i + \boldsymbol{\beta}^{'}\mathbf{X}_{it} + v_{it} \tag{3.4}$$

where u_i is a random error characterizing the i^{th} section and v_{it} is an uncorrelated error; the other parameters remain the same meanings as those in Eq.3.3.

The fixed-effect model suffers from a shortcoming for its prohibitive estimation of many parameters (i.e., constant terms, u_i) and associated loss of degree of freedom. A random-effect model can overcome this shortcoming, which estimates variance components for cross sections and error, assuming the intercept and slope. The differences among cross sections lie in the variance of the error term. This model can be estimated by generalized least squares method. Reflected in the formula, the disturbance term is:

$$u_{it} = u_i + v_{it} \tag{3.5}$$

where all the variables have the same meanings as those in Eq. 3.3. Rewriting Eq. 3.3 using Eq. 3.5, the one-way random-effect model is given by

$$y_{it} = \boldsymbol{\beta}^{'}\mathbf{X}_{it} + u_i + v_{it} \tag{3.6}$$

where all the variables have the same meanings as those in Eq. 3.3.

Before the regression analysis, the involved variables are further classified: average vehicle speed is the dependent variable; IRI and VCR are explanatory variables; speed limit, pavement lane number, and pavement type are dummy variables.

Analysis of variance (ANOVA) was firstly performed for the dummy variables to investigate their statistical significances and impacts. Table 3.19 and Fig.3.25 have the information of the inspection of speed limit.

Table 3.19 F-Test Results of Comparing Average Speeds of the 70 mph and 65 mph Speed Limit

Speed limit	70	65
Mean	68.55	67.13
Variance	5.08	4.16
Sample size	36662	13311
F	830.43	
P-value	<0.001	

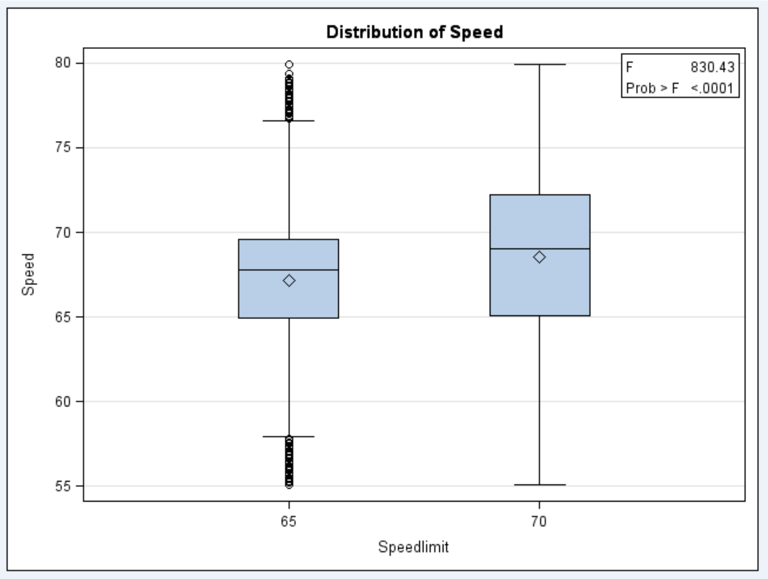


Figure 3.25 Box Plot of the Distribution of Speeds by Speed Limit

As can be seen in Table 3.19 and Fig.3.25, the F-test results indicate that at the 95 percent confidence level, there is statistical difference for the average speed under the two speed limit constraints but the difference does not reach 5 mph. The phenomenon reveals that the drivers tend to exceed the 65 mph speed limit a little bit. Also, preliminary regression analysis suggests that the speed limit factor is not significant in the regression model and therefore the variable will not be included. The possible explanation is the vehicles are already driven at a high speed and the speed is not significantly influenced by the two speed limits of an only 5 mph difference.

In a similar fashion, ANOVA was performed on the number of lanes, with the results listed in Table 3.20 and Fig.3.26.

Table 3.20 F-Test Results of Comparing Average Speeds of Different Pavement Lanes

Number of Lanes	3	4	5	6
Mean	65.94	66.98	69.67	69.63
Variance	4.92	4.43	4.67	4.31
Sample size	11169	12215	19033	7556
F	2063.53			
P-value	<0.001			

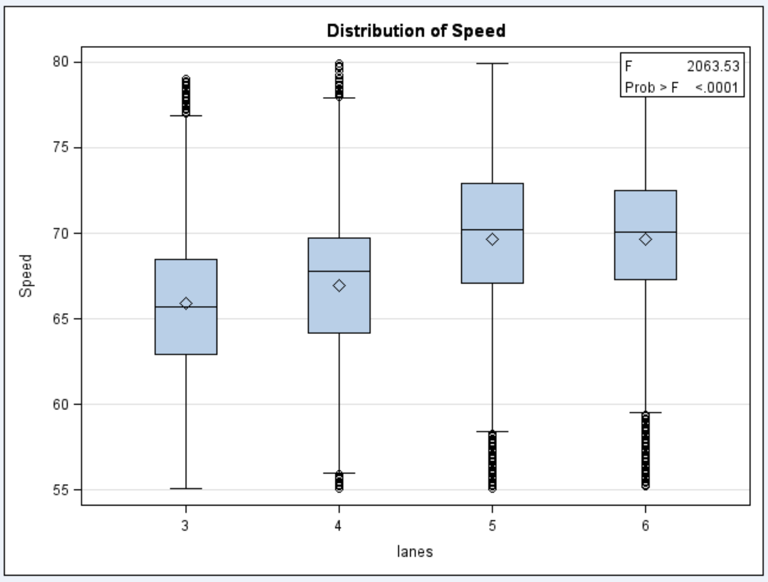


Figure 3.26 Box Plot of the Distribution of Speeds by Pavement Lanes

As can be seen, the “Number of lanes” variable is statistically significant at the 95 percent confidence level. Disparate average speeds are observed, with a trend of increasing with the number of lanes. Five-lane seems to be the watershed where average speeds of five-lane and six-lane have similar values. Therefore, 5-lane and 6-lane will be treated as the same category in the subsequent regression analysis.

Different pavement types, rigid one versus flexible one, were also evaluated about their impacts on the average speeds through ANOVA, with the results listed in Table 3.21 and Fig.3.27.

The F-test results indicate that at the 95 percent confidence level, there is statistically significant difference between the average speeds for the two pavement types, but the difference is very small, possibly because driving behavior is not significantly altered by pavement type. Considering this, pavement type is not included as an independent variable in further regression analysis.

Table 3.21 F-Test Results of Comparing Average Speeds of Different Pavement Types

Pavement Type	Flexible	Rigid
Mean	68.30	68.11
Variance	4.96	4.86
Sample size	15214	34759
F	15.47	
P-value	<0.001	

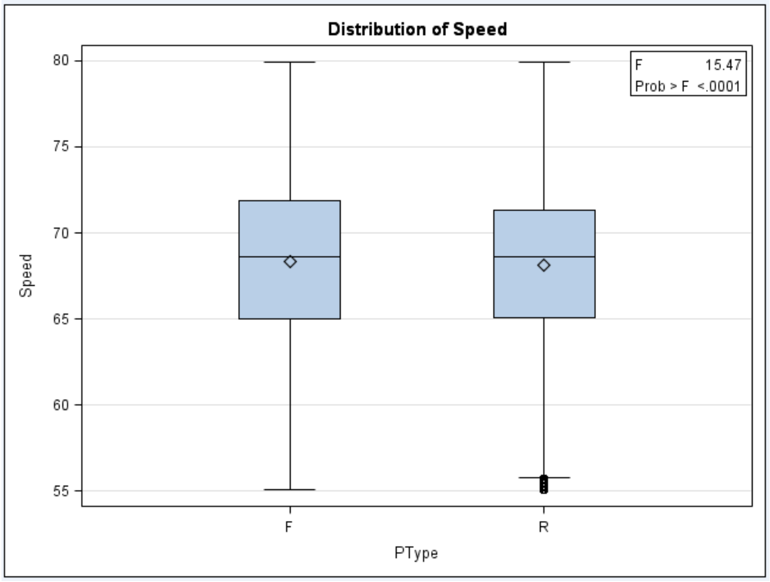


Figure 3.27 Box Plot of the Distribution of Speeds by Pavement Types

After performing the ANOVA, the one-way random-effect regression was performed to obtain the model, with average speed being the dependent variable, VCR and IRI being the independent variables, and number of lanes being the dummy variables. The regression results are summarized in Table 3.22.

Table 3.22 Estimation Results of the Regression Model

Variables	Coefficient	Std	t-statistics	P-value
Intercept	72.18	0.50	145.45	<0.001
IRI	-0.0083	8.01e-4	-10.31	<0.001
VCR	-3.035	0.070	-43.68	<0.001
L_3	-3.78	0.93	-4.11	0.008
L_4	-2.29	0.86	-2.65	0.027
L_{56}	0	-	-	-
Variance of Error Term	Value		Number of Observations:49973 Number of Cross Sections : 32 Akaike information criterion (AIC): 286655	
Sigma_v	18.01			
Sigma_i	3.05			

Based on the regression results, the Speed-IRI relationship is written as:

$$\text{Speed}=72.18-0.0083\text{IRI}-3.035\text{VCR}-3.78\text{L}_3-2.29\text{L}_4 \tag{3.7}$$

where speed represents the average vehicle speed (mph); IRI is the roughness (in/mi); L_3 and L_4, L_{56} represent the pavement sections that have three lanes, four lanes, and five or six lanes, respectively; Sigma_i represents the variance of u_i in Eq. 3.3, which accounts for cross-sectional unobserved heterogeneity; Sigma_v represents the variance of the random disturbances in Eq. 3.3, accounting for random error term, and L_3, L_4, and L_{56} are dummy variables, where $\begin{cases} L_3=1,\ L_4=0, L_{56}=0 \text{ or} \\ L_3=0,\ L_4=1, L_{56}=0 \text{ or} \\ L_3=0,\ L_4=0, L_{56}=1 \end{cases}$.

At the 95 percent confidence level, all the involved parameters are statistically significant. The error terms, Sigma_v and Sigma_i are large, which stand for great uncertainties from unobserved influencing factors. This is a natural result of the rough samples since all types of vehicle are clustered. The regression results comply with the prior expectations: the average speed decreases with the increase of roughness. Specifically, every 1 in/mi increase of the IRI leads to a 0.0083 mph decrease of the average speed (-0.84 km/h per m/km). The rate is within the range of estimations in Table 3.17.

3.3.5 Summary

Regarding the shortcomings in the models describing the vehicle speed-pavement roughness relationship, this sectional research selected 32 pavement sections and 191 set of roughness data as well as other measures, including vehicle speed, VCR, number of lanes, pavement type, and speed limit to build an empirical model. Through the study, the conclusions and limitations are summarized.

1. Under the context of this research, average vehicle speed decreases linearly with the IRI increase, at a rate of 0.84 km/h per m/km.
2. The addition of number of lanes tends to increase the average speed; however, differences between five-lanes and six-lane are very limited.
3. In the context of this study, an increase of speed limit from 65 mph to 70 mph leads to a slight increment of the average speed; pavement type is not a dominating factor influencing the average speed.
4. Due to data limitation, the model development did not considered vehicle type as an independent variable, which may reduce the reliability of the developed model and remains a topic for further research. The currently developed model, however, can be used reliably in most occasions with common traffic compositions.

3.4 Integration of LCA and LCCA

Pavement maintenance is routinely used to maintain the pavements at an acceptance level and the LCCA model is widely accepted in the U.S. DOTs to perform the pavement maintenance schedule optimizations, such as the practices of Chen and Flintsch (2007), Lee et al. (2011), and Praticò et al. (2011). However, those practices only consider agency cost and user cost and ignore the EDC, making their cost system incomplete. It is desired to improve the optimization process in this section, that is to feed LCA results to the LCCA optimization process to add the cost element.

Dynamic programming has long been used for pavement management optimization, such as Feighan and Shahin (1987), Smadi and Maze (1994), Durango-Cohen (2004), Robelin and Madanat (2007). Despite the simplicity of the application in the pavement field, the dynamic programming can sufficiently satisfy the engineering requirement. This study uses it as the optimization tool and defines the involved parameters as the beginning.

1. Stage variable: index of year in the analysis period.

2. State variable: present serviceability index (PSI) which is influenced by the maintenance decision.

PSI is closely related to the roughness in terms of IRI, with their relationship described by the equation set (Gulen et al. 1994).

$$\begin{aligned} &PSI=7.21e^{-0.47IRI} \quad (R^2=0.84) \text{ for asphalt pavement}\\ &PSI=14.05e^{-0.74IRI} \quad (R^2=0.93) \text{ for concrete pavement}\\ &PSI=9.00e^{-0.56IRI} \quad (R^2=0.84) \text{ for composite pavement} \end{aligned} \tag{3.8}$$

where IRI is in m/km.

Some other optimization parameters are also defined.

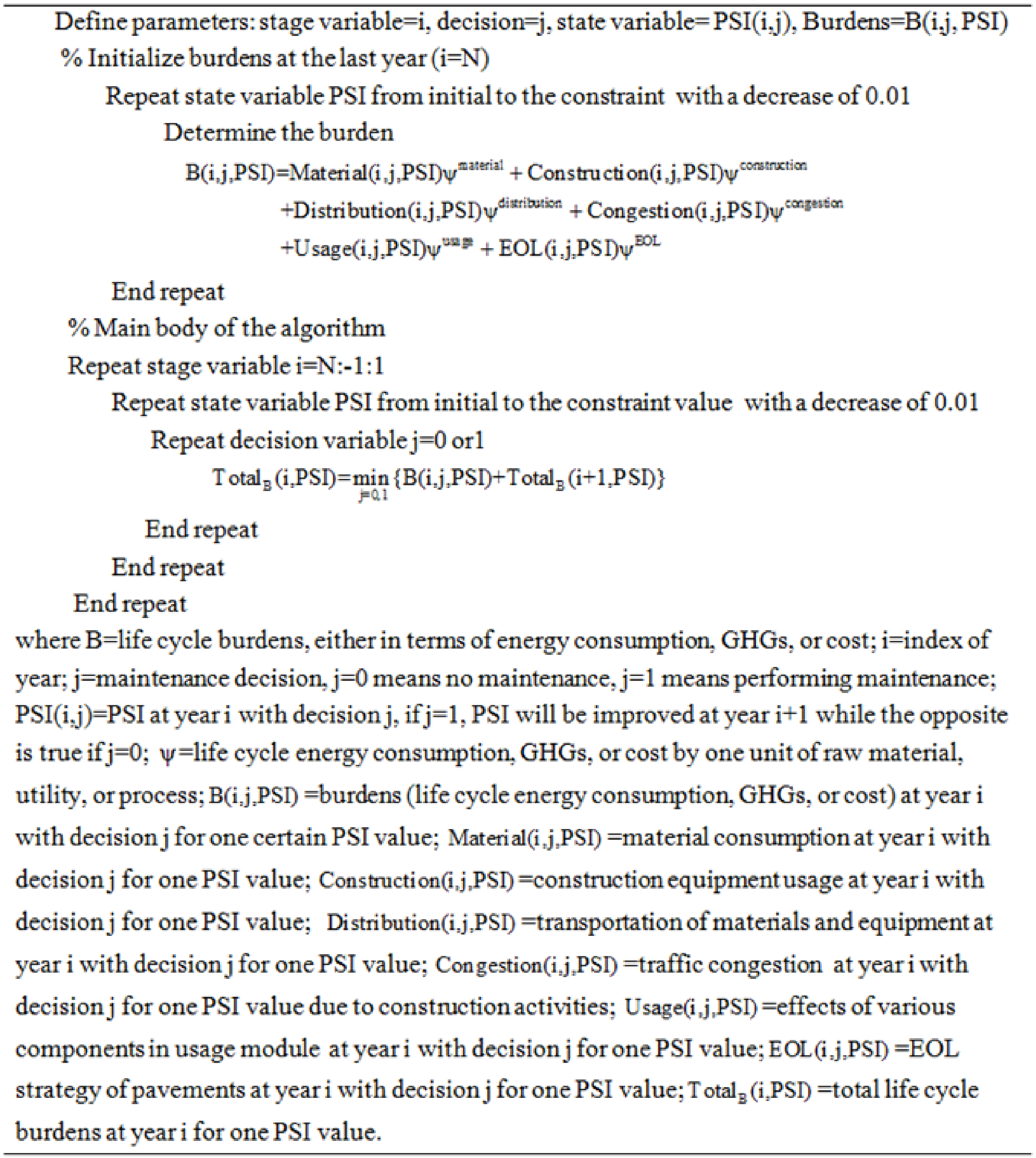
1. Constraint: $PSI \geq 2.5$.

2. Objective function: to minimize the life cycle burdens (energy consumption, GHGs, or cost).

3.Maintenance decision: Maintenance (1) or not (0).

4.Transition matrix: roughness development model which is case dependent and influenced by maintenance decision.

The problem formulated above can be solved using backward recursion, as shown in Fig. 3.28.



```
Define parameters: stage variable=i, decision=j, state variable= PSI(i,j), Burdens=B(i,j, PSI)
 % Initialize burdens at the last year (i=N)
    Repeat state variable PSI from initial to the constraint  with a decrease of 0.01
        Determine the burden
          $B(i,j,PSI)=Material(i,j,PSI)\psi^{material} + Construction(i,j,PSI)\psi^{construction}$
                 $+Distribution(i,j,PSI)\psi^{distribution} + Congestion(i,j,PSI)\psi^{congestion}$
                 $+Usage(i,j,PSI)\psi^{usage} + EOL(i,j,PSI)\psi^{EOL}$
    End repeat
 % Main body of the algorithm
 Repeat stage variable i=N:-1:1
    Repeat state variable PSI from initial to the constraint value  with a decrease of 0.01
       Repeat decision variable j=0 or1
            $Total_B(i,PSI)=\min_{j=0,1}\{B(i,j,PSI)+Total_B(i+1,PSI)\}$
       End repeat
    End repeat
 End repeat
```

where B=life cycle burdens, either in terms of energy consumption, GHGs, or cost; i=index of year; j=maintenance decision, j=0 means no maintenance, j=1 means performing maintenance; PSI(i,j)=PSI at year i with decision j, if j=1, PSI will be improved at year i+1 while the opposite is true if j=0; ψ=life cycle energy consumption, GHGs, or cost by one unit of raw material, utility, or process; $B(i,j,PSI)$ =burdens (life cycle energy consumption, GHGs, or cost) at year i with decision j for one certain PSI value; $Material(i,j,PSI)$ =material consumption at year i with decision j for one PSI value; $Construction(i,j,PSI)$ =construction equipment usage at year i with decision j for one PSI value; $Distribution(i,j,PSI)$ =transportation of materials and equipment at year i with decision j for one PSI value; $Congestion(i,j,PSI)$ =traffic congestion at year i with decision j for one PSI value due to construction activities; $Usage(i,j,PSI)$ =effects of various components in usage module at year i with decision j for one PSI value; $EOL(i,j,PSI)$ =EOL strategy of pavements at year i with decision j for one PSI value; $Total_B(i,PSI)$ =total life cycle burdens at year i for one PSI value.

Figure 3.28 Pseudocode of Backward Recursion Algorithm

CHAPTER 4: CASE STUDY OF PAVEMENT OVERLAYS

The proposed methodology is demonstrated with a case study to show how the methodology is implemented in detail. Also, the proposed M&R optimization algorithm built in section 3.4 is tested.

4.1 Background

The background information of the case study is: an old PCC pavement is at the end of the service life and demands rehabilitation to restore the serviceability. The existing base course is assumed to perform well and can still work without intensive maintenance activities. Three replacement options are considered.

1. Remove and replace the existing pavement with PCC (hereafter called the PCC option). Remove the existing PCC, keep the existing base and subgrade in place, and repave new PCC of 250 mm (10 in.). Use diamond grinding as a periodic rehabilitation strategy.
2. Remove and replace the existing pavement with HMA (hereafter called the HMA option). Remove the existing PCC, keep the existing base and subgrade in place, and repave new HMA of 225 mm (9 in.). Use a mill-and-fill (removal of the HMA surface with a cold planer and replacement of the same depth of new HMA) as a periodic rehabilitation strategy.

3. Crack, seat, and overlay (hereafter called the CSOL option). Crack and seat (Halil et al. 2005) the existing PCC pavement and then overlay it with 125 mm (5 in.) HMA. Use a mill-and-fill as a periodic rehabilitation strategy.

The three pavement overlay designs followed the AASHTO pavement design guide and were verified by the MEPDG software (2011).

The Caltrans reported that the average life of a diamond-grind surface is between 16 to 17 years (2005), so a diamond grinding action will be applied to the PCC option every 16 years. For the other two options, a HMA mill-and-fill plan commonly used by previous research with a frequency of every 16 years (Weiland and Muench, 2010; Zhang et al, 2010) is employed in this study. Table 4.1 lists the information of the three overlay system options.

Table 4.1 Structural Design and Rehabilitation Schedules for the Three Options

PCC	HMA	CSOL
Geometric (Width) Information of One Direction		
Inner paved shoulder: 1.2 m	Inner paved shoulder: 1.2 m	Inner paved shoulder: 1.2 m
Main lane: 3.6 m×2	Main lane: 3.6 m×2	Main lane: 3.6 m×2
Outside paved shoulder: 2.7 m	Outside paved shoulder: 2.7 m	Outside paved shoulder: 2.7 m
Structural (Thickness) Specifications		
250 mm (10 in.) PCC	50 mm (2 in.) HMA	50 mm (2 in.) HMA
	75 mm (3 in.) HMA	75 mm (3 in.) HMA
	100 mm (4 in.) HMA	225 mm (9 in.) cracked and seated existing PCC
250 mm (10 in.) existing crushed aggregate	250 mm (10 in.) existing crushed aggregate	250 mm (10 in.) existing crushed aggregate
Existing subgrade	Existing subgrade	Existing subgrade
Rehabilitation Techniques		
Diamond grind to restore surface smoothness (CALTRANS, 2005).	Remove and replace (mill-and-fill) the top 1.8 in. (45 mm) every 16 years (Weiland and Muench, 2010).	Remove and replace (mill-and-fill) the top 1.8 in. (45 mm) every 16 years (Weiland and Muench, 2010).
Rehabilitation Schedules		
1st Year: reconstruction 16th Year: diamond grind	1st Year: reconstruction 16th Year: mill-and-fill	1st Year: reconstruction 16th Year: mill-and-fill
32nd Year: diamond grind	32nd Year: mill-and-fill	32nd Year: mill-and-fill

4.2 Methodology Implementation

4.2.1 Functional Unit

Equivalent functionality shall be maintained for all candidates of an LCA model. For pavement, it means various pavement systems need to provide similar performance for the same traffic over a given period.

A functional unit quantifies a standard amount to be compared between options that serve this function. In this study, the functional unit is defined as one kilometer overlay system over an existing PCC pavement with four lanes in two directions that would provide satisfactory performance over a 40-year period.

The structure of the existing PCC pavement consists of a 225 mm (9 in.) PCC layer and a 250 mm (10 in.) crushed aggregate base course. The PCC layer is at the end of its service life and demands rehabilitation to restore the serviceability, while the existing base course is assumed to perform well and can still work without intensive maintenance activities. The traffic conditions include an AADT of 70000, with 8 percent of truck, and an annual traffic growth rate of 4 percent.

4.2.2 Methodology of LCA Model

To assess the environmental impacts of pavement overlay systems, the methodology of LCA model developed in section 3.1 is used and re-organized, as shown in Figure 4.1. The functionality of the methodology is fulfilled by five components, including material module, construction module, congestion module, usage module, and EOL module, with various supplementary models attached to the corresponding modules. Detailed explanations of each module are presented in the following sections.

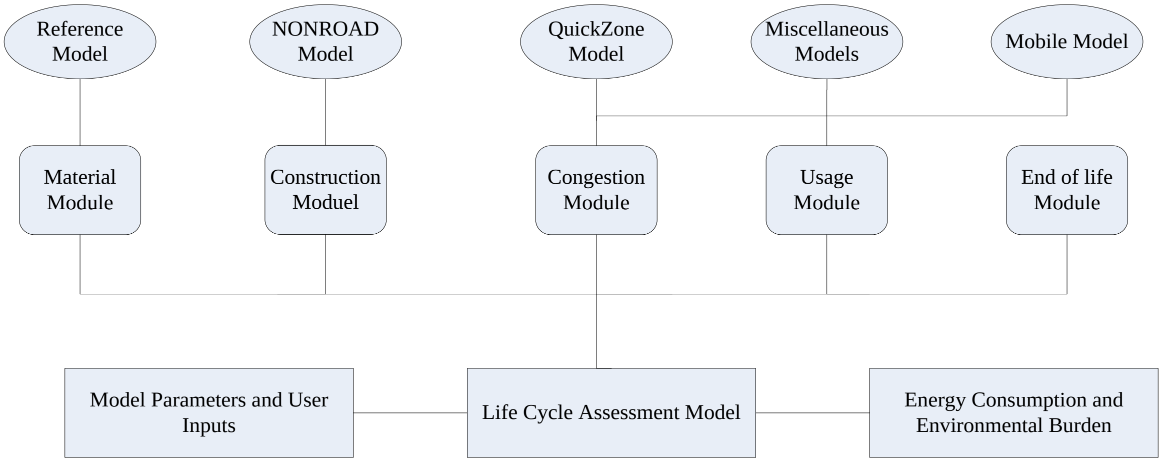


Figure 4.1 Logic Relationship among Various Modules

4.2.3 Material and Construction Modules

Material consumption is modeled with data from various reference sources, including the Portland Cement Association (PCA) (Marceau et al. 2007), the Swedish Environmental Research Institute (Stripple 2001), and the Athena Institute (AI) (2006). The data fields supplied by these references are energy consumptions and discharged environmental pollutants, including CO_2, CO, CH_4, NO_x, SO_x, VOC, and PM_{10}.

All the materials, equipments, and wastes are transported by a combination of roadway, railway, and waterway. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET 2010) model was used as a source of data for the amounts of fuel and electricity production, truck transportation, tie and dowel bar production, and natural gas burned in the HMA tack truck. Versions 1.8 (for material transportation) and 2.7 (for steel production) of the GREET model were used.

Emission data for all nonroad construction and vehicular equipments were obtained from the EPA NONROAD2008 model (2008). For each piece of construction equipment, an estimate of the engine horsepower was made on the basis of one or two typical machines. NONROAD model provides emission factors for various ranges of horsepower. All equipment used diesel fuel. Two Florida localized data were used as inputs: the average annual temperature range and Reid vapor pressure.

The inventories associated with the material and construction modules (with transportation implicitly incorporated) are listed in Table 4.2 through 4.4.

Table 4.2 Material and Construction Activity Inventories of the PCC Option

Item	Task	Data Source	Item	Quantity per km for one direction
Remove and Replace with PCC				
1	Breaking existing PCC	NONROAD	300-hp off-road truck 175-hp crushing processing	1.4 h
2	Load broken PCC	NONROAD	300-hp excavator	33.3 h
3	Waste PCC truck transport[a]	GREET 1.8	Heavy-heavy trucks[e]	157950 tonne-km
4	Utility excavator[b]	NONROAD	300-hp excavator	8.0 h
5	Base grading	NONROAD	175-hp grader	2.1 h
6	Base compaction	NONROAD	300-hp roller	1.7 h
7	PCC production	PCA (2007)	25 MPa, no slag, no fly ash	6660 tonne
8	PCC mix transportation[a]	GREET 1.8	Heavy-heavy trucks	166500 tonne-km
9	PCC placing and spreading	NONROAD	300-hp surfacing equipment	57.4 h
10	Dowel-tie bar production[c]	GREET 2.7	Low-grade steel	55 tonne
11	Dowel-tie bar transportation	GREET 1.8	Heavy-heavy trucks	4125 tonne-km
12	PCC paving and bar placement	NONROAD	300-hp paver	57.4 h
13	Texture-curing	NONROAD	75-hp surfacing equipment	51.6 h
14	PCC saw cutting	NONROAD	75-hp concrete-industrial. saw	15.0 h
Diamond Grinding (to be accomplished at years of 2026 and 2042)				
1	Diamond grinder[d]	NONROAD	600-hp surfacing equipment 100-hp surfacing equipment	17.0 h
2	Grinder transport[d]	GREET 1.8	Heavy-heavy trucks	4162 tonne-km

NOTE: [a]The distance from work zone to PCC recycling facility or PCC plant is 25 km; [b]Assumed to accomplish small work items at about 8 h per km of one direction; [c]Epoxy, stainless, or other coating or cladding is not included; [d]Must travel 25 km to the work zone. Need three passes per lane. Weight is 32 tonne; [e]The heavy–heavy truck class can haul up to 18 tonne (20 ton) of cargo, and remains the same meaning in following contents.

Table 4.3 Material and Construction Activity Inventories of the HMA Option

Item	Task	Data Source	Item	Quantity per km for one direction
Remove and Replace with HMA				
1-6	Same as in Table 4.2			
7	Bitumen production	Stripple (2001) AI (2006)	Grade B60, 50/70 pen	306 tonne
8	Bitumen transportation	GREET 2.7	Heavy-heavy trucks	24480 tonne-km
9	Crushed aggregate production[a]	Stripple (2001) AI (2006)		5695 tonne
10	Crushed aggregate transportation	GREET 1.8	Heavy-heavy trucks	56950 tonne-km
11	HMA production[b]	Stripple (2001) AI (2006)		6001 tonne
12	HMA transportation[c]	GREET 1.8	Heavy-heavy trucks	150025 tonne-km
13	Emulsion production	Stripple (2001)	CSS-1 emulsion tack coat	12.5 tonne
14	Material transfer vehicle	NONROAD	300-hp surfacing equipment	33.7 h
15	HMA paver	NONROAD	300-hp paver	33.7 h
16	Breakdown rolling	NONROAD	Two 300-hp rollers	67.6 h
17	Finish rolling	NONROAD	100-hp roller	33.7 h
18	Tack coat application	GREET 1.8	Medium-heavy vehicle	504 tonne-km
19	Tack coat truck heater	GREET 1.8	Small natural gas turbine	528 MJ of propane
45 mm (1.8 in.) HMA mill and fill (to be accomplished at years of 2026 and 2042)				
1	Milling machine	NONROAD	750-hp surfacing equipment	13.5 h
2	RAP transportation[c]	GREET 1.8	Heavy-heavy vehicle	30007 tonne-km
3	Street sweeping	GREET 1.8	Medium-heavy trucks	77.2 tonne-km
4	Sweeper auxiliary engine	NONROAD	100-hp cement-mortar mixer	0.8 h
5	Bitumen production	Stripple (2001) AI (2006)	Grade B60, 60/70 pen	61.7 tonne
6	Bitumen transportation	GREET 1.8	Heavy-heavy vehicle	4933 tonne-km
7	Crushed aggregate production[a]	Stripple (2001) AI (2006)		1147 tonne
8	Crushed aggregate transportation	GREET 1.8	Heavy-heavy vehicle	11470 tonne-km
9	HMA production[b]	Stripple (2001) AI (2006)		1209 tonne
10	HMA transportation[c]	GREET 1.8	Heavy-heavy vehicle	30228 tonne-km
11	Emulsion production	Stripple (2001) AI (2006)	CSS-1 emulsion tack coat	6.6 tonne
12	Material transfer vehicle	NONROAD	300-hp surfacing equipment	11.4 h
13	HMA paver	NONROAD	300-hp paver	11.4 h
14	Breakdown rolling	NONROAD	Two 300-hp rollers	22.6 h
15	Finish rolling	NONROAD	100-hp roller	11.4 h

Table 4.3 (Continued)

Item	Task	Data Source	Item	Quantity per km for one direction
16	Tack coat application	GREET 1.8	Medium-heavy vehicle	160 tonne-km
17	Tack coat truck heater	GREET 1.8	Small natural gas turbine	151 MJ of propane

NOTE: [a]A hundred percent crushed aggregate was used in HMA;[b]5.1 percent binder, no RAP in baseline case; [c]Distance from work zone to the PCC recycling facility, HMA plant, or RAP storage area is 25 km; [d]The medium–heavy truck class can haul up to 7.2 tonne (8 ton) of cargo, and remains the same meaning in following contents.

Table 4.4 Material and Construction Activity Inventories of the CSOL Option

Item	Task	Data Source	Item	Quantity per km for one direction
Remove and Replace with HMA				
1-6	Same as in Table 4.2			
7	Bitumen production	Stripple (2001) AI (2006)	Grade B60, 50/70 pen	179 tonne
8	Bitumen transportation	GREET 1.8	Heavy-heavy truck	14321 tonne-km
9	Crushed aggregate production[a]	Stripple (2001) AI (2006)		3331 tonne
10	Crushed aggregate transportation	GREET 1.8	Heavy-heavy truck	33310 tonne-km
11	HMA production[b]	Stripple (2001) AI (2006)		3510 tonne
12	HMA transportation[c]	GREET 1.8	Heavy-heavy truck	150025 tonne-km
13	Emulsion production	Stripple (2001) AI (2006)	CSS-1 emulsion tack coat	8.3 tonne
14	Material transfer vehicle	NONROAD	300-hp surfacing equipment	22.5 h
15	HMA paver	NONROAD	300-hp paver	22.5 h
16	Breakdown rolling	NONROAD	Two 300-hp rollers	45.1 h
17	Finish rolling	NONROAD	100-hp roller	22.5 h
18	Tack coat application	GREET 1.8	Medium-heavy vehicle	336 tonne-km
19	Tack coat truck heater	GREET 1.8	Small natural gas turbine	352 MJ of propane
45 mm (1.8 in.) HMA mill and fill (to be accomplished at years of 2026 and 2042)				
Same as in Table 4.3				

NOTE: [a]A hundred percent crushed aggregate was used; [b]5.1 percent binder, no RAP in baseline case; [c]Distance from work zone to the PCC recycling facility, HMA plant, or RAP storage area is 25 km.

One limitation of this inventory is that maintenance activities (e.g., patching, joint repairing, and crack sealing) between major rehabilitation plans are not considered because these maintenance activities are generally small, isolated and hard to be precisely predicted.

4.2.4 Congestion Module

Traffic delays brought by construction and rehabilitation activities have significant influences on the energy consumption and pollutant emissions compared with those under normal vehicular operations, and thus are included in the scope of this study. The changes in traffic flow, traffic delay, and queue length are estimated using the QuickZone model (McTrans, version beta 0.99, 2001). In the baseline scenario, the annual traffic growth rate is zero percent. For construction activities, it is assumed that the two lanes in each direction are both closed so that all traffics take detour, with a speed reduction from 104 km/h (65 mph, highway speed) to 60 km/h (40 mph, local speed), and a longer travel distance of 2.4 km (1.5 mi). For the two rehabilitation activities, it is assumed that only one lane will be temporarily closed. Under this scenario, the outputs from QuickZone model reveal that 27 percent of traffics take detour, and the remaining traffic causes a 1 km (0.62 mi) queue.

Once vehicle delays due to construction and maintenance events are determined, they are coupled with fuel consumptions and vehicle emissions to measure their environmental impacts. Two drive cycles, city one and highway one, are used to determine the fuel economy and to calculate the fuel consumptions, with the former one describing the fuel consumptions of stop-and-go vehicular behaviors during construction and rehabilitation period and the latter one characterizing normal conditions. Vehicle fuel economy is taken from the U.S. EPA fuel economy guide (U.S. EPA 2006). CO_2 is calculated by the fuel consumptions (Emission Facts, 2005), based on the assumption that all passenger cars burn gasoline and trucks combust diesel. Other vehicle emissions are calculated at varying traffic speeds using U.S. EPA's MOBILE 6.2 software, which supplies the tailpipe emissions and evaporative emissions on a per year basis through 2050 (EPA 2002).

The outputs of the fuel consumptions and environmental burdens are calculated as the differences between those of construction and rehabilitation periods and those of normal operations, which are given by:

$$Y_{total} = VMT_{queue} \times Y_{queue} + VMT_{workzone} \times Y_{workzone} + VMT_{\det our} \times Y_{\det our} - VMT_{normal} \times Y_{normal} \quad (4.1)$$

where Y_i represents the value of different environmental indicators, such as fuel usage (L/km) or emission values (g/km); VMT_i is the total miles travelled by vehicles (km or mile); i is scenario index, representing the total, waiting in queue, passing through work zone, taking detour, or operating under normal conditions.

Because traffic volume is an important determinant of traffic delay, estimating future trends of traffic can play a large role in determining the environmental impacts of construction and rehabilitation projects. This will be addressed in the sensitive analysis.

4.2.5 Usage Module

The usage module focuses on the fuel consumptions and pollutant emissions due to vehicle operations as well as some other pavement related environmental impacts within the scope period. This section is of great importance and complexity compared with the former modules.

4.2.5.1 Roughness Effect

Only the side effects released by the vehicles due to increased pavement surface roughness are considered within this sub-section. Three major factors pose great influences on the LCA inventory, including: traffic volume, fuel economy, and pavement roughness. The traffic volume factor will be addressed in the sensitive analysis together with the case of congestion module. Similarly, a baseline scenario with zero traffic growth rate is used. The fuel economy is derived directly from the Vision model, which provides the fuel economies for passenger cars and trucks until 2100 (US DOE, 2010). The model presents the fuel economy by a decade interval so a linear interpolation is used if fuel economy of a certain year is desired. In LCA modeling, a fleet on-road average fuel economy is used instead of the ideal one specified by auto manufacturers.

Increasing pavement roughness causes more vibrations and reduces driving speed, and thus increases fuel consumptions and pollutant emissions of vehicles. The IRI is used to describe the level of roughness. No field data are available to describe the IRI development trends in this case study, so the IRI development trends estimated from the MEPDG software are used, as depicted in Fig. 4.2.

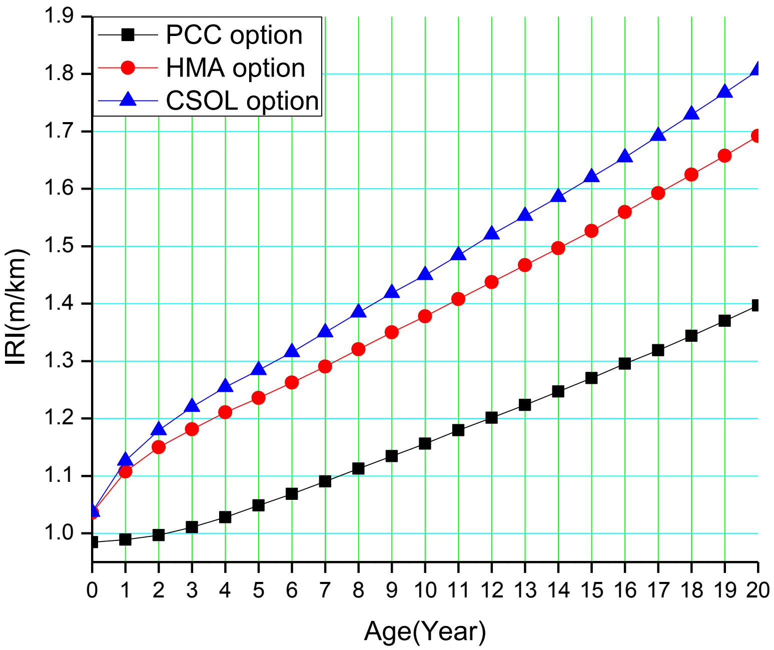


Figure 4.2 Development Trends of IRI as Predicted by MEPDG

Increase of IRI reduces fuel economy, and the relationship was revealed by the findings of Missouri DOT: the fuel economy was promoted from 21.30 mpg to 21.47 mpg for gasoline powered passenger cars, and from 5.91 mpg to 6.11 mpg for diesel powered trucks as the IRI was ameliorated from 2.03 m/km to 0.95 m/km (Amos, 2006). Based on the above data, a fuel consumption factor (FCF) is developed to describe the real fuel consumptions of vehicles driving on pavements with different IRI values, which is estimated by:

$$\begin{aligned} FCF &= 7.377e-3IRI+0.993 \qquad \text{for passenger cars} \\ FCF &= 2.163e-2IRI+0.953 \qquad \text{for trucks} \end{aligned} \tag{4.2}$$

It is assumed that IRI is restored to its initial values when rehabilitation activity of every 16 years is performed. The LCA inventory is calculated as the differences between driving on real pavement and on an ideally smooth pavement.

Besides the influence on fuel economy, increase of IRI reduces the driving speed and thus leads to a reduction of highway capacity. The relationship of IRI and average vehicle speed built in section 3.3 is used here. Under the three IRI development scenarios from Fig. 4.2, the average speed and potential highway capacity reductions are estimated accordingly, which are then reflected into the QuickZone model to estimate the possible delay and amounts of detours. The reduced speed also influences the air pollutant emission rate, as reflected in MOBILE 6.2 model.

4.2.5.2 Pavement Structure Effect

Pavement structures have significant influences on fuel consumptions of vehicles, especially for asphalt pavements as compared with PCC and composite pavements (CSOL option is treated as composite pavement in this case study) (Taylor et al. 2000). The third phase of the study performed by the National Research Council and Cement

Association of Canada (Taylor and Patten 2006) suggested that PCC and composite pavements have phenomenal fuel economy advantages over HMA pavement. Their results are summarized and transformed to be applied to Florida temperature range, as shown in Table 4.5. The concrete pavement is set as the baseline road type. The transformation was carried out by discarding winter season data, applying spring data to winter season, summer data to summer and fall seasons, fall data to winter season in Florida State.

Table 4.5 Fuel Economy Comparisons of Three Pavement Structures

Season	Winter		Spring		Fall		Winter	
For passenger cars								
Pavement type	HMA	CSOL	HMA	CSOL	HMA	CSOL	HMA	CSOL
Comparison (in percent)	3.1	-2.07	-0.42	1.2	-0.42	1.2	-0.42	1.2
For trucks								
Pavement type	HMA	CSOL	HMA	CSOL	HMA	CSOL	HMA	CSOL
Comparison (in percent)	0.86	2.0	1.58	0.9	1.6	-1.34	1.6	-1.34

The additional fuel consumptions are expressed as the differences between the HMA, CSOL pavements and the PCC pavements. And the associated air emissions are calculated following the convention of estimating the air emissions in the sub-section 4.2.5.1.

4.2.5.3 Albedo

Albedo directly contributes to global cooling by adjusting the radiative forcing of the earth’s surface. As a surface covering, pavements can reflect a portion of the incoming solar radiation back into space, thus adjusting the global energy balance. Akbari et al. (2008) estimated that for every square meter, 2.55 kg of emitted CO_2 is offset for every 0.01 increase in albedo due to increased radiative forcing. Eq.4.3 gives the means to calculate the benefit.

$$\Delta m_{co_2} = 100 \times C \times A \times \Delta\alpha \tag{4.3}$$

where Δm_{co_2} is the mass equivalents of CO_2 mitigated (kg); C is the CO_2 offset constant (kg CO_2/m^2); A is the area of pavement (m^2); $\Delta\alpha$ is the change in albedo.

The expected albedo range is 0.05 to 0.20 for a typical asphalt pavement, and 0.25 to 0.46 for a typical concrete pavement (Pomerantz et al. 1998). Aged asphalt pavements tend to have higher albedo, while the opposite is true for concrete pavements (Pomerantz and Akbari. 1997). In this case study, the three plans are compared with the old PCC pavement with an albedo of 0.25. For PCC plan, the albedo is set to 0.35; for HMA and CSOL plans, the albedo values are set to 0.15 (Pomerantz and Akbari. 1997).

4.2.5.4 Carbonation

Over time, much of the CO_2 that was originally liberated from limestone during cement kiln processes will rebind itself to the cement in the pavement through the carbonation process. The carbonation of concrete can be modeled using a simplification of Fick's second law of diffusion (Lagerblad 2006).

$$d_c = k\sqrt{t} \tag{4.4}$$

where d_c is the depth of carbonation (mm); k is the rate factor (mm/y1/2); t is time (year).

A study by Portland Cement Association found the carbonation rate factors of 8.5, 6.7, and 4.9 for concrete with compressive strengths of 21, 28, and 35 MPa, respectively (Gajda 2001). The k value used in this study is 6.3 via linear interpolation.

However, not all of the calcium in the concrete is expected to bind CO_2 molecules; the binding efficiency is suggested to be roughly 75% (Stolaroff et al. 2005). The mass of CO_2 sequestered is given by Eq. 4.5.

$$m_{co_2} = d_c \times A \times \rho_{concrete} \times m_{cement/concrete} \times \frac{M_{co_2}}{M_{CaO}} \times \varepsilon \tag{4.5}$$

where m_{co_2} is the mass of CO_2 sequestered through carbonation (kg); d_c is the depth of carbonation (m); A is the surface area of pavement (m^2); $\rho_{concrete}$ is the density of concrete (kg/m^3); $m_{cement/concrete}$ is the mass ratio of cement in concrete; M_{co_2} is the molar mass of CO_2 (44g/mol); M_{CaO} is the molar mass of CaO; ε is the binding efficiency of CO_2 to CaO.

4.2.6 EOL Module

Most of the previous studies do not include this module because they deem the pavement structure with indefinite life span which can still provide service as long as rehabilitation and M&R activities are performed. For those considering EOL module, the majority simply landfill the pavement materials.

In the U.S., RAP is routinely used in the new construction of pavements, either in the base course or the surface layer. A survey was performed by Copeland (2011) to investigate the percentage of the RAP usage for all 50 States as well as Ontario, Canada. According to the survey results, the majority of U.S. State DOTs allow the use of RAP in HMA mixtures, ranging from 10 to 30 percent, and very few States allow little or no RAP due to performance concern. However, RAP is typically allowed in subsurface, base and shoulder mixtures but may be restricted in surface/wearing course (Copeland, 2011). The national average RAP usage is estimated to be 12 percent in HMA and less than half of State DOTs use more than 20 percent RAP.

In the 2009 NCDOT survey, two most cited reasons that limit or preclude the usage of RAP in HMA are: quality of the blended virgin and RAP binder, and stiffening of mix and the resulting cracking performance. The long term performances of HMA mixed with RAP, compared to the virgin HMA performance, have been supported by some field data but not yet been fully disclosed. Paul (1996) collected field performance data of RAP sections contained 20-50 percent RAP and conventional HMA pavements that are 6-9 years old. He found no significant difference in terms of pavement conditions and serviceability ratings between the two categories.

National Center for Asphalt Technology (NCAT) initiated a study comparing the performances of virgin and RAP pavements using data from long term pavement performance (LTPP) program (NCAT, 2009). The selected sections range from 6 to 17 years old. The distress parameters include rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling. Statically analysis shows that no significant differences are observed between the virgin and RAP sections except for the fatigue, longitudinal cracking, and transverse cracking, where the former sections perform slightly better overall than the later sections.

Hong et al. (2010) also investigated the LTPP test sections in Texas with 35 percent RAP and concluded that, the RAP pavements with 35 percent RAP, if properly designed, can perform well and as satisfactorily as virgin HMA pavement for a normal pavement life span. More relevant studies about the performance investigations of RAP pavement can be found in Zaghloul and Holland (2008), Musselman (2009), and

Carvalho et al. (2010). In summary, no significant performance differences between RAP pavements and virgin HMA pavements are observed. Thus, the recycling and usage of RAP will mainly be reflected in the material module and ignored in the usage module in the sensitivity analysis.

Other questions that bother are: what additional process needs to be done before the RAP can be fed into the plant and what special requirements need to be satisfied during the mixing process? RAP can be collected from various sources, either from milling, full-depth pavement removal, or waste HMA materials generated at the plant. Milling process involves grinding, picking up, and loading RAP into a truck for transportation. Generally, RAP from milling process is very consistent and can be used in the new mixes without further screening or crushing, saving processing cost (Copeland, 2011). And the majority of State DOTs do not place restrictions on the use of RAP in certain plant types (Copeland, 2011). In this sense, the additional environmental burdens of mixing RAP collected from the milling process are ignored.

Reclaimed concrete material (RCM) is generated from the demolition of PCC pavements and consists of high-quality, well-graded aggregates (usually mineral aggregates), bonded by a hardened cementitious paste. RCM can be used as an aggregate for cement-treated or lean concrete bases, a concrete aggregate, an aggregate for flowable fill, or an asphalt concrete aggregate (FHWA, 2008). However, mixing over 20 percent RCM aggregates into the concrete mix decreases the quality of concrete because high amounts of water are required to maintain sufficient workability of concrete mix (FHWA, 2008).

Based on the above reasoning, two recycling scenarios are tested: recycling 10 percent and 20 percent RAP and RCM into the HMA, PCC and CSOL options. The inclusions of recycled materials are reflected by the energy demand reduction in material module.

4.2.7 Life Cycle Assessment Results

The inventories of the three overlay systems over a 40-year life span are obtained from previous sections, including energy consumption, GHGs, and other air pollutant emissions.

4.2.7.1 Energy Consumption

As reflected in Table 4.6 and Fig. 4.3, the total energy consumed for 1 km of PCC, HMA, and CSOL overlays are 61 TJ, 129 TJ, and 101 TJ, respectively. That is, the HMA and CSOL options consume 109 and 65 percent more energy as compared with the PCC option. The energy consumptions for the three options are all dominated by the material, congestion, and usage modules. If usage phase is not considered, as many previous studies did, the energy consumptions for the PCC, HMA, and CSOL options witness a reduction of 40, 50, and 44 percent. Feedstock energy is treated as separate component and occupies a significant portion of the total consumed energy. It will significantly reduce the energy consumption for the HMA and CSOL options if not counted. However, the table information does not give the final suggestions because of great uncertainties are introduced during the modeling process.

4.2.7.2 Greenhouse Gas Emissions

GHG emission inventory in this LCA study includes CO_2, CH_4, and N_2O. The global warming impact is expressed as GHG emissions in tonne of CO_2 equivalent. This is calculated by multiplying the mass of each GHG emission by its GWP. Specifically, GWP is 1 for CO_2, 23 for CH_4, and 296 for N_2O (Houghton 2001). Fig. 4.4 shows the global warming impact of each overlay system. GHG is dominated by the material, congestion, and usage modules for all the three pavement rehabilitation options. It looks like GHG emissions from the usage phase are overwhelming for the HMA and CSOL, which can be explained by the following reasons: firstly, carbonation gives credit to the PCC overlay which offsets certain amount of CO_2 while the HMA and CSOL option cannot enjoy this benefit; and secondly, albedo brings benefits to the PCC option as compared with the HMA and CSOL options since PCC overlay has a lighter color, and thus reflects more heat back to air. But still, this needs to be examined in the sensitivity analysis. For the three GHGs, CO_2 dominates, sharing more than 90 percent fraction.

Table 4.6 Inventories of the Three Alternatives

Input-output		Energy (GJ)		CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
		Primary	Feedstock								
PCC	Material	12709	NA	1219	659	4	111	2194	14118	3168	1158
	Construction	285	NA	18	16	0.3	28	308	141	16	12
	Congestion	11274	NA	759	-	-	877	-2908	-27414	116	1
	Usage	37083	NA	1863	-	-	3057	3376	73470	55	59
	EOL	100	NA	13	8	0.2	5	44	17	4	3
HMA	Material	13958	39034	930	2247	1	205	1994	199	64	879
	Construction	342	NA	73	21	0.4	37	412	183	33	16
	Congestion	10792	NA	726	-	-	1103	-1625	-15291	67	3
	Usage	64688	NA	4964	-	-	4814	5343	115670	85	92
	EOL	143	NA	37	7	0.14	22	297	168	22	8
CSOL	Material	9539	26668	636	1535	1	140	1362	136	44	60
	Construction	192	NA	50	10	1	26	323	148	25	11
	Congestion	8190	NA	551	-	-	1104	-1625	-15291	67	3
	Usage	56419	NA	4340	-	-	4767	5227	115215	86	92
	EOL	79	NA	21	4	0.1	12	165	93	12	5

Note: The empty entry means that the item is not within outputs of the specific models and thus a zero value is assigned. This will not influence the results significantly because CO_2 emission is three orders bigger than other GHGs.

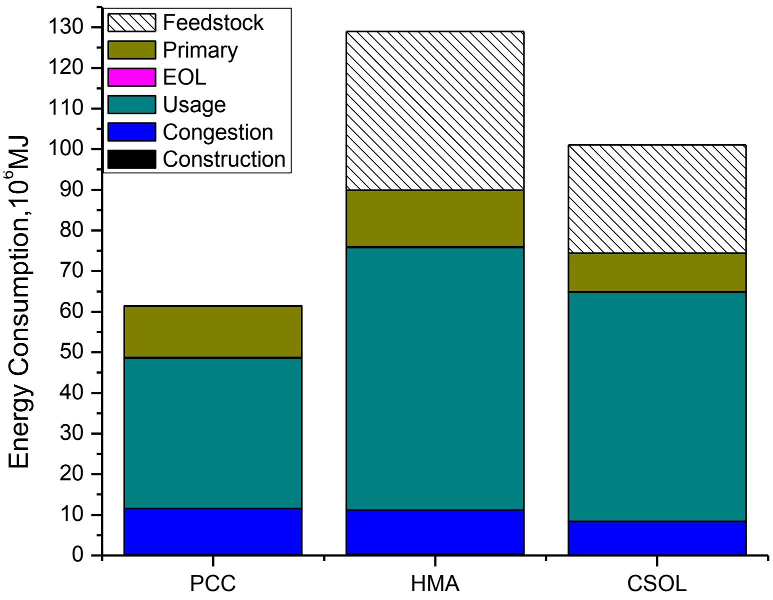


Figure 4.3 Total Energy Consumption by Life Cycle Module

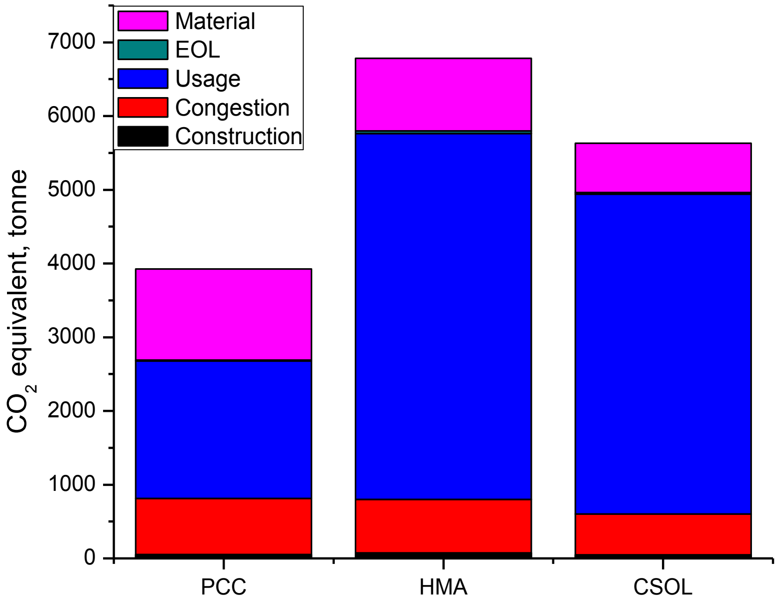


Figure 4.4 Greenhouse Gas Emissions by Life Cycle Module

4.2.7.3 Other Air Pollutants

The air pollutant emissions other than GHGs in this LCA case study include: VOC, NO_x, CO, PM_{10}, and SO_x, as depicted in Fig. 4.5.

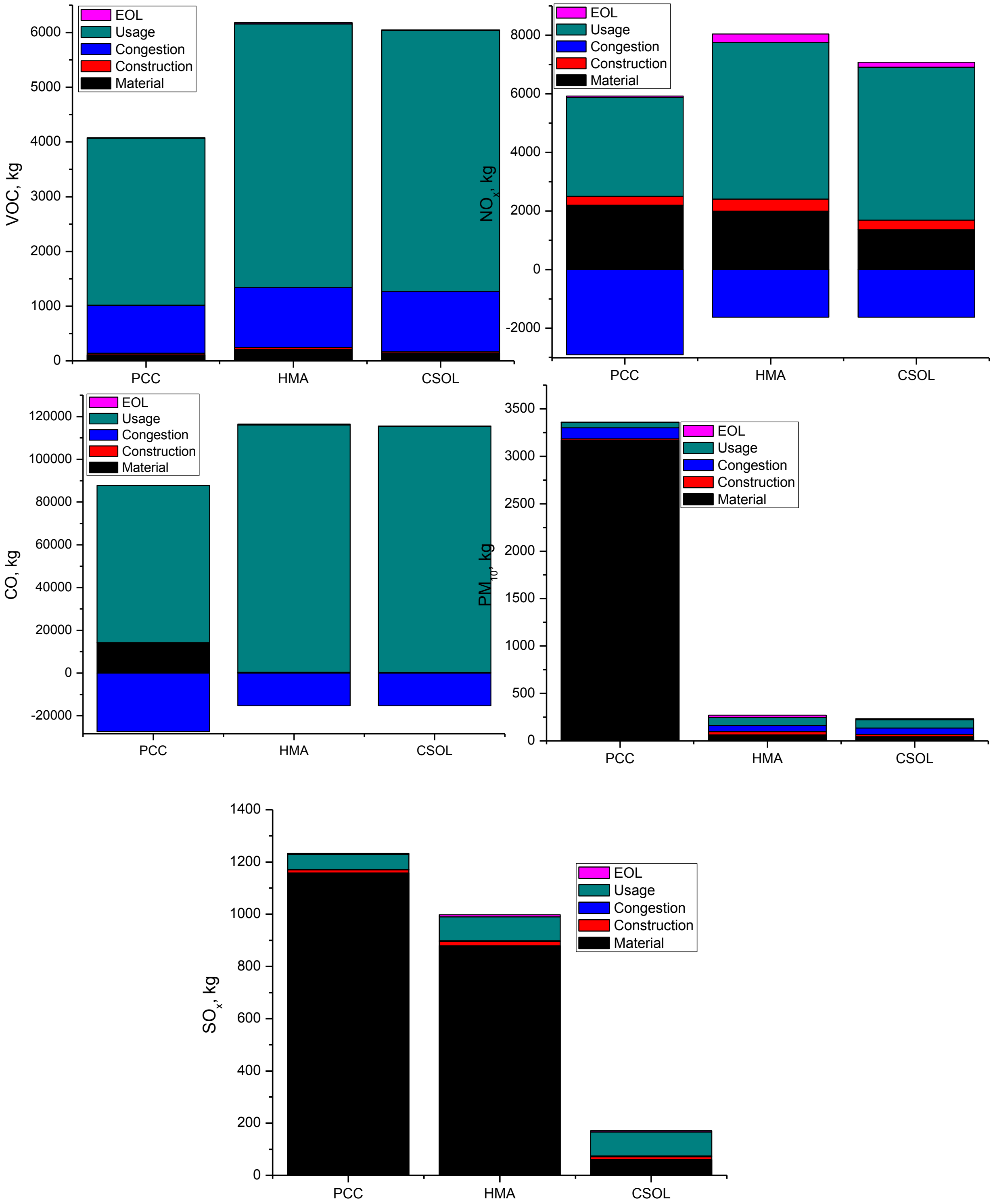


Figure 4.5 Air Emissions by Life Cycle Module

For VOC and CO, congestion and usage modules dominate the air emissions, whether in a positive or negative way. For NO$_x$, material, congestion, and usage modules overwhelm the other two to contribute most. The emissions of NO_x and CO show negative values for congestion module. The reason is the emission rates of NO_x and CO are higher at low speeds than those at high speeds while the fleet speed decreases significantly during construction periods (Sher 1998). The amount of PM_{10} emission from the PCC option is substantially higher than that of the HMA and CSOL options which shall be ascribed to the fact that production of cement produces tremendous amount of particle matters. For SO_x, material module shares a dominating portion while usage module, unlike for other air emissions, is not the major source. New regulations requiring sulfur content in diesel fuel to be significantly reduced to 15 ppm by 2010 and to 30 ppm in gasoline by 2006 may account for this finding (EPA 2009, Gasoline Sulfur Standards, 2002).

4.2.7.4 Sensitivity Analysis

The LCA model in this study consists of various models and employs some critical assumptions, and thus may introduce significant level of uncertainties. Those assumptions, including traffic developing pattern, fuel economy improvement, and recycling percentage, may greatly influence the LCA inventory and deserve further evaluation.

The traffic growth rate in the baseline scenario is set to zero percent, while in reality traffic growth may significantly affect the fuel consumptions and air pollutant emissions. Several traffic scenarios with various annual growth rates were selected to investigate their impacts on fuel consumptions. The results are shown in Figure 4.6. Only traffic related fuel consumption are discussed here, including the congestion module and the usage module.

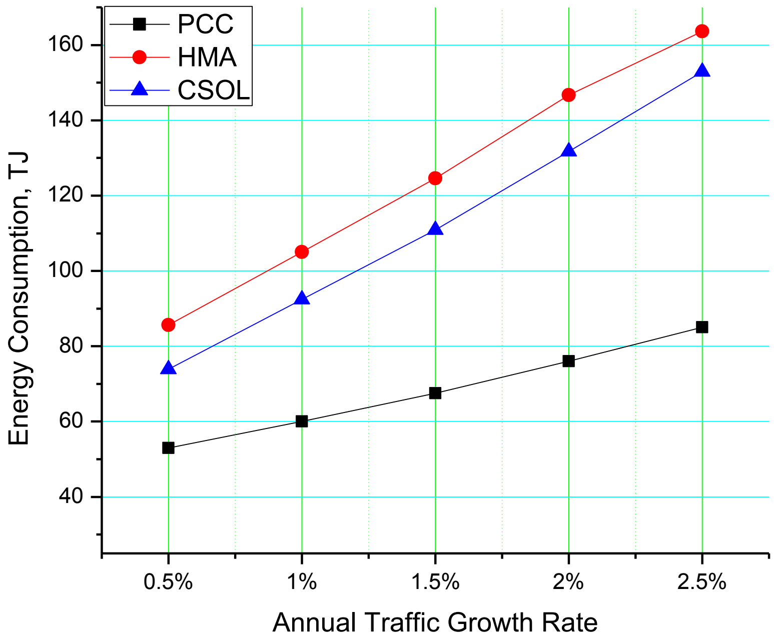


Figure 4.6 Sensitivity of Traffic Related Energy Consumptions due to Traffic Growth

As can be seen, at various annual traffic growth rates, traffic related energy consumption increases significantly, almost following a linear mode. The slopes of the HMA and CSOL options are much steeper than that of the PCC option, which suggest that the former two options are more sensitive to traffic growth. It needs to be addressed here that, at the 2.5 percent traffic growth rate, the queue length in congestion module at the 32nd year reaches 12.0 mi, which is less likely to occur in reality. This abnormity on one hand suggests the inability of the model to account for the potential increase of highway capacity, and on the other hand hints that a road expansion may need. However, this does demonstrate that the energy consumption (as well as GHG emission although not presented here) is very sensitive to congestion module and could increase significantly under a high traffic growth rate scenario.

Fuel economy is also a critical factor influencing the traffic related energy consumption. In the previous LCA steps, the fuel economies for passenger cars and trucks are derived from the Vision model which has considered the fuel economy improvement scenario (US DOE, 2010). Here, the baseline scenario is set to a zero fuel economy improvement and the fuel economies use 2010's values. Three alternatives, with one percent annual fuel economy improvement, hybrid technology, and two percent annual fuel economy improvement, are studied to measure the impact of the fuel economy parameter. The impact of gasoline internal combustion engine (ICE) hybrid vehicle revealed by Heywood et al. (2004) is used. The results are plotted in Figure 4.7. For traffic related energy consumption, fuel economy improvement of two percent annually brings a fuel reduction of 26, 27, and 28 percent for the PCC, HMA, and CSOL options, respectively.

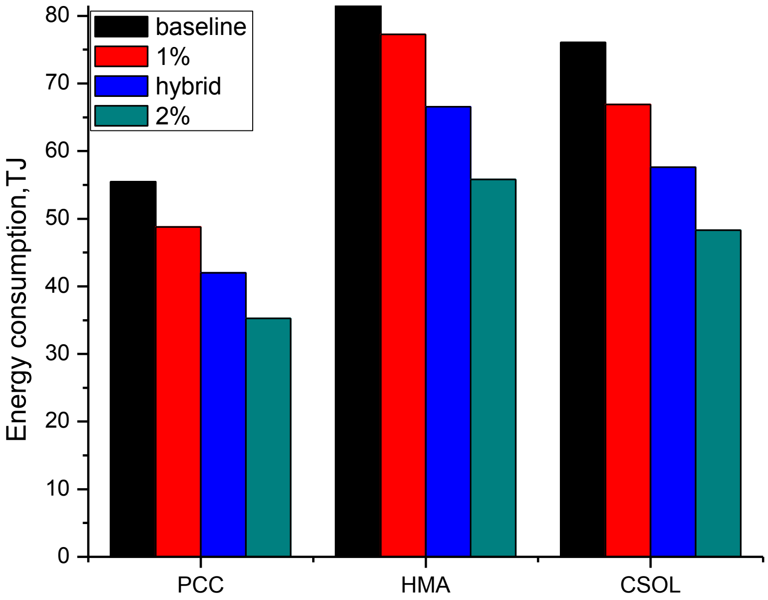


Figure 4.7 Energy Consumption Based on Different Fuel Economy Improvement Scenario

The hybrid vehicle seems to be a promising technology to greatly reduce the fuel consumption in the congestion and usage modules. The marketing share is one of the key factors that determine the energy savings introduced by the hybrid vehicle technology. A further investigation on the impact of hybrid vehicle market share is performed.

Currently, the adoption rate for the hybrid technology is small (under 3 percent of new car sales in the U.S. for August 2010) (HybridCars website, 2010). And estimation of the future market share of the hybrid vehicles varies widely, from never over 10 percent of the U.S. auto market (Marketwatch website, 2010) to domination of the new car sales in the U.S. and elsewhere over the next 10 to 20 years (AllianceBernstein, 2006). Therefore, following the convention of Heywood et al. (2004), three cases of market penetration scenarios are assumed, as listed in Table 4.7.

Table 4.7 Three Market Share Scenarios of Hybrid Vehicles

Year	Low	Medium	High
2010	1%	3%	5%
2020	13%	27%	40%
2030	25%	50%	75%
2040	25%	50%	75%
2050	25%	50%	75%

These scenarios are tested for their impacts on the energy consumptions of the three options, as revealed in Fig. 4.8.

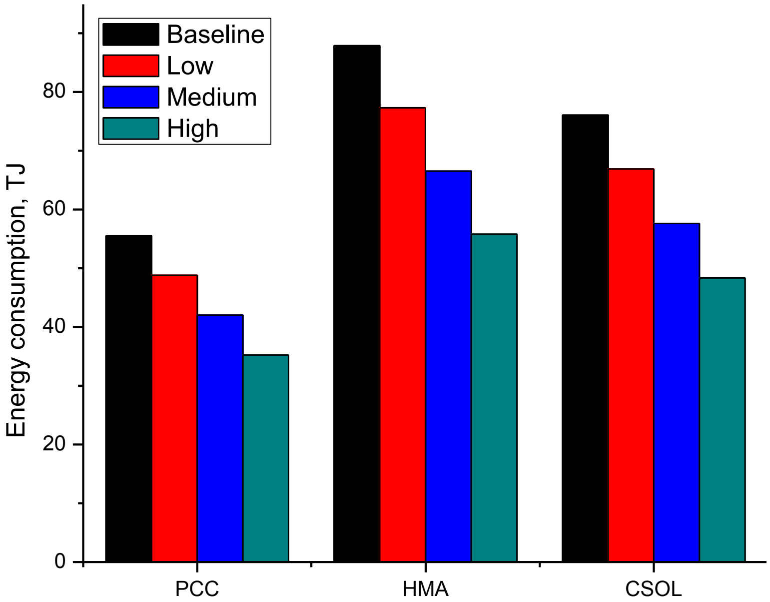


Figure 4.8 Energy Consumption Based on Different Hybrid Vehicle Market Penetration Scenarios

As revealed in Fig. 4.8, the increased market share of hybrid vehicles reduces the traffic related energy consumption greatly. For the low, medium and high market share scenarios, the energy consumption are reduced by 12.1%, 24.3, and 36.5%, respectively. The popularization of hybrid vehicles, therefore, is desired but subject to other factors, such as government policy, sale price, and maintenance fee, etc.

Material recycling is also investigated in the sensitivity analysis. As stated in section 4.2.6. Two scenarios, 10 percent and 20 percent recycling portion, are studied, with the results plotted in Fig. 4.9.

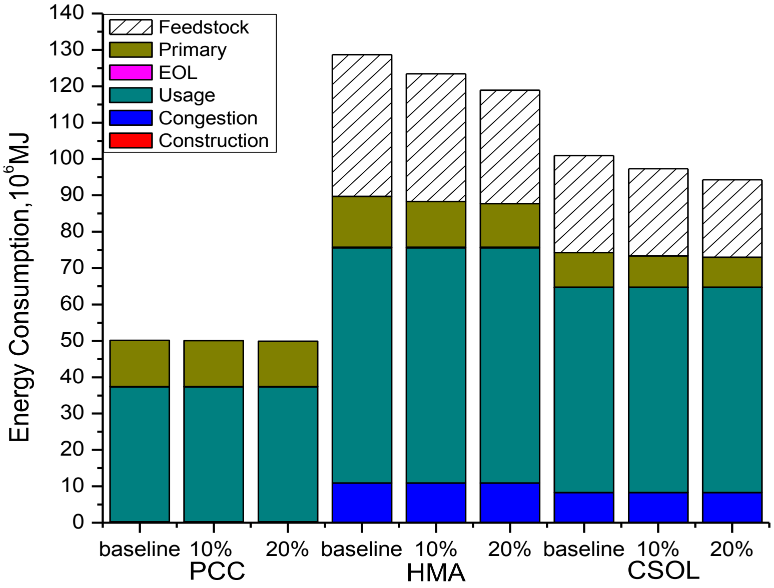


Figure 4.9 Benefits of Recycling Waste Materials

Recycling PCC to substitute aggregates in base course layer brings almost negligible energy consumption reduction. However, it will save plenitude of landfill space and thus bring environmental benefits. Recycling 20 percent of old HMA into new paved overlay reduces the energy demand from material modules significantly.

Usage module contributes dominantly to the LCIs but carries uncertainty which may significantly alter the results. Influenced by many factors, such as chemical composition of the concrete, pavement structural dimensions, and the ambient environment, the carbonation process can take from years to millennia to complete (Damtoft et al. 2008). For the extreme low scenario, no carbonation is expected for the PCC option; for the extreme high scenario, an 8.5 mm/y½ of carbonation rate is used (Gajda 2001).

Albedo brings advantage to the PCC option but disadvantage to the HMA and CSOL options at the selected albedo values. Actually, albedo tends to have a broad range for typical concrete pavement and asphalt pavement, being 0.27-0.58 and 0.12-0.46, respectively (Pomerantz 1997). Extreme cases are calculated accordingly.

Pavement structure influences fuel consumption and air emissions of vehicles greatly. However, research conclusions regarding the comparison of different pavement structures also vary greatly. Through literature review, the possible ranges of additional fuel consumption for asphalt and composite pavements versus concrete pavement are listed in Table 4.8. Extreme values in the table are used to calculate the range. The above three “what-if” calculations are plotted in Fig. 4.10.

Table 4.8 Fuel Economy Comparisons between Asphalt, Composite and Concrete Pavement

Number	Asphalt versus Concrete (in percent)		Composite versus Concrete (in percent)		Sources
	Passenger car	Heavy trucks	Passenger car	Heavy trucks	
1	0	20	NA	NA	Zaniewski (1989)
2	NA	0.2-4.9	NA	-1.1-3.2	Taylor(2002)
3	-0.3-2.9	0.8-1.8	-2.3-1.5	-1.5-3.1	Taylor(2006)
4	0.05-0.88	0.05-0.88	NA	NA	Beuving et al. (2004)

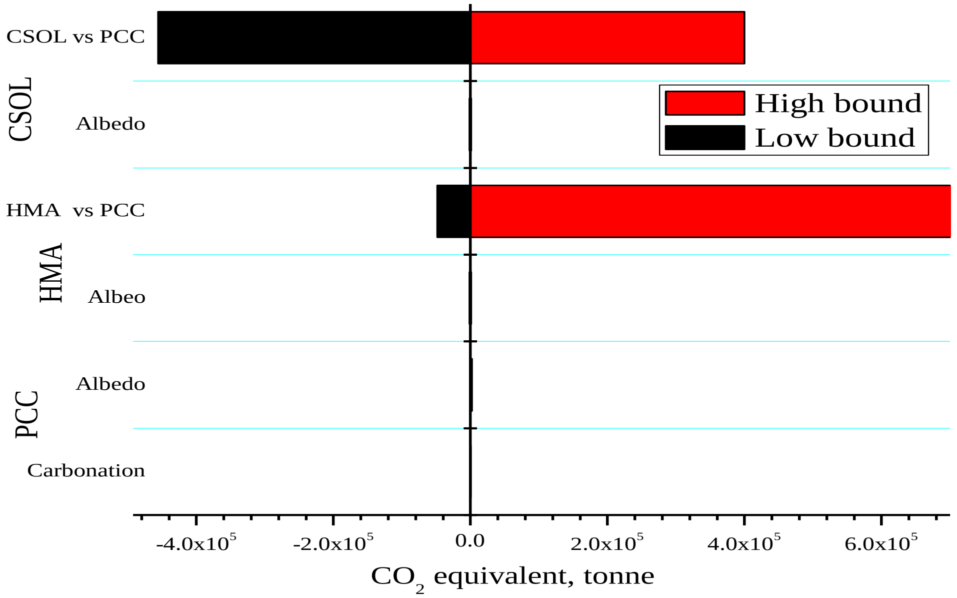


Figure 4.10 Uncertainty Ranges of Carbonation, Albedo and Pavement Structure Effects

Observations of Figure 4.10 suggest: firstly, the effect due to the albedo and carbonation effects are completely overwhelmed by the pavement structure effect; secondly, colossal uncertainties are associated with the pavement structure effect; and thirdly, the low bound and high bound for the “CSOL vs. PCC” bar is approximating while the high bound is orders larger than the low bound for the “HMA vs. PCC” bar. In this sense, it is fair reasonable to expect less environmental burdens from the PCC option as compared with the HMA option while quite skeptical about the same conclusion if compared with the CSOL option. In simple words, more evidence is needed to differentiate the PCC option from the CSOL option.

4.2.8 Summary

For the proposed LCA methodology, a detailed case study of the three overlay options, PCC, HMA and CSOL option, over the old PCC pavement was performed. Through the study, the following conclusions are obtained:

1. The proposed LCA model is a useful and relatively complete tool to estimate the environmental impacts of pavement, and can be used or modified by the readers.

2. It is reasonable to expect less environmental burdens from the PCC option and CSOL options as opposed to the HMA option while the comparison between the former two is indeterminate due to the great uncertainties associated with usage stage, especially the pavement structure effect.

3. Materials, congestion, and usage modules are the three major sources of energy consumptions and air pollutant emissions, especially usage module.

4. Traffic related fuel consumption is very sensitive to traffic growth and fuel economy improvement. Fuel consumption basically increases linearly with the traffic growth rate.

4.3 Algorithm for Maintenance Optimization

The proposed M&R optimization algorithm, as built in section 3.4, is implemented to validate the effectiveness.

4.3.1 Cost Constitution

Traditionally, the M&R maintenance schedule optimizations are determined based on the goal of minimizing the agency cost and user cost subject to the pavement condition constraint while EDC seldom appear in the DOTs' manuals. In this study, it is added as another cost element and the holistic cost consists of agency cost, user cost, and EDC. The agency cost is the investment from the DOTs to perform the construction and maintenance activities. For the case study, Table 4.9 lists the breakdown items of the involved construction activities.

Table 4.9 Agency Cost Breakdown for Overlay Construction and M&R Activities

Item	Bid price	Source	Note
Roadway excavation	\$10.38 per m^3	(Caltrans 2010)	Avg. of 2010 year
PCC	\$160.64 per m^3	(Caltrans 2010)	Avg. of 2010 year
HMA	\$88.47 per tonne	(Caltrans 2010)	Avg. of 2010 year
Bar reinforcing steel	\$1.579 per kg	(Caltrans 2010)	Avg. of 2010 year
Diamond grinding	\$2.00- \$8.00 per m^2	(FHWA, 2012a)	Avg. value is used
Mill and fill	\$66875 to \$151560 per lane-km	(FHWA, 2012b)	Avg. value is used

User cost is an aggregation of user delay cost and vehicle operation cost. The user delay cost is obtained by multiplying the unit price of time and the additional time that vehicles wait in the queue, pass through working zone or taking detours, etc. The average unit prices for passenger cars, single unit trucks, and combination trucks are $10.20/h, $19.62/h, and $24.63/h, respectively, as supplied in the report by Kentucky Transportation Center (2002). The value is in 1998 price and updated to 2010 price through consumer price index. The user delay can be calculated using the delay time from QuickZone model. However, the accident rate and fatality increase during construction and maintenance periods as opposed to the normal conditions and the resulting increase of damage cost are purposely missing in this study since great uncertainties are found about the unit cost and occurrence rates.

Vehicle operation cost accounts for the additional fuel consumption when vehicle drives through working zone or on a deteriorated pavement surface. The additional fuels induced by abnormal driving behaviors due to construction and maintenance activities are estimated by the congestion module of the LCA model. The roughness of the overlay increases gradually with the time and the trends for the three overlay options are depicted in Fig.4.2 by the MEPDG software. And the additional fuel consumption is the difference of the true fuel consumption driving on real pavement, as calculated by Eq.4.2, and the ideal fuel consumption driving on ideally smooth pavement. The fuel price is determined as \$2.76/gallon for ten-year average. The analysis period is 40 years and the discount rate is selected to be 4% as recommended by the U.S. Office of Management and Budget.

EDC is a summation of products of quality of air pollutants and the corresponding MDCs. For the original maintenance plans, the air pollutant inventories are listed in Table 4.6. The MDCs for each pollutant are estimated in Section 3.2.2 and listed in Table 3.16. Contrary to a constant discount rate of agency cost and user cost, the EDC is discounted at a sliding rate due to the long term effects of atmospheric pollutants. A gamma discounting approach proposed by Weitzman (2001) is used: for the immediate future (years 1–5), the discount rate is 4%; for the near future (years 6–25), the discount rate is 3%; and for the medium future (years 26–75), the discount rate is 2%, as discussed in Section 3.2.1.

And the IRI's trend in Fig.4.2 is used to form the transition matrix and then fed into the proposed algorithm to optimize the maintenance activities. If no maintenance activity is implemented, the IRI increases or restores to its initial value when maintenance activity is performed.

4.3.2 Before and After Optimization Results Comparison

The proposed algorithm linking LCA and LCCA was performed in the context of the case study. And the optimized maintenance schedules are presented in Fig.4.11 as opposed to the original M&R plans in terms of the objectives of minimizing the life cycle energy consumptions, GHGs emissions and holistic costs.

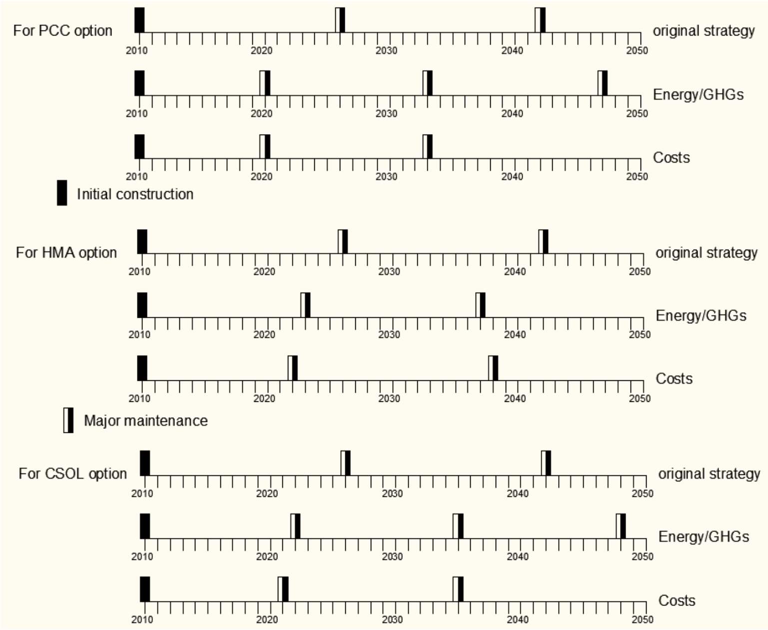


Figure 4.11 Optimized Maintenance Schedule for the Three Overlay Designs

As can be seen in Fig.4.11, compared with the original maintenance plans, the optimized schedules increase the maintenance frequency for the PCC option and CSOL options and advance the maintenance plans of the HMA option for the energy/GHGs objectives. For the cost objective, the maintenance plans remain the same frequency but are performed ahead of original strategies. This suggests that it is preferred to treat the pavement early than later. Also, the energy/GHGs objectives demand more maintenance frequency for the PCC option and CSOL options than the cost objective, which is attributed to the great portion of user delay cost among the user cost. More maintenance activities increase the user delay cost significantly, which cannot be sufficiently compensated by the savings of fuel consumption.

The comparisons of the before and after optimization results either in terms of energy/GHGs, or costs, are presented in Fig.4.12.

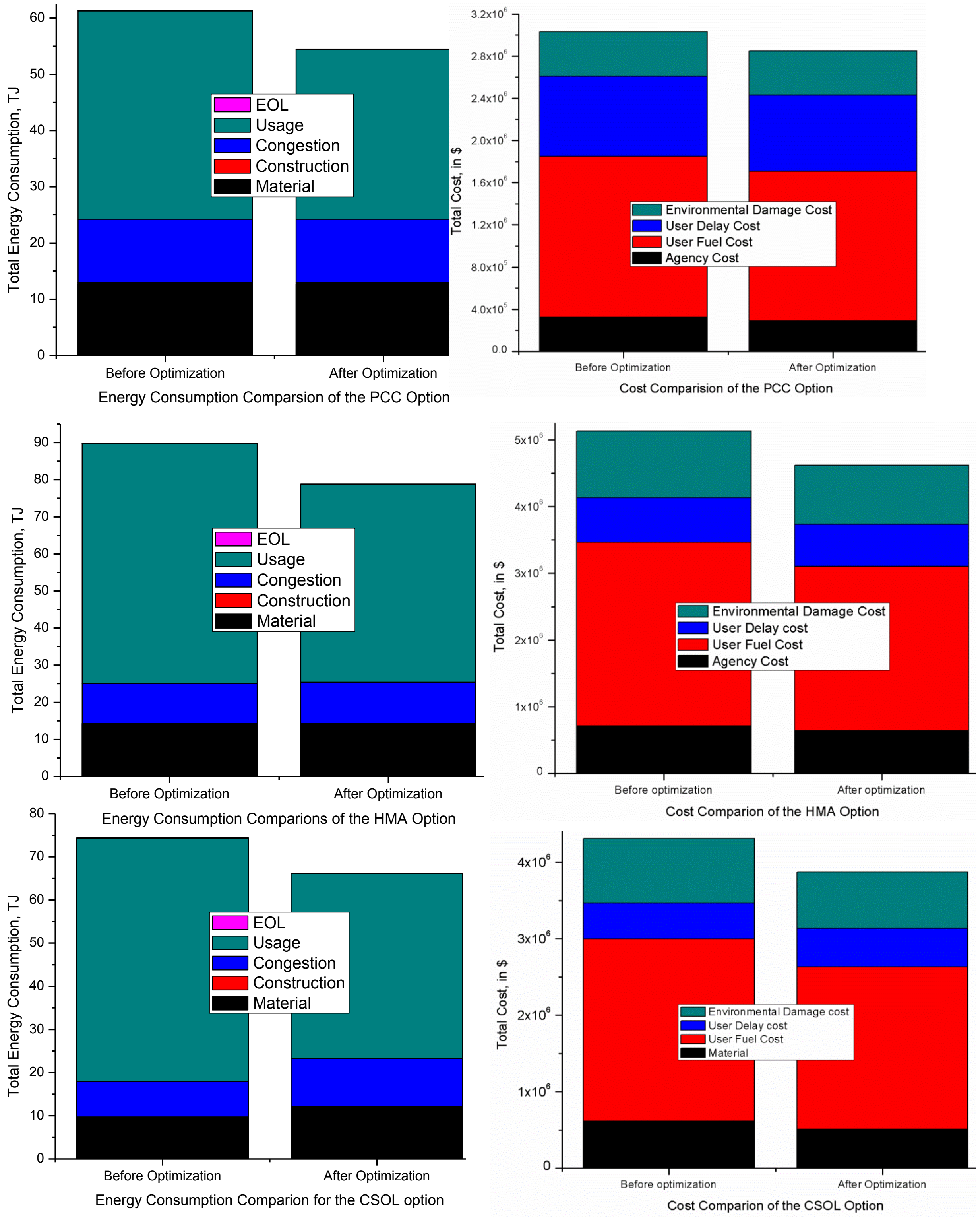


Figure 4.12 Comparisons of the Before and After Optimization Results in Terms of Energy Consumption and Costs for the Three Overlay Options

As can be seen in Fig.4.12, the proposed algorithm proves to be effective in optimizing the maintenance schedules to reduce both the energy consumption and the total cost. The obtained reductions in energy consumption and cost for the three overlay designs are 10.9, 12.3, 8.2 percent and 5.9, 10.0, 10.2 percent, respectively. Also, EDC for the three overlay designs occupy a considerable portion of the cost constitutions which demonstrates the effectiveness and necessity of the incorporation of EDC into the cost evaluation system. User cost is the dominating factor, among which user fuel consumption provides the major contribution. However, as suggested by previous studies (Zhang et al 2010a; Wilde et al, 2001) and found in this study, user delay cost is also a significant contributor. How to optimize the construction and maintenance activities to reduce their durations and impacts on the neighboring traffics and thus reduce the user delay cost is a promising research area. For the three overlay designs, the estimated overall costs for the 40-year analysis period are $\$2.85\times10^6$, $\$4.62\times10^6$, and $\$3.87\times10^6$, respectively. Furthermore, it seems that a rank of PCC<CSOL<HMA can be inferred in terms of cost-effectiveness. However, this inferring should be further examined since great uncertainties are introduced in the modeling and optimizing processes.

4.3.3 Sensitivity Analysis

Again, the uncertainty range in terms of CO_2 as well as fuel consumption in the congestion and usage modules, which is closely related to the EDC, is partially reflected in Fig.4.10. The lower bound and upper bound for the “CSOL vs. PCC” bar are similar while the upper bound is orders of magnitude larger than the lower bound for the “HMA vs. PCC” bar. In this sense, it is expected to harvest a less environmental burden and cost from the PCC option as compared with the HMA option while quite skeptical about the same conclusion if compared with the CSOL option.

4.3.4 Limitations

The proposed algorithm aims to integrate the LCA and LCCA models to obtain the improved maintenance optimization with the consideration of EDC. Despite the efforts above, the algorithm can be further augmented at the following aspects:

1. The case study only considers the major maintenance activities while ignores the minor ones. One can easily update the algorithm to incorporate more maintenance scenarios by adding more elements to the maintenance decision variable.
2. Roughness development model is significant to the LCIs and cost calculation which uses the result by MEPDG software in this study. An experimental or empirical model under the reader's circumstance is welcome to substitute the transition matrix in the algorithm.
3. Substantial uncertainties are found in various models, like the relationship between fuel economy and roughness, albedo, carbonation, and pavement structure. Their influences over the LCIs and resulting costs are significant. More reliable models describing the listed items are in urgent need.
4. Some other factors that contribute to the LCIs are not referred, such as lighting requirement, noise and leachate. One can add them and evaluate the associated cost if feasible.

4.3.5 Summary

This section integrates the LCA model and LCCA model in order to optimize the pavement maintenance schedule in terms of either energy consumption/GHGs or costs. After implementing the algorithm, the optimized maintenance schedules gain a substantial reduction in terms of energy consumption and holistic cost compared to the before optimization plans. For the three overlay designs, great uncertainties exist in the LCIs and cost evaluation systems, especially for the usage module. Considering this, it is reasonable to expect less environmental burden and holistic cost from the PCC and CSOL options as opposed to the HMA option while the comparison between the former two is undetermined. More suggestions from the case study are summarized as: the energy/GHGs objectives demand more frequent maintenance activities than the cost objective, but they all prefer an early maintenance implementation that later. The tradeoffs between material consumption, traffic congestion, and pavement surface roughness effects on the fuel consumption and the EDC are possible explanations. For the proposed model, it is a promising optimization tool that will provide a more comprehensive cost evaluation methodology but still has a great potential to be improved.

CHAPTER 5: EVALUATION OF 20- AND 40-YEAR PAVEMENT DESIGNS

5.1 Introduction

This chapter aims to evaluate several common pavement designs in the U.S. The design factors are pavement type, traffic volume, and design life. Both flexible and rigid pavements are considered, including HMA, JPCP, and CRCP, with design lives of 20-year and 40-year. Traditionally, the design period of pavements is limited to 20-year or less, although many existing pavements still function over the design life under timely maintenances. Driven by the design, material, and construction technology developments, it is a natural idea to consider extending the pavement design life, such as 40-year design and even 100-year design. The motivation in favor of long term pavement design is the assumption that small increase of pavement thickness leads to longer pavement service life and thus a relatively small marginal cost of long term pavement design compared to regular designs. However, while the reliability of the assumption about the economic advantages has not been fully verified, the environmental drawbacks or benefits of long term pavement designs are rarely considered. Actually, a recent study by Rawool and Pyle (2008) indicated that a long term pavement design (100-year) does not necessarily enjoy economic benefits after considering the discount rate. While both 100-year and 40-year designs demonstrate to be economic saving compared to the 20-year designs, the differences between the former two designs are negligibly small. Although the study is not conclusive about the economic comparisons, it does trigger the research interests of the environmental impacts of the normal pavement designs and long term pavement designs, which may sway the initial preference of long term pavement designs.

5.2 Objective and Scope

The LCA studies of various commonly adopted pavement designs in the U.S. are performed following the procedures of the overlay system case study. Two main objectives are expected:

1. Understand the concrete environment impacts of various pavement designs.
2. Compare the environment burdens of 20- and 40-year designs to support or sway the preference of long term pavements.

The first objective builds the understanding of the level of environmental impact of each pavement design and the second objective provides information to agency about their choices of regular designs and long term designs.

Several commonly adopted pavement types are considered, including HMA, JPCP and CRCP, with pavement design lives of 20-year and 40-year, to evaluate their environmental burdens. The 100-year design is deliberately missing due to great uncertainties associated. For instance, as suggested in the overlay design case study, the traffic delay is a significant contributor while the precise predictions of traffic patterns and delay scenarios for a 100-year range are basically impractical. Three levels of traffic volumes, small, medium, and high, are input as external factors. The typical DOT traffic data are used to describe the three traffic levels. The AADT range is from 80 to 452000. The 25th percentile, 50th percentile, and 75th percentile of AADT values, that is 5600, 20000 and 76000, are deemed as representative values to loosely represent the small, medium, and high traffic levels. The truck percentage range is from 0 to 81.9 percent, and the 50th percentile is 7.2 percent, which is regarded as the truck percentage for the three levels of AADT.

A similar functional unit as the overlay case study in Chapter 4 is used, that is one kilometer pavement section with two lanes in one direction that would provide satisfactory performances over a 40-year period. The widths of the inner paved shoulder, main lanes, and outsider paved shoulder for one direction are 1.2 m, 3.6 × 2 m, and 2.7 m, respectively. It is a reasonable assumption that the AADTs are halved for one direction. Thus, the representative AADTs for the low, medium and high volume traffics for one direction are 2800, 10000, and 38000, respectively, each with 7.2 percent trucks. The AADTs are rough estimates and their effects will be carefully examined in the sensitivity analysis. Under the three traffic levels, each pavement is designed following the AASHTO design guide and verified by the MEPDG software. Detailed design parameters are listed in Table 5.1.

Table 5.1 Pavement Designs of Three Pavement Types, Three Traffics and Two Periods

Pavement Type	AADT, with 7.2% truck	Design Life	Thickness, mm (in)		
			Surface	Base	Subbase
HMA	2800	20	203 (8)	152 (6)	152 (6)
	10000	20	229 (9)	152 (6)	152 (6)
	38000	20	292 (11.5)	152 (6)	152 (6)
	2800	40	229 (9)	152 (6)	152 (6)
	10000	40	254 (10)	152 (6)	152 (6)
	38000	40	318 (12.5)	152 (6)	152 (6)
JPCP	2800	20	216 (8.5)	152 (6)	152 (6)
	10000	20	241 (9.5)	152 (6)	152 (6)
	38000	20	292 (11.5)	152 (6)	152 (6)
	2800	40	229 (9)	152 (6)	152 (6)
	10000	40	279 (11)	152 (6)	152 (6)
	38000	40	330 (13)	152 (6)	152 (6)
CRCP	38000	20	254 (10), 0.7% steel	152 (6)	152 (6)
	38000	40	305 (12), 0.8% steel	152 (6)	152 (6)

5.3 Methodology

The methodology built in Chapter 3 is used to perform the LCA studies, with the detailed executions following the steps of the overlay LCA case study in Chapter 4. Five modules, material module, construction and M&R module, congestion module, usage module, and EOL module, are described separately. The inventories of the environmental burdens include: energy consumption, CO_2, CO, CH_4, NO_x, SO_x, VOC, and PM_{10}.

5.3.1 Material Module

Material module consists of both the materials consumed during the initial construction and in the following maintenance activities. To maintain a neat format, both parts' material consumptions are compiled in single Table, despite that the material consumptions of maintenance activities as well as the maintenance plans are determined in the construction and M&R module. For all the pavement designs, the base course uses cement stabilized aggregate and the subbase uses crushed stone. The environmental impacts of associated materials, such as HMA, PCC, cement, aggregate, and steel, are determined by various sources, including Portland Cement Association (Marceau et al., 2007), the Swedish Environmental Research Institute (Stripple, 2001), the Athena Institute (2006), and the GREET model (version 2.7 for steel production).

Table 5.2 Material Consumptions for the HMA Design (2800 AADT, 20-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone(tonne)	Cement (tonne)	Water (tonne)	HMA (tonne)	Emulsified asphalt[a](m^2)
Initial construction	surface	0	203				5419	33300
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/ mill and fill	surface	32nd	45				796[b]	7200

Note: [a]The emulsified asphalt serves as adhesion membrane before HMA paving; [b] only the main lanes are milled and filled while the two shoulders remain untouched. The same conventions are followed for Table 5.3 through Table 5.13.

Table 5.3 Material Consumptions for the HMA Design (10000 AADT, 20-Year Design)

Phase	Layer	Year	Depth (mm)	Crushed stone(tonne)	Cement (tonne)	Water (tonne)	HMA (tonne)	Emulsified asphalt(m^2)
Initial construction	surface	0	229				6097	33300
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/ mill and fill	surface	28th	45				796	7200

Table 5.4 Material Consumptions for the HMA Design (38000 AADT, 20-Year Design)

Phase	Layer	Year	Depth (mm)	Crushed stone(tonne)	Cement (tonne)	Water (tonne)	HMA (tonne)	Emulsified asphalt(m^2)
Initial construction	surface	0	292				7774	44400
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/ mill and fill	surface	20th	76				1344	7200
	surface	36th	45				796	7200

Table 5.5 Material Consumptions for the HMA Design (2800 AADT, 40-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone(tonne)	Cement (tonne)	Water (tonne)	HMA (tonne)	Emulsified asphalt(m^2)
Initial construction	surface	0	229				6097	33300
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/ mill and fill	surface	32nd	45				796	7200

Table 5.6 Material Consumptions for the HMA Design (10000 AADT, 40-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone(tonne)	Cement (tonne)	Water (tonne)	HMA (tonne)	Emulsified asphalt(m^2)
Initial construction	surface	0	254				6762	44400
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/ mill and fill	surface	30th	45				796	7200

Table 5.7 Material Consumptions for the HMA Design (38000 AADT, 40-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone(tonne)	Cement (tonne)	Water (tonne)	HMA (tonne)	Emulsified asphalt(m^2)
Initial construction	surface	0	318				8503	55500
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/ mill and fill	surface	25th	76				1344	7200

Table 5.8 Material Consumptions for the JPCP Design (2800 AADT, 20-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone (tonne)	Cement (tonne)	Water (tonne)	Ready Mix (m^3)	Dowel Bar (tonne)
Initial construction	surface	0	216				2397	20.6
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/slab replacement	surface	28th	76				844	

Table 5.9 Material Consumptions for the JPCP Design (10000 AADT, 20-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone (tonne)	Cement (tonne)	Water (tonne)	Ready Mix (m^3)	Dowel Bar (tonne)
Initial construction	surface	0	241				2678	20.6
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/ diamond grinding	surface	28th						

Table 5.10 Material Consumptions for the JPCP Design (38000 AADT, 20-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone (tonne)	Cement (tonne)	Water (tonne)	Ready Mix (m^3)	Dowel Bar (tonne)
Initial construction	surface	0	292				3242	20.6
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/diamond grinding	surface	22nd						
	surface	38th						

Table 5.11 Material Consumptions for the JPCP Designs (40-Year Design)

Phase	Layer	Year	Depth (mm)	Crushed stone (tonne)	Cement (tonne)	Water (tonne)	Ready Mix (m^3)	Dowel Bar (tonne)
2800 AADT								
Initial construction	surface	0	229				2538	20.6
	base	0	152	3862	203	193		
	subbase	0	152	3383				
10000 AADT								
Initial construction	surface	0	279				3101	20.6
	base	0	152	3862	203	193		
	subbase	0	152	3383				
38000 AADT								
Initial construction	surface	0	330				3665	20.6
	base	0	152	3862	203	193		
	subbase	0	152	3383				

Table 5.12 Material Consumptions for the CRCP Design (38000 AADT, 20-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone (tonne)	Cement (tonne)	Water (tonne)	Ready Mix (m^3)	Steel (tonne)
Initial construction	surface	0	254				2819	154
	base	0	152	3862	203	193		
	subbase	0	152	3383				
Maintenance/slab replacement	surface	32nd	76				844	

Table 5.13 Material Consumptions for the CRCP Design (38000 AADT, 40-Year Design)

Phase/Strategy	Layer	Year	Depth (mm)	Crushed stone (tonne)	Cement (tonne)	Water (tonne)	Ready Mix (m^3)	Steel (tonne)
Initial construction	surface	0	305				3383	176
	base	0	152	3862	203	193		
	subbase	0	152	3383				

5.3.2 Construction and M&R Module

All the construction activities for the initial construction and the following maintenances are accounted for in this module. Material distributions and construction equipment transportations are also included in this module. Similarly, the construction processes are break down into individual activities and then estimated by the NONROAD model, as is the practice of Table 4.2 through Table 4.4 in Chapter 4. One thing to be emphasized here is that the construction activities for the base and subbase structures are not included since all the pavement designs have the same ones. And the resulting congestion delays are also ignored. The durations of initial construction and subsequent maintenances for each design are estimated by the CA4PRS (version 2.5) software (CalTrans, 2012), with the results listed in Table 5.14.

Table 5.14 Durations of Construction and Maintenance Activities of Various Designs

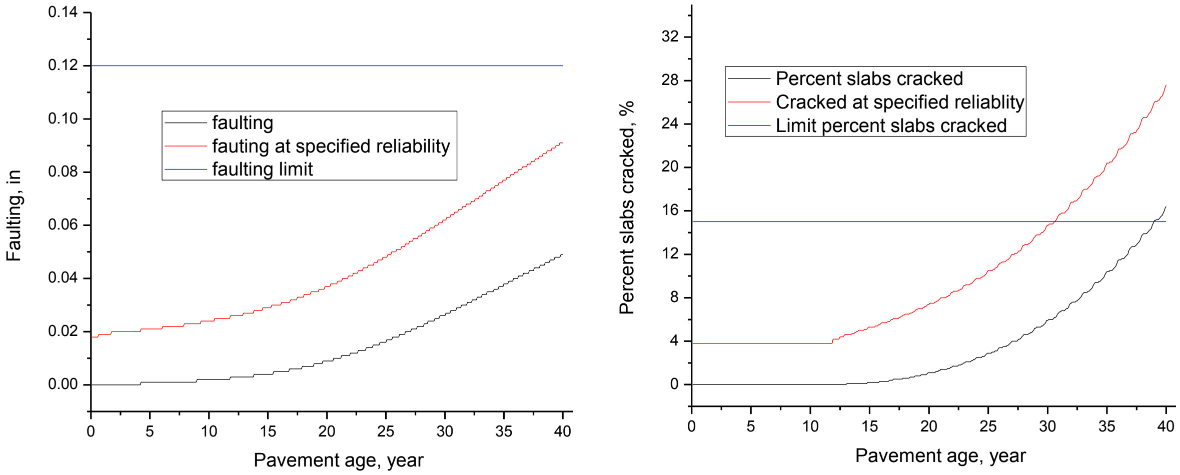
Design	Phase	Durations (d)	Construction window	Working Method
HMA-2800 AADT-20 years	Initial construction	15	Continues closure/shift operations	Full closure
	Maintenance	3	Continues closure/shift operations	Full closure

Table 5.14 (Continued)

Design	Phase	Durations (d)	Construction window	Working Method
HMA-10000 AADT-20 years	Initial construction	17	Continues closure/shift operations	Full closure
	Maintenance	3	Continues closure/shift operations	Full closure
HMA-38000 AADT-20 years	Initial construction	22	Continues closure/shift operations	Full closure
	Maintenance	5+3	Continues closure/shift operations	Full closure
HMA-2800 AADT-40 years	Initial construction	17	Continues closure/shift operations	Full closure
	Maintenance	3	Continues closure/shift operations	Full closure
HMA-10000 AADT-40 years	Initial construction	22	Continues closure/shift operations	Full closure
	Maintenance	3	Continues closure/shift operations	Full closure
HMA-38000 AADT-40 years	Initial construction	25	Continues closure/shift operations	Full closure
	Maintenance	5	Continues closure/shift operations	Full closure
JPCP-2800 AADT-20 years	Initial construction	18	Continues closure/shift operations	Concurrent double lane
	Maintenance	6	Continues closure/shift operations	Concurrent double lane
JPCP-10000 AADT-20 year	Initial construction	20	Continues closure/shift operations	Concurrent double lane
	Maintenance	3	Continues closure/shift operations	Concurrent double lane
JPCP-38000 AADT-20 years	Initial construction	24	Continues closure/shift operations	Concurrent double lane
	Maintenance	3+3	Continues closure/shift operations	Concurrent double lane
JPCP-2800 AADT-40 years	Initial construction	19	Continues closure/shift operations	Concurrent double lane
JPCP-10000 AADT-40 years	Initial construction	23	Continues closure/shift operations	Concurrent double lane
JPCP-38000 AADT-40 years	Initial construction	27	Continues closure/shift operations Continues closure/shift operations	Concurrent double lane

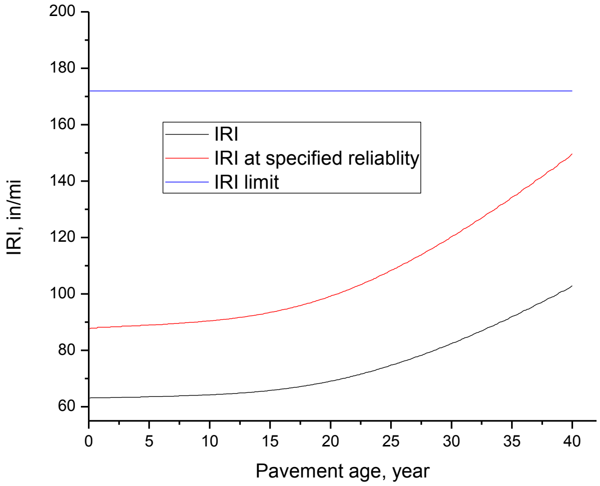
Maintenances act to prolong the regular pavement designs, making them to provide comparative service as long life pavement designs. However, the determination of maintenance pathway is a challenging problem and needs some empirical judgments. The outputs of MEPDG software are the major sources to form the maintenance decisions.

For the JPCP-2800 AADT-20 years design, the distress developing trends are extended to 40-year and plotted, as shown in Fig.5.1.



Faulting developing trend

Slab cracking developing trend

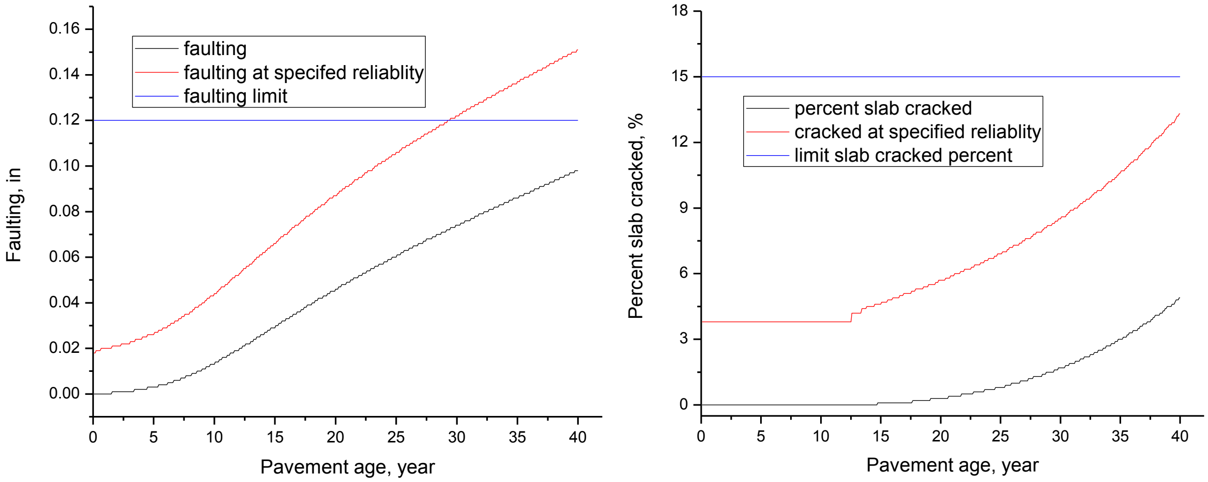


IRI developing trend

Figure 5.1 Distress Developing Trends of JPCP-2800 AADT-20 Years Design

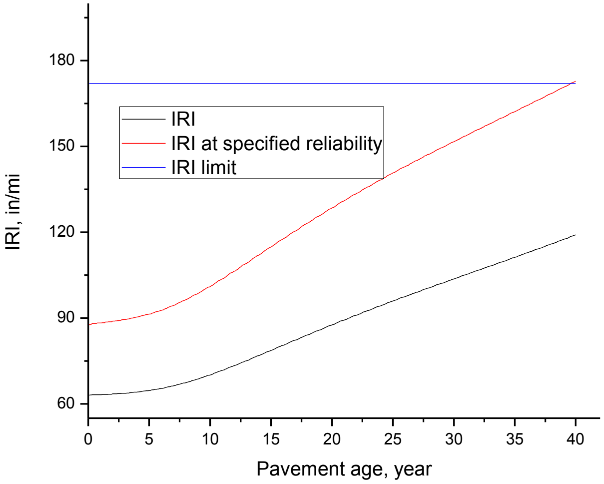
As can be seen in Fig.5.1, out of the three distress indices, the percent of cracked slabs exceeds the limit at the 30th year. According to the experience, an early maintenance activity is preferred than to wait until the limit. Thus a slab replacement (76 mm) is performed at the 28th year.

In a similar fashion, the JPCP-10000 AADT-20 years design is examined, with the distress developing trends plotted in Fig.5.2.



Faulting developing trend

Slab cracking developing trend

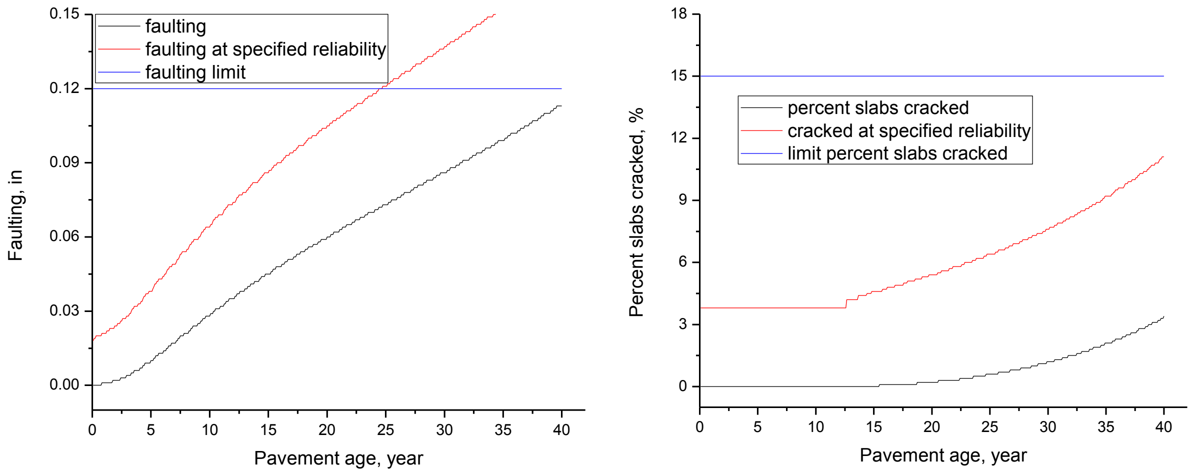


IRI developing trend

Figure 5.2 Distress Developing Trends of JPCP-10000 AADT-20 Years Design

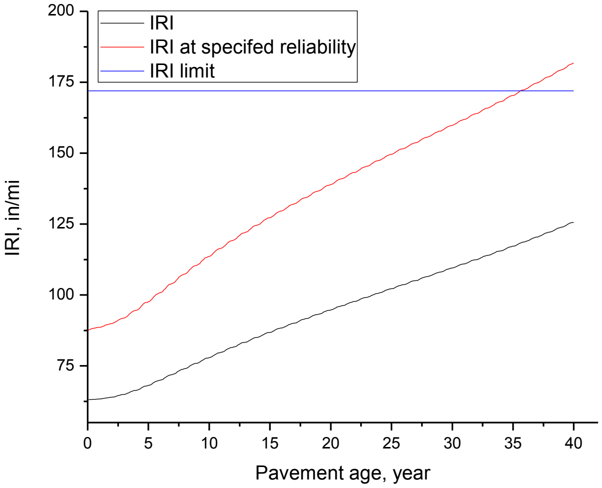
As can be seen in Fig.5.2, faulting of the pavement design exceeds the limit at the 30th year. Thus a diamond grinding is performed at the 28th year, which is estimated to take 3 days.

Similarly, the JPCP-38000 AADT-20 years design is examined, with the distress developing trends plotted in Fig.5.3.



Faulting developing trend

Slab cracking developing trend

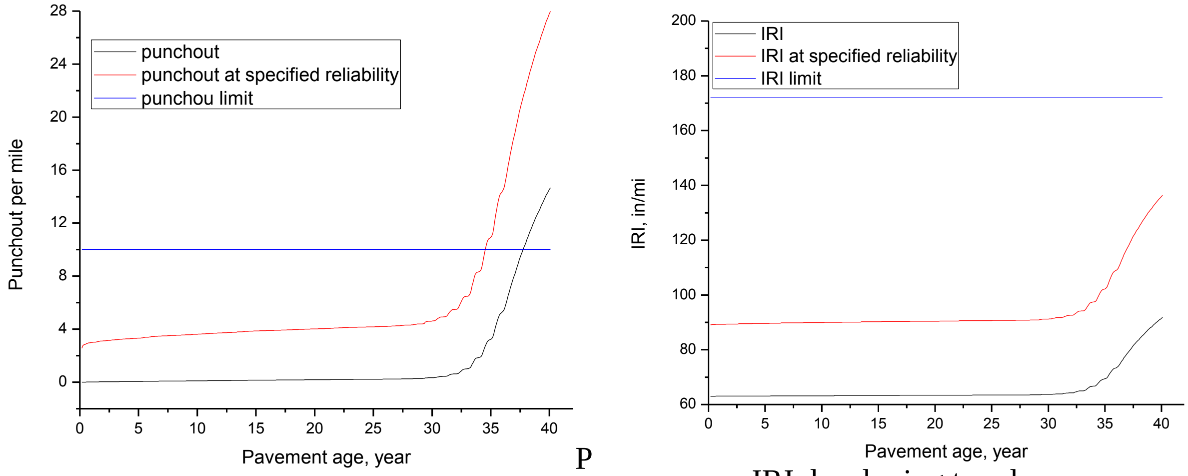


IRI developing trend

Figure 5.3 Distress Developing Trends of JPCP-38000 AADT-20 Years Design

As can be seen in Fig.5.3, both the faulting index and the IRI index exceed the limits during the 40-year span, at the 24th and the 36th year, respectively. Therefore, a diamonding grinding is performed at the 22nd year. It is assumed that the faulting and the IRI restore to their initial conditions after the diamond grinding. It is reported that the diamond grinding is valid through 16 years and thus the diamonding grinding needs to be implemented again at the 38th year. Because of the implementations of diamonding grinding, the roughness never grows to the limit value during the 40-year span.

For the CRCP-38000 AADT-20 years design, plots of the relating distresses are provided, as shown in Fig.5.4.



P

IRI developing trend

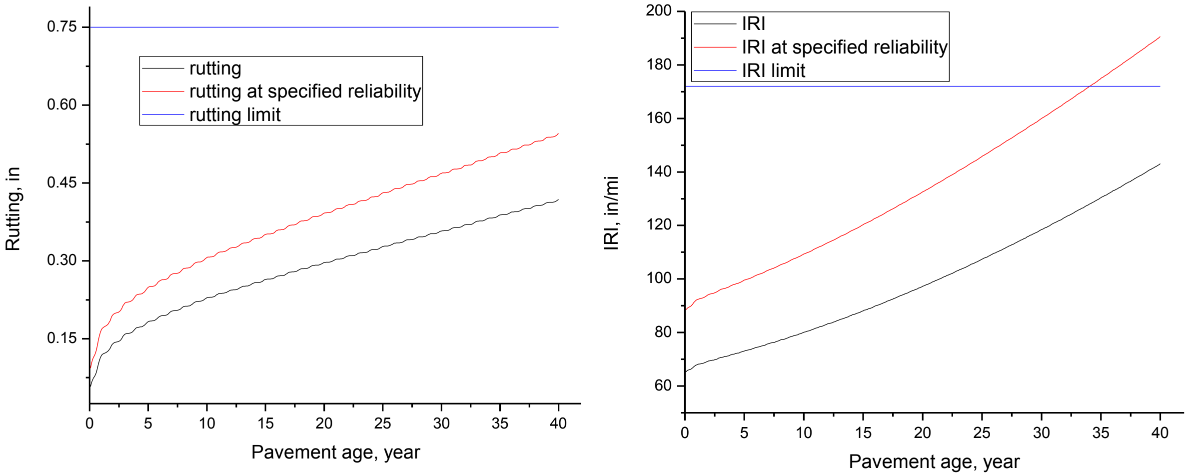
unchout developing trend

Figure 5.4 Distress Developing Trends of CRCP-38000 AADT-20 Years Design

As can be seen in Fig.5.4, the punchout index exceeds the limit and the slab replacement (76 mm) is performed at the 32nd year. For the JPCP-40 years designs and the CRCP-38000 AADT- 40 years design, they all pass the distress examinations and therefore, no maintenance activities are necessary.

After determining the maintenance schedules for the rigid pavements, it is continued to schedule the maintenance activities for the flexible pavements. There are a bunch of indices that are used to monitor the status of flexible pavements, including fatigue cracking, bottom-up cracking, thermal cracking, asphalt concrete (AC) rutting, total rutting, and roughness, etc.

For the HMA-20 years designs, after verifying in the MEPDG software, their total rutting and IRI are found to be critical indices and their developing trends are plotted in Fig.5.5 through Fig.5.7.



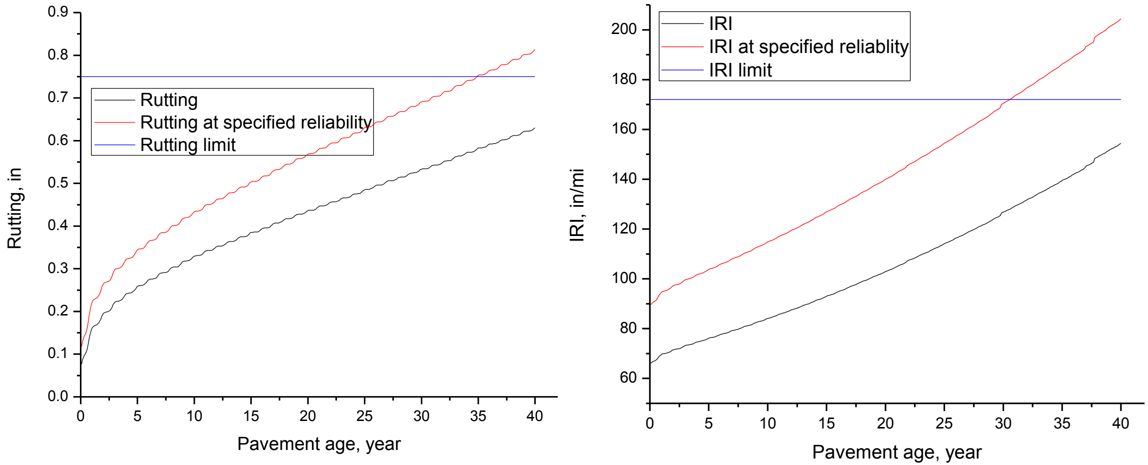
Total rutting developing trend

IRI developing trend

Figure 5.5 Distress Developing Trends of HMA-2800 AADT-20 Years Design

As can be seen in Fig.5.5, the IRI of the design exceeds the limit at the 34th year. Thus a mill-and-fill plan is performed at the 32nd year to restore the smoothness, which is estimated to take 3 days. The mill-and-fill depth is 45 mm.

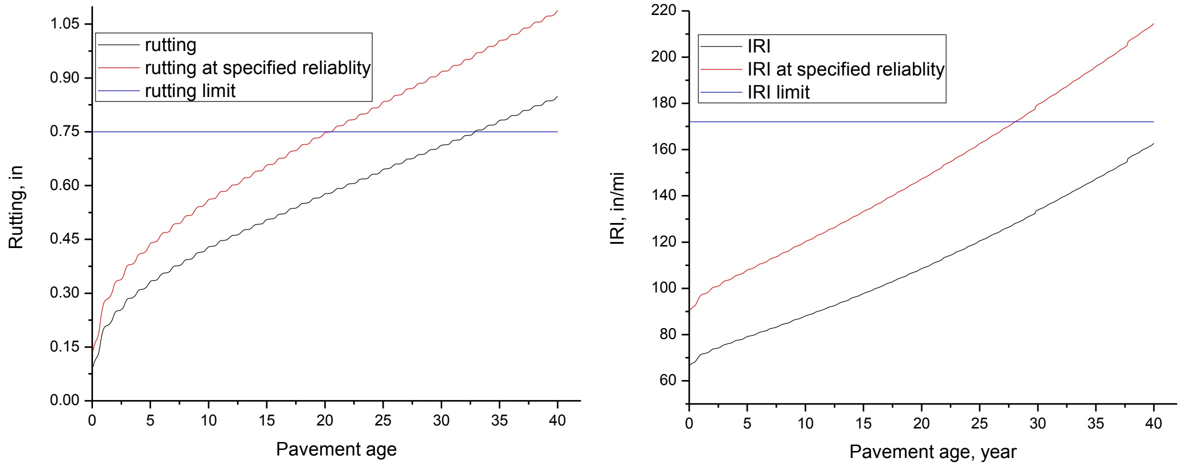
Fig. 5.6 depicts the distresses developing trends of HMA-10000 AADT-20 years design. The roughness developing trend and the rutting developing trend are found to be significant while the other distresses, such as fatigue cracking, bottom-up cracking, thermal cracking, are not critical.



Rutting developing trend IRI developing trend

Figure 5.6 Distress Developing Trends of HMA-10000 AADT-20 Years Design

As can be seen in Fig.5.6, the total rutting and IRI exceed the limit values, at the 35th and 30th year. Thus a fill-and-mill of a depth of 45 mm is performed at the 28th year.



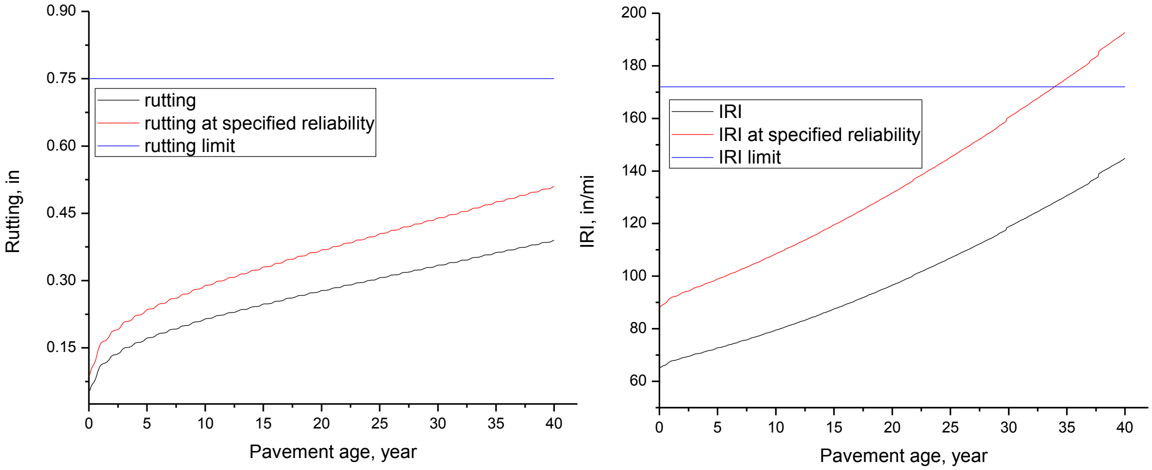
Total rutting developing trend IRI developing trend

Figure 5.7 Distress Developing Trends of HMA-38000 AADT-20 Years Design

As can be seen in Fig.5.7, the rutting and the IRI exceed the limit values at the 21st and 28th year. Thus the mill and fill plan of a thickness of 76 mm at the 20th year is performed. Following, the mill and fill plan is performed again at the 36th year but at a thickness of 45 mm.

After checking the HMA-20 years designs, it is continued to check the HMA-40 years designs. For the HMA-2800 AADT-40 years design, the total rutting developing trend and the IRI developing trend are plotted in Fig.5.8.

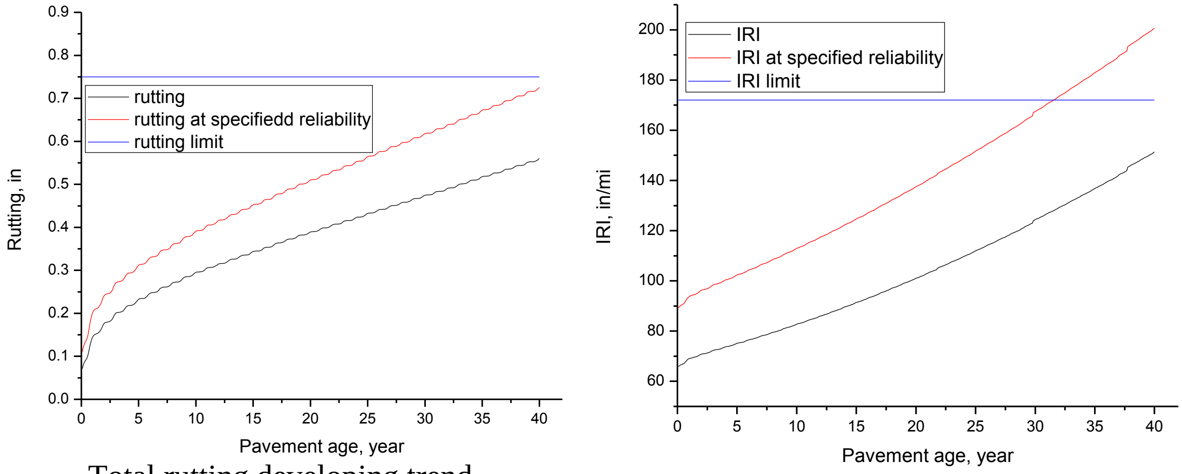
As can be seen in Fig.5.8, the IRI exceeds the limit value at the 34th year. Thus the mill-and-fill of a depth of 45 mm is performed at the 32nd year.



Total rutting developing trend IRI developing trend

Figure 5.8 Distress Developing Trends of HMA-2800 AADT-40 Years Design

The distresses developing trends of the HMA-10000 AADT- 40 years design are plotted in Fig.5.9.

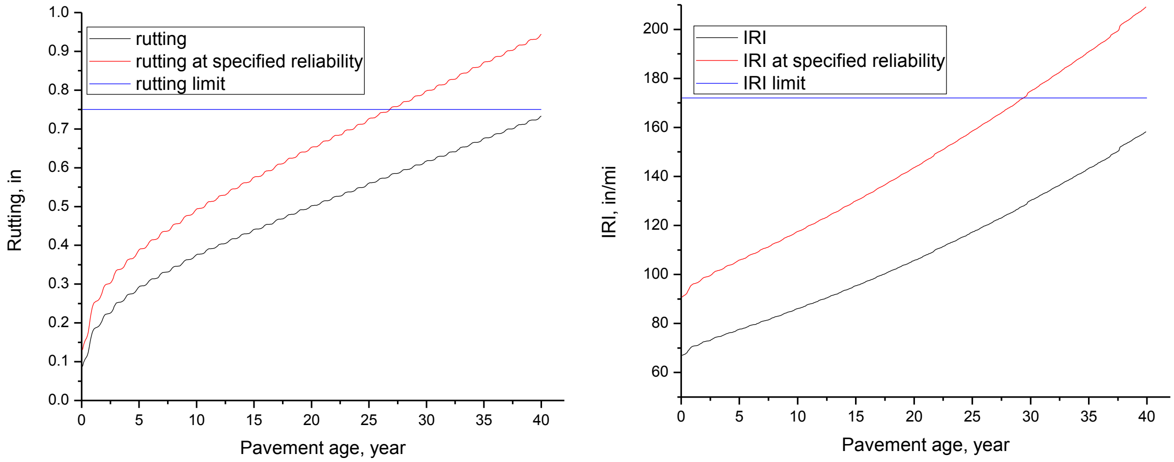


Total rutting developing trend IRI developing trend

Figure 5.9 Distress Developing Trends of HMA-10000 AADT-40 Years Design

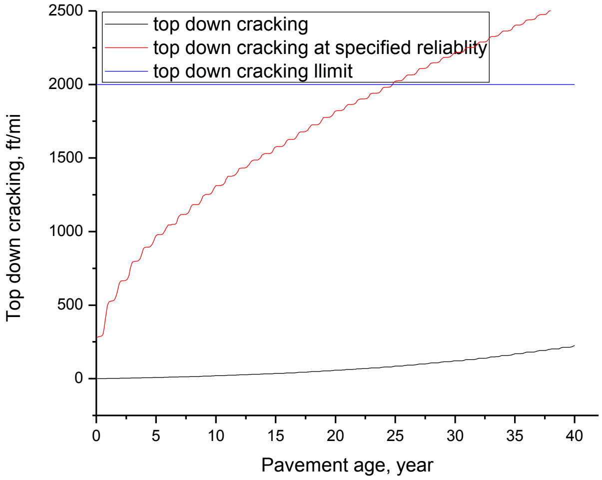
As can be seen in Fig.5.9, the IRI exceeds the limit value at the 32nd year. Thus the mill-and-fill of a depth of 45 mm is performed at the 30th year.

The distress developing trends of the HMA-38000 AADT- 40 years design are plotted in Fig.5.10.



Total rutting developing trend

IRI developing trend



Top down cracking developing trends

Figure 5.10 Distress Developing Trends of HMA-38000 AADT-40 Years Design

As can be seen in Fig.5.10, the total rutting, the IRI, and the top down cracking all exceed the limit values, at the 27th, 30th, and 27th year. Due to the severe conditions of the pavement, a thicker mill-and-fill plan is performed at the 25th year, with a thickness of 76 mm.

5.3.3 Congestion Module

Congestion module accounts for the additional fuel consumption and air pollutant emissions that vehicles pass through working zones compared to vehicles operate under normal conditions. It is assumed that all the traffics take detour on local road with a length of 1.5 mi and a speed limit of 40 mph during the initial constructions and one lane is closed for each pavement design during the maintenance periods. Eq. 4.1 is used to express the differences between the two scenarios. The congestion module is closely linked to the traffic volume and the construction and maintenance durations. The durations can be found in Table 5.14. The delay during construction and maintenance periods are estimated by the QuickZone model and summarized in Table 5.15.

Table 5.15 Traffic Delays for Various Pavement Designs under Different Maintenance Activities

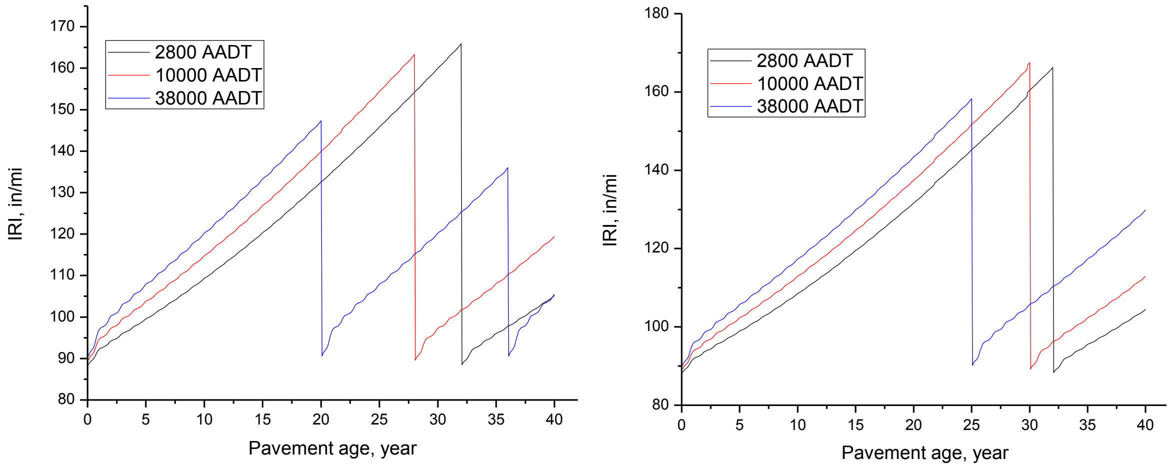
Design	Activity	Year	AADT	Detour	Queen length, mi	User delay, min	Additional length, mi
HMA-2800 AADT-20 years	Initial construction	0	2800	2800	0	0	0.875
	Mill and fill	32nd	2800	0	0	0	0
HMA-10000 AADT- 20 years	Initial construction	0	10000	10000	0	0	0.875
	Mill and fill	28th	10000	0	0	0	0
HMA-38000 AADT- 20 years	Initial construction	0	38000	38000	0	0	0.875
	Mill and fill	20th	38000	9946	0.79	2.3	0
	Mill and fill	36th	38000	9946	0.79	2.3	0
HMA- 2800 AADT- 40 years	Initial construction	0	2800	2800	0	0	0.875
	Mill and fill	32nd	2800	0	0	0	0
HMA-10000 AADT- 40 years	Initial construction	0	10000	10000	0	0	0.875
	Mill and fill	30th	10000	0	0	0	0
HMA-38000 AADT- 40 years	Initial construction	0	38000	38000	0	0	0.875
	Mill and fill	25th	38000	9946	0.79	2.3	0

Table 5.15 (Continued)

Design	Activity	Year	AADT	Detour	Queen length, mi	User delay, min	Additional length, mi
JPCP- 2800 AADT- 20 years	Initial construction	0	2800	2800	0	0	0.875
	Slab replacement	28th	2800	0	0	0	0
JPCP- 10000 AADT- 20 years	Initial construction	0	10000	10000	0	0	0.875
	Diamond grinding	28th	10000	0	0	0	0
JPCP- 38000 AADT- 20 years	Initial construction	0	38000	38000	0	0	0.875
	Diamond grinding	22nd	38000	9946	0.79	2.3	0
	Diamond grinding	38th	38000	9946	0.79	2.3	0
JPCP- 2800 AADT- 40 years	Initial construction	0	2800	2800	0	0	0.875
JPCP- 10000 AADT- 40 years	Initial construction	0	10000	10000	0	0	0.875
JPCP- 38000 AADT- 40 years	Initial construction	0	38000	38000	0	0	0.875
CRCP- 38000 AADT- 20 years	Initial construction	0	38000	38000	0	0	0.875
	Slab replacement	32nd	38000	9946	0.79	2.3	0
CRCP- 38000 AADT- 40 years	Initial construction	0	38000	38000	0	0	0.875

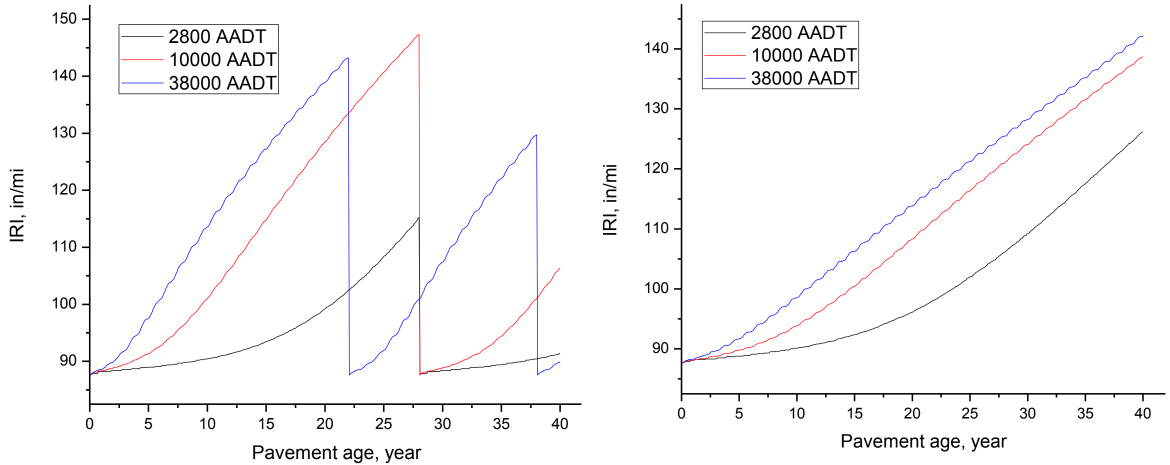
5.3.4 Usage Module

In Chapter 4, the overlay case study suggests there are great uncertainties associated with the usage module, especially with the pavement structure effect. Thus, only the roughness effect is evaluated. The roughness developing trends of various pavement designs are plotted in Fig.5.11. The sudden drop in the IRI developing trends means a maintenance activity is implemented and the IRI restores to the initial value.



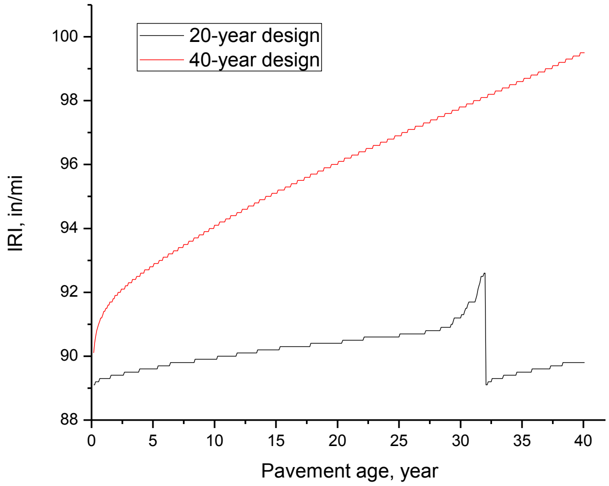
HMA-20 years designs

HMA-40 years designs



JPCP-20 years designs

JPCP-40 years designs



CRCP-38000 AADT designs

Figure 5.11 IRI Developing Trends of Various Pavement Designs under Maintenance Activities

The impacts of roughness are mainly reflected on two aspects, reducing the fuel economy and the average riding speed of vehicles with the increase of roughness level. The IRI-fuel economy relationship is suggested by the FCF, which is used to describe the real fuel consumptions of vehicles driving on pavements with different IRIs, as depicted in Eq.4.2. The relationship between IRI and average speed uses the finding in Section 3.3, that is the average vehicle speed decreases linearly with the IRI increase, at a rate of 0.84 km/h per m/km.

5.3.5 EOL Module

EOL is simply treated as landfill and considers only the activities of dismantling the pavements and transporting the debris.

5.4 LCIs of Various Pavement Designs

After the completion of the above modules for each pavement design, the LCIs are compiled and listed in the following tables. The feedstock energy is not included.

Table 5.16 LCIs of HMA Designs (20-Year Designs)

Input-output		Energy (MJ)	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
2800 AADT-20 years design	Material	6830530	517	830	0.8	76	1230	84	230	533
	Construction	244745	55	19	0.4	27	308	143	24	12
	Congestion	120064	8	-	-	8	-34	-329	1	negligible
	Usage	2395364	163	-	-	186	204	4481	3	4
	EOL	66859	18	3.5	negligible	11	148	83.5	11	4
10000 AADT-20 years design	Material	7728060	577	974	0.9	88	1358	97	234	589
	Construction	258973	57	20	0.4	29	319	147	25	13
	Congestion	485529	33	-	-	34	-141	-1332	6	negligible
	Usage	8620080	586	-	-	663	734	15933	11	13
	EOL	71641	18.5	3.5	negligible	11	148.5	84	11	4
38000 AADT-20 years design	Material	9892140	721	1323	1	120	1667	128	244	624
	Construction	388845	93	26	0.5	48	560	263	43	21
	Congestion	4929327	331	-	-	423	-61	-4604	26	3
	Usage	31935342	2169	-	-	2496	2791	59663	43	47
	EOL	83469	19.5	4.5	0.1	11.5	149.5	84.5	110.5	4.5

Note: The empty entries in the table mean the items are not within outputs of the models, which are the same for Table 5.17 through Table 5.20. This does not influence the results significantly because CO_2 emissions are three orders bigger than other GHGs.

Table 5.17 LCIs of HMA Designs (40-Year Designs)

Input-output		Energy (MJ)	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
5600 AADT-40 years design	Material	7347573	552	912	0.9	83	1304	92	232	565
	Construction	258202	58	20	0.4	29	320	147	25	13
	Congestion	136073	9	-	-	10	-40	-373	2	negligible
	Usage	2384251	162	-	-	185	203	4472	3	4
	EOL	71641	18.5	3.5	negligible	11	148.5	84	11	4
10000 AADT-40 years design	Material	7945658	591	1009	1	92	1390	100	235	603
	Construction	280303	61	21	0.4	30	337	154	26	14
	Congestion	628331	42	-	-	44	-176	-1721	7	0.3
	Usage	8903726	605	-	-	689	755	16657	12	13
	EOL	76331.5	19	4	0.1	11	149	84	11	4
38000 AADT-40 years design	Material	9842382	717	1314	1	120	1660	127	244	723
	Construction	332807	66	24	0.5	33	359	163	28	15
	Congestion	4300649	107	-	-	378	-718	-5701	30	2
	Usage	32299287	2194	-	-	2477	2766	59245	42	47
	EOL	88610	20	5	0.1	11.5	150	84.5	11	4.5

Table 5.16 and Table 5.17 are inventories for the HMA designs. The energy consumptions in the tables are plotted to give a clear view of the comparisons between each design.

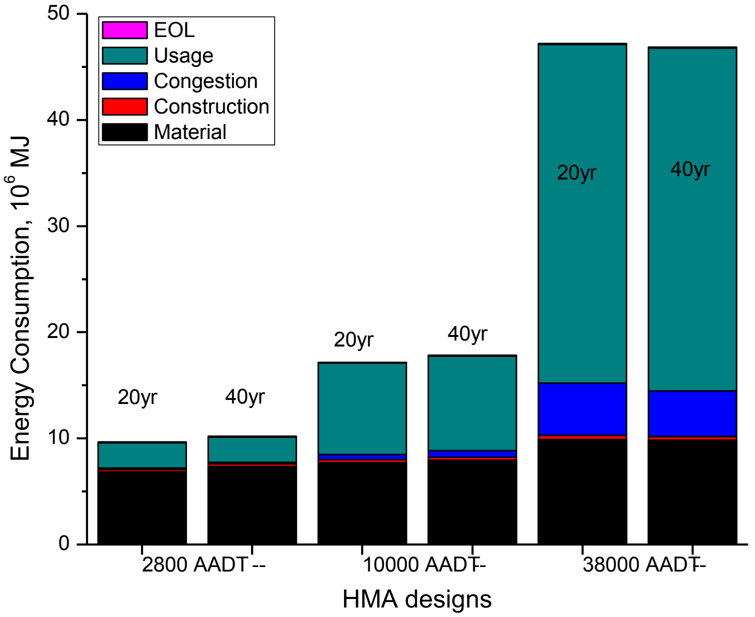


Figure 5.12 Life Cycle Energy Consumptions of HMA Designs

As revealed in Fig.5.12, the energy consumption grows quickly with the increase of AADT, with the major contribution components varying. At the small traffic volume, the energy consumption due to material input dominants; at the medium level of traffic, material input and usage consumption are two main sources; and at the high traffic volume, the usage module dominates.

Moreover, the congestion due to construction and maintenance activities occupy a growing fraction among the whole share with the increase of traffic volume. And the 20-year designs are very approximate to their 40-year counterparts in terms of life cycle energy consumptions, with the difference being 5.6, 3.9 and -0.7 percent in sequence. The differences are so small that slight disturbance will change the pattern. The comparisons will be re-examined in the sensitivity analysis.

Fig.5.13 is the plot of the GHGs of HMA designs for their lifetimes. The distributions of GHGs inventories are similar to those of energy consumptions and thus no detailed discussion is performed here.

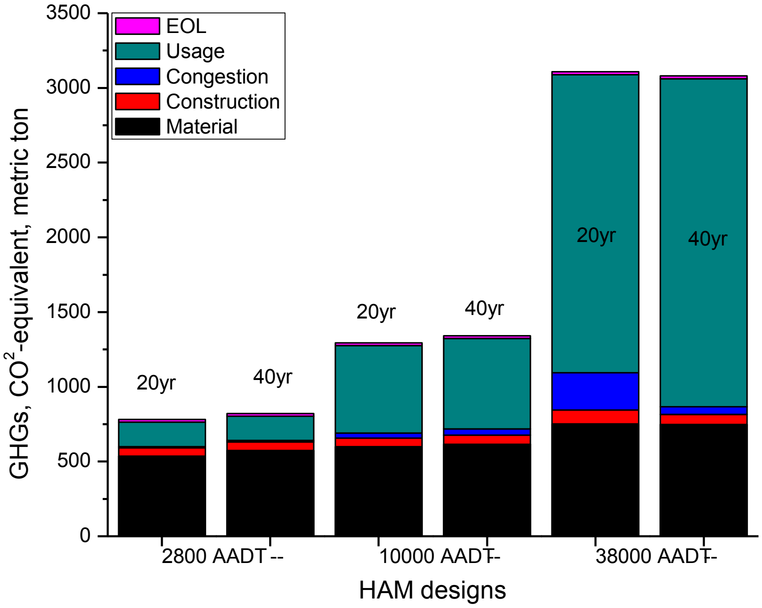


Figure 5.13 Life Cycle GHGs of HMA Designs

Table 5.18 LCIs of JPCP Designs (20-Year Designs)

Input-output		Energy (MJ)	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
5600 AADT-20 years design	Material	6396354	643	122	0.7	37	1504	2730	1313	778
	Construction	211512	34	20	0.4	16	144	67	12	8
	Congestion	143945	10	-	-	10	-42	-395	2	negligible
	Usage	1895117	129	-	-	161	177	3862	3	3
	EOL	40575	3	4	negligible	1	4	2	0.5	0.8
10000 AADT-20 years design	Material	5614896	576	120	0.7	33	1327	2646	1173	640
	Construction	219731	34	18	0.3	18	174	88	14	8
	Congestion	571210	38	-	-	40	-170	-1614	7	0.1
	Usage	7746577	526	-	-	649	705	15754	12	1
	EOL	45331	3	4	negligible	1	4	4	0.5	0.9
38000 AADT-20 years design	Material	7030110	654	123	0.9	38	1594	2742	1317	738
	Construction	256524	38	-	-	20	194	95	16	9
	Congestion	4540228	305			390	-687	-5159	31	2
	Usage	30556851	2076	-	-	2563	2795	62064	45	50
	EOL	54879	4	5	negligible	2	5	2	0.6	1

Table 5.19 LCIs of JPCP Designs (40-Year Designs)

Input-output		Energy (MJ)	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
5600 AADT-40 years design	Material	6050438	570	119	0.9	32	1372	2636	1141	623
	Construction	211996	26	17	negligible	12	96	40	8	6
	Congestion	151942	10	-	-	11	-44	-417	2	negligible
	Usage	2011837	137	-	-	170	185	4114	3	3
	EOL	42962	3	4	negligible	1	4	2	0.4	0.8
10000 AADT-40 years design	Material	6834120	637	122	0.9	37	1549	2720	1282	715
	Construction	235775	30	18	negligible	14	115	48	10	7
	Congestion	657496	44	-	-	46	-191	-1802	8	negligible
	Usage	7822931	531	-	-	657	707	16000	12	13
	EOL	52492	4	4	negligible	1	5	2	0.5	0.8
38000 AADT-40 years design	Material	7617663	704	124	0.9	41	172	2805	1423	807
	Construction	259539	34	19	negligible	15	134	55	11	6
	Congestion	2930309	197	-	-	206	-852	-8041	34	0.2
	Usage	30815249	2093	-	-	2582	2772	62996	48	51
	EOL	62039	5	5	negligible	2	6	3	0.6	1

Table 5.18 and Table 5.19 are inventories for the JPCP designs. The energy consumptions in the tables are plotted in Fig.5.14.

As reflected in Fig.5.14, similar rules can be observed as from Fig.5.12. In short, the usage module replaces the material module to be major contributor to the life cycle energy consumption with the increase of traffic volume; congestion module increase quickly with the traffic growth; and the differences between the 20-year designs and the 40-year designs are not large, being -2.5, 9.9, 8.5 percent, respectively. The GHGs distribution patterns are similar to the energy consumption distributions and the plot is not provided here.

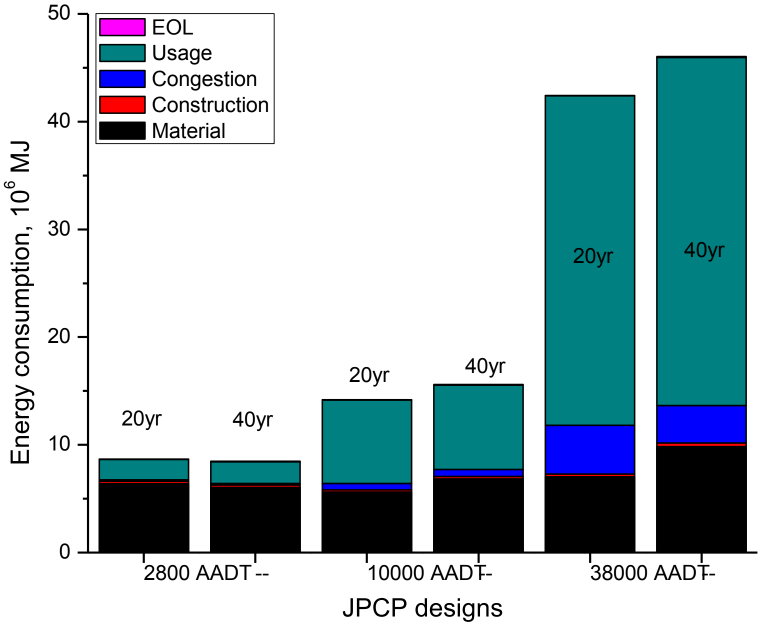


Figure 5.14 Life Cycle Energy Consumptions of JPCP Designs

Table 5.20 LCIs of CRCP Designs

Input-output		Energy (MJ)	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
38000 AADT-20 years design	Material	13117777	1320	815	5	112	2218	173124	3375	812
	Construction	225642	28	17	negligible	13	120	58	10	7
	Congestion	7439908	464	-	-	612	-1536	-13123	65	2
	Usage	24756721	1682	-	-	2109	2344	50474	38	40
	EOL	47719	2	4	negligible	1	4	2	0.5	0.9
38000 AADT-40 years design	Material	13583220	1381	928	6	122	2198	19670	3619	761
	Construction	247657	32	19	negligible	14	124	51	10	8
	Congestion	6077678	409	-	-	427	-1768	-16678	70	0.3
	Usage	26284833	1785	-	-	2234	2470	53610	40	43
	EOL	57266	4	5	0.1	2	5	3	0.6	1

Table 5.20 is the inventories for the CRCP designs. The energy consumptions are plotted in Fig.5.15. As shown in Fig.5.15, usage module, material module, and congestion module are the three main components to comprise the total energy consumption, ranked by the significance. The 20-year designs still consume similar amount of energy consumption as opposed to the 40-yer designs. The energy

consumptions from material module of the CRCP designs are much higher than those of the HMA and JPCP designs due to existence of steel grid.

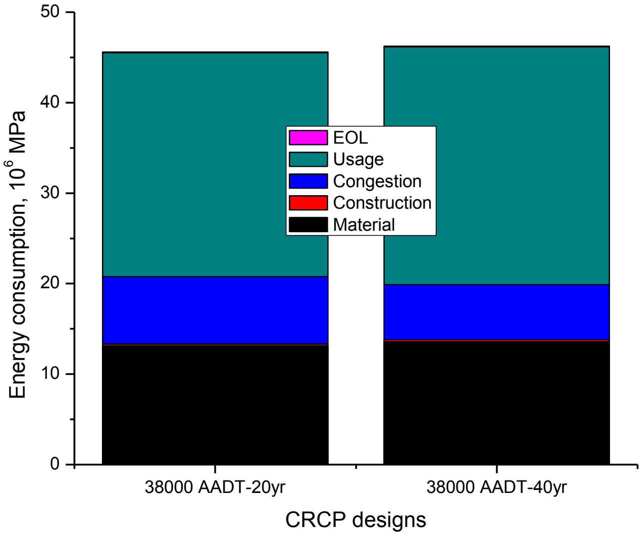


Figure 5.15 Life Cycle Energy Consumptions of CRCP Designs

5.5 Sensitivity Analysis

A handful of parameters affect the final LCIs tremendously but are calculated with assumed or predicted values. Their uncertainties need to be captured in the sensitivity analysis.

5.5.1 Traffic Volume Disturbance

As has been admitted at the beginning of this chapter, the AADTs of the designs are estimated roughly. The associated uncertainty and the role of AADT level on the LCIs are investigated herein. The life cycle energy consumption is chosen as the evaluation index. Four adjustments of the original AADT value, decreasing by 25 and 50 percent, and increasing by 25 and 50 percent, as well as the original value are compiled to suggest any potential trend. Only the traffic related modules are investigated and the maintenance activities assume to be unchanged. Fig.5.16 plots the analysis results for the three designs.

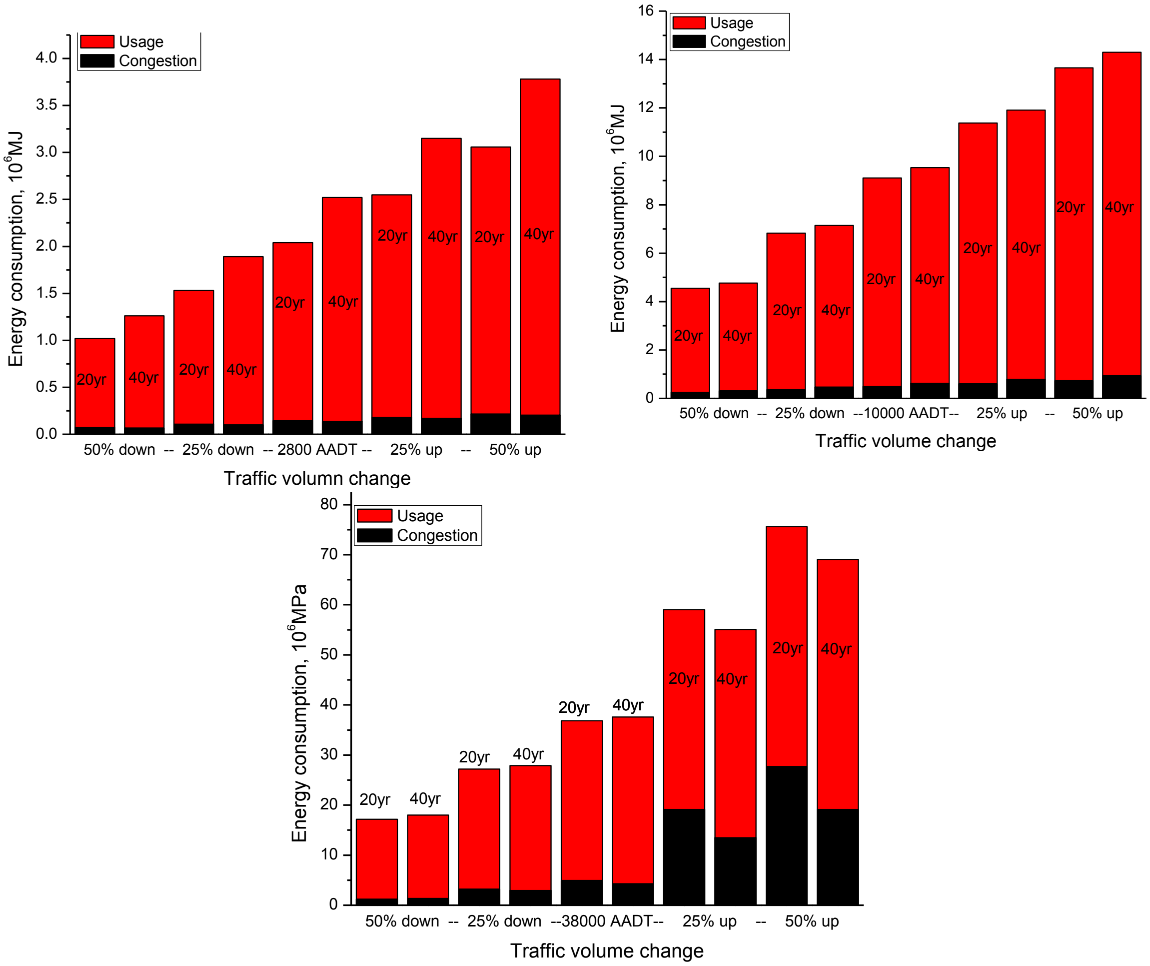


Figure 5.16 Sensitivity Analysis of Traffic Volume Variations of HMA Designs

As can be seen in Fig.5.16, traffic volumes influence the traffic-related energy consumptions tremendously. And the two modules, usage one and congestion one, contribute significantly different. At a not high traffic volume, the usage module is overwhelming and the congestion related energy consumption grows slowly. Nevertheless, at a high traffic volume (especially greater than 38000 AADT), the congestion-related energy consumption grows rapidly and the congestion module becomes significant contributor.

Moreover, at a not high traffic volume, the increase of AADT actually gives credits to the 20-year designs because: firstly, more frequent maintenance activities maintain the pavement in a better condition compared to the 40-year designs and thus reduce the user energy consumption, and secondly, the increase of congestion energy consumption is limited and can be fully compensated by the savings of usage module. However, when the traffic volume reaches a certain value (greater than 38000 AADT according to Fig.5.16), the congestion during the maintenance periods skyrockets and the resulting congestion energy consumption neutralize the savings of usage module easily. In other words, at low or medium volume traffics, 20-year designs are preferred in terms of energy consumptions while the opposite is true if the traffic volume is substantially high. Unfortunately, the traffic volume here is a qualitative not a quantitative notion because many external factors disturb the determination of the watershed traffic, such as lane capacity loss due to maintenance, number of lanes, organizations of maintenance activities and so on.

The sensitive analysis of the traffic volumes on the JPCP designs are performed using the same method. Fig.5.17 plots the obtained results. As revealed in Fig. 5.17, basically, similar developing patterns can be observed of the JPCP designs as those of the HMA designs. In short, AADTs have significant influence on the traffic-related energy consumption. And the congestion under high AADTs results in substantial portion of energy consumption that will easily offset the savings brought by the usage module due to more frequently maintenance activities, which, on the other hand, suggests the significance of maintenance frequencies, methods and durations, etc. The AADT influence on the CRCP designs is continuing to be explored.

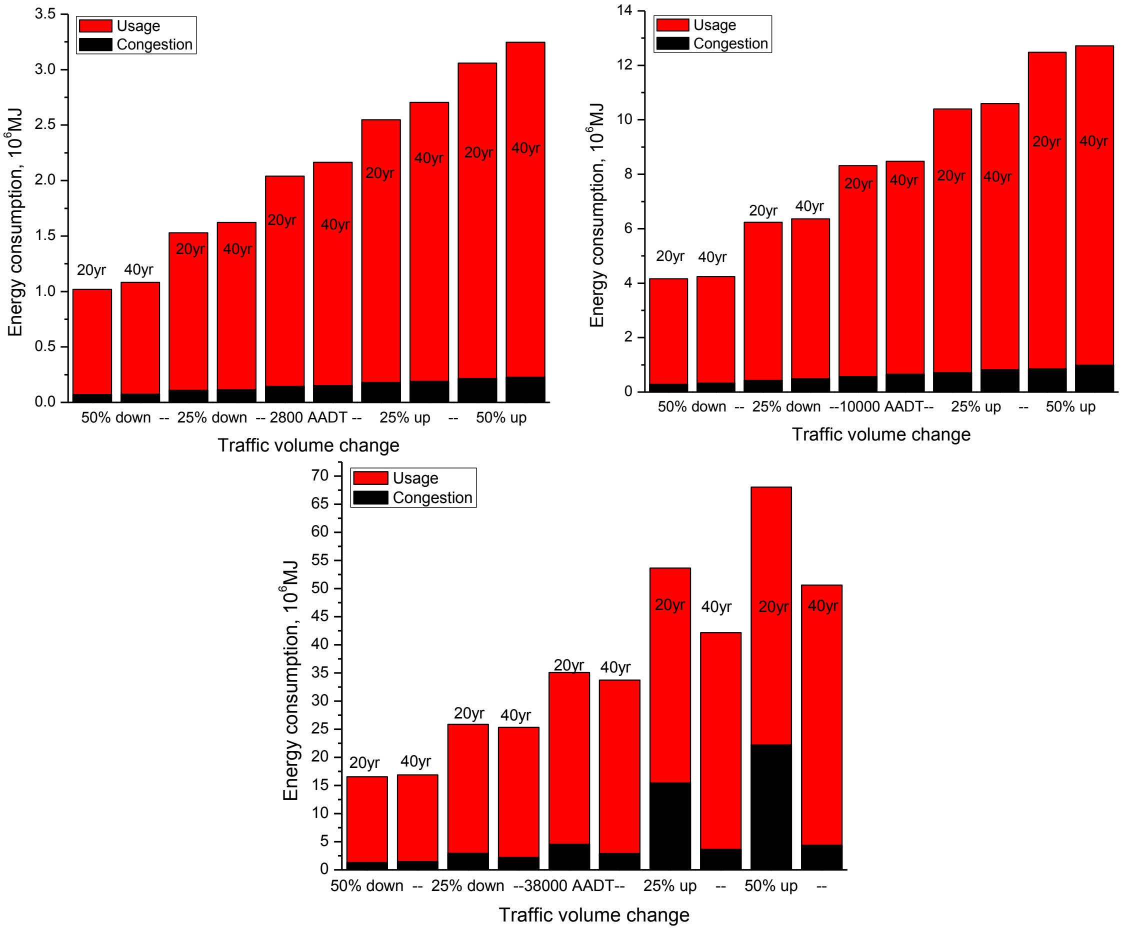


Figure 5.17 Sensitivity Analysis of Traffic Volume Variations of JPCP Designs

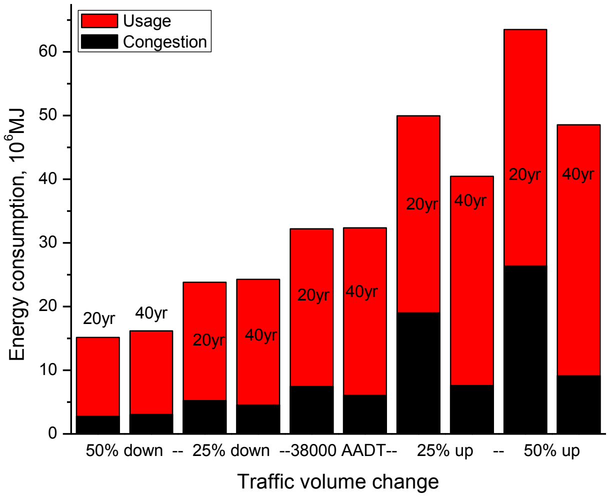


Figure 5.18 Sensitivity Analysis of Traffic Volume Variations of CRCP Designs

As observed from Fig.5.18, a similar distribution can be found as those of the HMA and JPCP designs. The congestion burdens because of more frequent maintenance activities for the 20-year design exceed the corresponding benefits from usage module at a high traffic volume as opposed to the 40-year design.

5.5.2 Recycling Exploration

The EOL just considers dismantling and transporting the old structure and then landfill them while the debris are typically recycled and reused. Only the surface materials are recycled, including asphalt mix, concrete blocks, and steel, while the base and subbase remain untouched, which may be further paved with new surface layer after suitable treatments. As stated in Section 4.2.6., two recycling scenarios are tested: recycling 10 and 20 percent RAP and RCM into the new HMA and PCC pavements. The steel bar and rods are separated by the well-established technology of magnetic separation, which is used as a routine procedure in the crushing process (Muller and Winkler 1998). Therefore, the steel are recycled 100 percent for the JPCP and CRCP designs. Only the 38000 AADT, 20-year designs are evaluated to suggest the impacts.

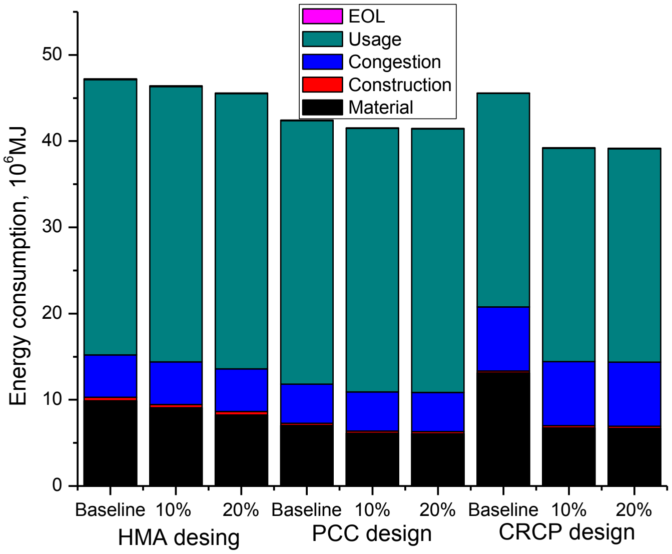


Figure 5.19 Benefits of Recycling Pavement Materials for Different Designs

As revealed in Fig.5.19, there are certain levels of energy savings due to recycling for each design, although very limited for the HMA and PCC designs. The CRCP design witnesses a substantial energy consumption reduction due to the recycling and reuse of old steel grid into new pavement construction. The energy saving due to RCM is very limited, which can found from comparisons between the “10%” and the “20%” bars of the PCC design as well as the CRCP design. The energy savings for the HMA design basically linearly increases with the recycling percentage.

5.5.3 Pavement Maintenance Schedule

Pavement maintenance schedules account for when and how pavements need to be maintained after being opened to traffic. The precise prediction of distress developments and strategic maintenance activities are always challenging tasks. Unlike that DOTs can monitor distress levels in field and then decide maintenance plans, the modeler can only predict future conditions of pavements and then determine appropriate maintenance strategies at given conditions. The prediction and determination inevitably suffer from uncertainties.

In this study, the MEPDG software is used as the distress prediction tool, of which the results are used to suggest suitable maintenance plans. The HMA 20-year designs are selected as examples to carry out the sensitivity analysis. It is assumed that the distresses develop at a -10, -5, +5, and 10 percent slower or faster rates compared to the original rates. The distress development will influence the maintenance activities, and therefore influence all the modules except the EOL one. Table 5.21 lists the resulting changes. Life cycle energy consumption is used as the evaluation indicator.

Table 5.21 Maintenance Activities at Different Distress Developing Rates for the HMA Designs

Design	Distress developing rate	Maintenance reason	Maintenance year	Maintenance strategy	Maintenance duration (d)
HMA-2800 AADT-20 year	-10%	-	-	-	-
	-5%	roughness	36th	Mill and fill (45 mm)	3
	original	roughness	32nd	Mill and fill (45 mm)	3
	+5%	roughness	30th	Mill and fill (45 mm)	3
	+10%	roughness	27th	Mill and fill (45 mm)	3
HMA-10000 AADT-20 year	-10%	roughness	35th	Mill and fill (45 mm)	3
	-5%	roughness	32nd	Mill and fill (45 mm)	3
	original	roughness	28th	Mill and fill (45 mm)	3
	+5%	roughness	26th	Mill and fill (45 mm)	3
	+10%	roughness	24th	Mill and fill (45 mm)	3
HMA-38000 AADT-20 year	-10%	rutting	24th	Mill and fill (76 mm)	5
	-5%	rutting	22nd and 38th	Mill and fill (76 mm+45mm)	5+3
	original	rutting	20th and 36th	Mill and fill (76mm+45 mm)	5+3
	+5%	rutting	16th and 32nd	Mill and fill (76mm+45 mm)	5+3
	+10%	rutting	14th and 30th	Mill and fill (76mm+45 mm)	5+3

Note: There is no maintenance needed for the HMA-2800 AADT- 20 year design.

The traffic related energy consumptions are plotted in Fig. 5.20 at different distress developing rates. As revealed in Fig.5.20, the distress developing rates influence the maintenance plans, either advancing or postponing the maintenance year, or reducing the maintenance frequency, which leads to the variations of the LCIs. In general, the influences are limited. The differences of the “-10%” bar and the “+10%” for the three HMA designs are 9.0, 6.7 and 11.8 percent in sequence. Compared with the effect of maintenance time change, maintenance frequency is dominating, as clearly suggested in the “-10%” bar in the 2800 AADT subfigure and the “-10%” bar in the 38000 AADT subfigure, both of which reduce one time of maintenance due to the slow distress developments. Reducing the maintenance frequency leads to a reduction of material usage as well as traffic congestion at a high traffic volume, which can sufficiently compensate the additional user energy consumption because of less maintenance. Also, for all the three HMA designs, the maintenance schedules are advanced or postponed at the faster or slower distress developing rates.

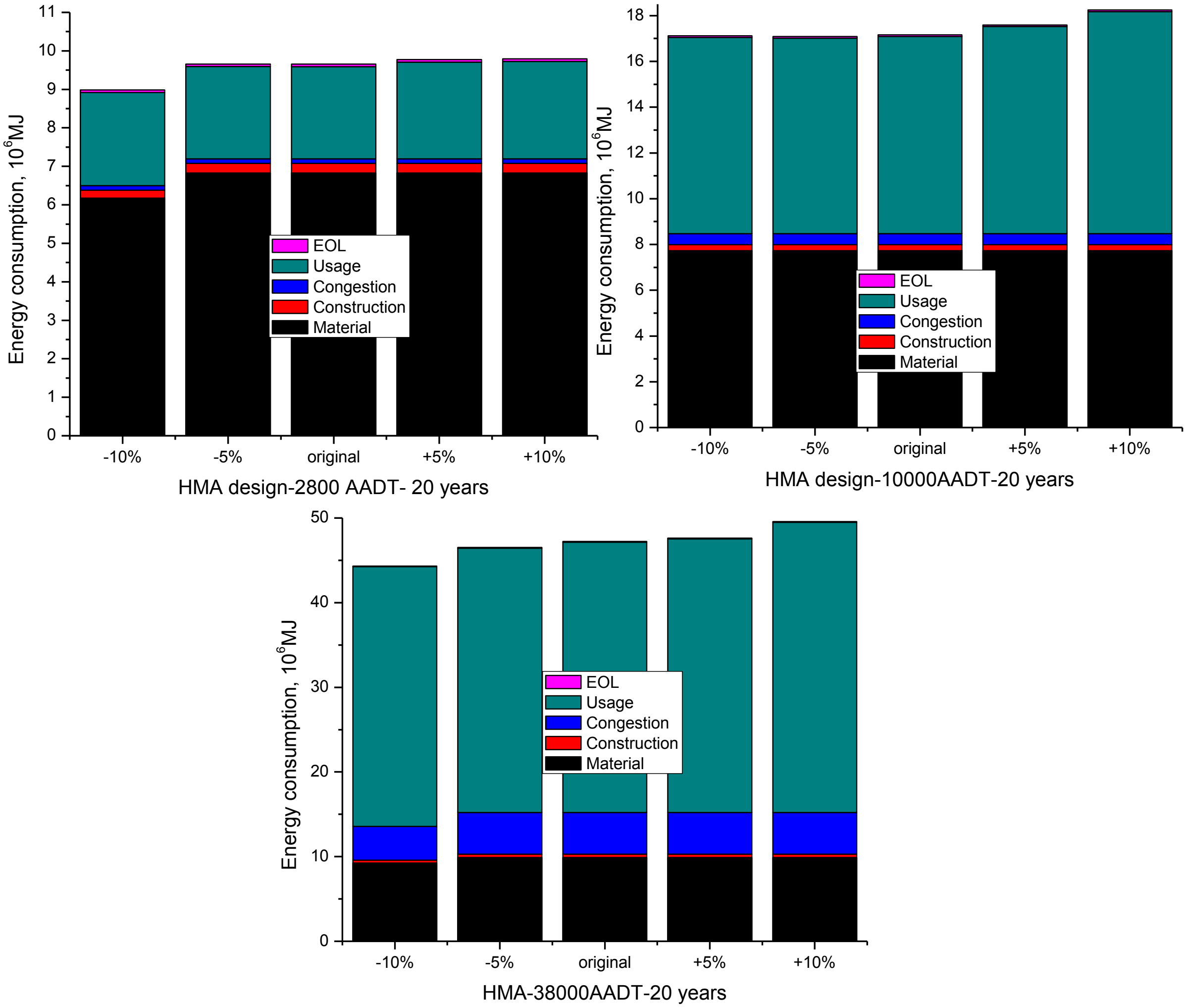


Figure 5.20 Distress Developing Rate Sensitivity Analysis of HMA Designs

5.6 Summary

This chapter examines the life cycle environmental burdens of the 20-year and 40-year pavement designs of different pavement types at three levels of traffic volume. It is not intended to make a comprehensive comparison of the flexible pavements verses rigid pavements due to the missing of several significant components, such as albedo, carbonation, and fuel economy variation on different pavement types, for their great uncertainties or lack of reliable knowledge. However, unlike the inconclusive findings that the 40-year designs yield significant life cycle cost advantages over the 20-year designs (Rawool and Pyle 2008), the comparisons between the 20-year and 40-year designs suggest no consistent rule in terms of environmental burdens. Specifically, at low and medium volumes of traffic, the 20-year designs indicate environmental advantages as opposed to the 40-year counterparts while the opposite is true at a high traffic volume. Unfortunately, the term “high” is a quantitative concept because many factors, such as maintenance activity, durations, and construction window, etc., influence the precise determination of the critical traffic volume.

Among the five modules, material and usage are two dominating factors. With the increase of AADT, usage module replaces material module to be the major contributor and the congestion module occupies a growing fraction among the whole share. Moreover, recycling brings limited benefits for each design since the recycling rate is small. Maintenance frequency proves to have limited influences on shifting the LCA results. The maintenance time is even less influential and prefers to be performed early than later. In general, the selection of long term pavement is not ubiquitous but rather depends on the concrete situations.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Environmental protection is a growing concern among international organizations, governments, industries, and academies. However, the environmental aspect of pavement, compared to its economic counterpart, is seldom considered in the previous theoretical research and field practice. As has been stated in Chapter 1(ASCE 2009), pavement infrastructures of U.S. are in poor conditions and demand tremendous amounts of material and energy inputs to maintain them at an acceptable level. Unfortunately, the knowledge about the environmental impacts of pavement is in great shortage, especially the overall methodology to perform the evaluation. It prevents the pavement community to step forward to building and maintaining the pavement in an environmentally friendly way. This dissertation aims to solve some of the dilemmas that plague the understanding of the relationship between pavement and environment and indicates some measures to improve. In detail, the following work and contributions have been done:

1. Critical review of existing LCA studies relevant to the pavement field to determine the research gaps.
2. Proposal of a comprehensive methodology to evaluate the life cycle environmental burdens of pavements.
3. Solving three concrete issues that torture the utility of LCA model in pavement field, including the estimation of MDC of certain air pollutants, establishment of the relationship of pavement roughness and average vehicle speed, and the

incorporation of EDC into the cost evaluation system to optimize the maintenance schedules.

4. A case study of three overlay systems using the proposed methodology.

5. Comparisons of the environmental burdens of 20-year designs and 40-year designs of pavements at different traffic volumes.

6.1 Critique of Current LCA Studies in Pavement Field

The critical review in Chapter 2 provides insight into the *status quo* of applying LCA model to assess the environmental impacts of pavements. In general, the overall status is still immature and leaves many research gaps to be filled. Several of the significant shortcomings are summarized:

1. Lack of widely accepted methodology to perform the LCA study on pavements: the constitutions of the pavement LCA methodology vary greatly, most of which suffer from missing of significant components, such as usage module and congestion module.
2. Obscure of the functional unit. The functional units of current LCA studies are case dependent, making the available studies hard to be compared on the same ground. The complexity of pavement structure and functionality hinders the determination of a universal and single functional unit.
3. Great uncertainties in some most significant components. Usage module and congestion module are found to be significant but are far from perfect till date. For instance, the relationship of rolling resistance and fuel economy is indeterminate.

4. Feedstock energy. The treatment of feedstock energy in most previous studies is to ignore. Recycling the feedstock energy in asphalt has never been considered in the LCA studies.

5. Limited environmental indicators. Many researchers in their previous studies are satisfied with the GHGs and energy consumptions while some include more air pollutants in the LCIs as an improvement, which is still not enough. More indicators, e.g., water pollutants, landfill, noise, are suggested to be incorporated.

6. Shortage of supplementary models for the LCA methodology. The methodology of applying LCA to pavement turns to be complex, consisting of many modules. Lacking reliable sub-models to build the structure is an annoying issue. The model bank of the methodology needs to be enriched or updated.

6.2 Proposal of a Comprehensive Pavement LCA Methodology

Based on the efforts of Chapter 2, a comprehensive pavement LCA methodology is proposed, consisting of five modules: material module, construction and M&R module, congestion module, usage module, and EOL module. The proposed methodology is comprehensive and complete, covering almost all the significant contributors during the life cycle.

And the proposed pavement LCA methodology is a mixture of available resources and self-developed models. Therefore, it is beneficial to differentiate the originations of different contributions, as listed in Table 6.1.

Table 6.1 Pavement LCA Methodology Markup

Modules	Major components	Existing work	Contributions from the dissertation
Material module	Cement production	Marceau et al. (2007)	NA
	Bitumen production	Stripple (2001)	NA
	Steel production	GREET model (version 2.7)	NA
	Transportation	GREET model (version 1.8)	NA
Congestion module	Additional fuel consumptions due to M&R activities	Zhang et al. (2010a) assumed detour rate to predict queue length and speed reduction, etc.	QuickZone mode (Beta version) was used to automatically predict detour rate and queue length, etc.
Usage module	Roughness effect on fuel economy	WesTrack project data (Epps et al.1999)	Amos's data (2006)
	Roughness effect on vehicle speed	Chandra's study (2004)	Self-developed model (section 3.3)
	LCA and LCCA integration	Kendall (2004)	Estimate of reliable MDCs of air pollutants
			Development of the algorithm using dynamic programming
			Cost system is further enriched
	Pavement structure effect	NA	Parallel comparison and sensitivity analysis for different pavement types
	Albedo	Santero (2009) calculated the GWP range	More precise estimation is reported
	Carbonation	Santero (2009) calculated the GWP range	More precise estimation is reported
	Lighting	Santero (2009) calculated the GWP range	NA
EOL module	Landfill, leave, or recycle	Athena Institute (2006)	NA

6.3 Three Contributions to the LCA Methodology

Three minor contributions to the progress of pavement LCA methodology are made. The first is the establishment of the relationship between pavement roughness and average vehicle speed. 32 individual pavement sections, each of which has roughness data of up to eight years, were selected to build the model. The roughness data covers a wide range and the selected pavement sections contain both flexible and rigid sections and possess different number of lanes. Involved regression parameters include: vehicle speed, roughness, volume-capacity ratio, pavement type, number of lanes, and speed limit. Through regression it is found that the average vehicle speed decreases 0.84 km/h with every 1m/km increase of the roughness. The vehicle speed is further linked to the air pollutant emission rates and lane capacity variation.

The cost evaluation system is incomplete due to the lack of EDC. The LCIs provides the amount of air pollutants and needs the MDCs to calculate the total EDC, which is the goal of the second contribution. An extensive literature review was performed to collect large sample size to estimate the central values and the uncertainty ranges of the MDCs of involved air pollutants.

The third contribution is to combine the LCA and LCCA in the pavement maintenance optimization process. The dynamic programming algorithm is adopted to execute the optimization. The proposed algorithm is used in the case study of Chapter 4 and demonstrates to be quite useful.

6.4 Case Study of the Three Overlay Systems

Three pavement overlay systems, the PCC option, the HMA option, and the CSOL option, are evaluated about their environmental burdens using the proposed methodology. Through the case study, it is reasonable to expect a smaller environmental burden from the PCC and CSOL options as opposed to the HMA option although comparisons between the former two are indeterminate because of uncertainties in the usage stage, especially pavement structure effects. Material, congestion, and usage are the three major sources of energy consumption and air pollutant emissions in the inventory. Traffic related fuel consumption emerges very sensitive to traffic growth and fuel economy improvements. Fuel consumption basically increases linearly with the traffic growth rate.

Furthermore, an integrated LCA and LCCA model was performed to optimize the maintenance schedule. The optimized maintenance schedule gains a reduction of 8.2 to12.3 percent, and 5.9 to 10.2 percent in terms of energy consumption and holistic cost compared to the before optimization plans for the three overlay plans. However, great uncertainties exist in the LCIs and cost evaluation systems, especially for the usage module. From the case study, it is also found: the energy/GHGs objectives demand more frequent maintenance activities than the cost objective, but they all prefer an early maintenance implementation that later. The tradeoffs between material consumption, traffic congestion, and pavement surface roughness effects on the fuel consumption and the EDC are the possible explanations.

6.5 20-Year and 40-Year Pavement Designs Comparisons

The life cycle environmental burdens of 20-year and 40-year designs of different pavement types at three traffic volumes are investigated. During the modeling process, several significant components in the usage module, such as albedo, carbonation, and fuel economy variation, are not included due to great uncertainties or lack of reliable knowledge. Since it is not intended to make conclusive comparisons between the three pavement types, this treatment is acceptable. The comparisons between the 20-year and 40-year designs suggest no consistent rule. Specifically, at the low and medium volumes of traffic, the 20-year designs indicate environmental advantage as opposed to the 40-year counterparts while the opposite is true at the high traffic volume. Unfortunately, it is not possible to determine the precise traffic watershed that shift the preference of the 20-

year and 40-year pavement designs. Recycling benefit for each design is limited due to the limited use of recycled materials. For the maintenance, it is preferred to maintain the pavement early than later. In general, the 40-year pavements do not necessarily carry environmental advantages compared to their 20-year counterparts.

6.6 Opportunities to Improve the LCA Methodology

Given the work this dissertation has done, still many parts of the LCA methodology can be improved and the priorities of future research are determined by their significance, as listed in Table 6.2.

Table 6.2 Research Priority Recommendations of Pavement LCA Methodology

Priority rank	Scenarios	Status quo	Comments
1st level	Pavement structure effect on fuel consumption	Relevant researches are limited; conclusions are empirical, varying in figures or even rules.	Both filed test and mechanical analysis are desired. Finite element modeling might be beneficial.
	Roughens effect on fuel consumption	Only WesTrack project data and Amos's data are available.	Sample size is very limited. More field tests are urgently needed specified for different types of vehicles.
	Traffic delay during constriction and M&R periods.	QuickZone model and Mobile model are combined to estimate the additional burdens.	Far from perfect to estimate the abnormal traffics.
2nd level	Material production	Inconsistency for bitumen production and concern of feedstock energy consumption.	A hybrid technology combing project data and IO LCA model may be more suitable.
	Lighting	The classifications of lighting requirements for different pavement types are rough.	Lighting is project dependent.
	Transportation	A variety of models are developed to predict the outputs of different transportation modes.	Transportation is project dependent. Sensitivity analysis will help ease the concern of uncertainty.

Table 6.2 (Continued)

Priority rank	Scenarios	Status quo	Comments
2nd level	Recycling	The materials are recycled, considering only dismantling and transporting the old pavement structures.	The future impact of recycled materials on the usage module is desired.
3rd level	Albedo	A deterministic and rough estimation is used.	A time-dependent climatological model is desired.
	Carbonation	Empirical model is used.	Sensitivity analysis is useful.
	Construction activity	The contribution is limited in a relatively complete LCA methodology; missing the consideration of equipment wear.	Project construction information is welcome to give a more precise estimation.

The entries in Table 6.2 indicate the research priorities according to the significance. And the author wants to further discuss the following sections in more detail.

6.6.1 Further Improvement of the LCA-LCCA Model

The proposed LCA and LCCA model can be used to perform the maintenance schedule optimization using the dynamic programming algorithm, which is sufficient for the engineering practice purpose. The case study only considers the major maintenance activities while ignores the minor ones. One can easily update the algorithm to incorporate more maintenance scenarios by adding more elements to the maintenance decision variable. Roughness developing model is significant to the LCIs and cost calculation which uses the results by the MEPDG software in the case study. An experimental or empirical model is welcome to substitute the transition matrix in the algorithm.

Substantial uncertainties are found in various models, like the relationship between fuel economy and roughness, albedo, carbonation, and pavement structure effect, etc. Their influences over the LCIs and resulting costs are significant. More reliable models describing the listed items are in urgent need.

6.6.2 Discounting the LCIs

In the current LCA studies, no one makes explicit differentiation between emissions (and ultimately, damages) at different points in the timeline. For instance, whether an air pollutant emitted today or 30 year later does not reflect any differences in the final LCIs. Discounting in economics is motivated by pure time preference, productivity of capital, and uncertainties. Is it possible and necessary to discount the air pollutants in terms of time? The answer seems to be yes but needs further evidence to support and practice. Or in a more convenient way, the question turns to be: whether the environmental damages should be measured in monetary units and at which rate the discounting should be applied? In the dissertation, the environmental damage is described by the monetary index and the Gamma discount rate is used as a meaningful trial. Four following aspects, as summarized by Hellweg (2000), changes in the magnitude of damage in terms of time and location, discounting of environmental damages because of time preference, capital productivity, as well as uncertainties, may shed lights on the future research direction.

6.6.3 Urgent Need of Rolling Resistance Study

As suggested in the case study in Chapter 4, two significant components of the usage module, pavement structure and roughness, which are two pavement-related factors that affect the rolling resistance, influence the LCIs greatly and bring tremendous amount of uncertainties. The clear understanding of the relationship between fuel economy and rolling resistance is the footstone to start comprehensive comparisons between PCC pavements and HMA pavements. Unfortunately, current available studies are very limited and the findings vary in figures or even rules, as summarized in Table 6.2. The study of the relationship of rolling resistance and fuel economy is therefore strongly recommended in both empirical and mechanistic ways.

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APPENDIX 1: LCA MODELS

A1.1 LCA Approach

LCA is a tool used to identify all cradle-to-grave inputs and outputs of a system that are relevant to the environment. The goal of LCA is to compare the full range of environmental effects assignable to products and services in order to improve processes, support policy and provide a sound basis for informed decisions.

The International Organization for Standardization (ISO) 14040 series of standards (14040:2006, 14044:2006, 14047:2003, 14048:2002) defines LCA as the *compilation and evaluation of the inputs, outputs and the environmental impacts of a product system throughout its life cycle* (ISO 2006) . The LCA technique is structured along a framework with a number of steps or activities in each of these steps. There are four steps:

> *"1. Goal Definition and Scope - Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.*
> *2. Inventory Analysis - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).*
> *3. Impact Assessment - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.*
> *4. Interpretation - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.*

APPENDIX 1 (Continued)

The ISO 14040 series of standards provides only a generalized framework. In using the LCA technique for carrying out an LCA study, one may distinguish several types of activities (Heijungs and Suh 2002):

> *"1. There are activities, related to the design of the system, the collection of data, the making of assumptions and choices, and so on. This, for instance, include steps like the drawing of system boundaries, the collection of process data, the choice of allocation method, and the choice of an impact method.*
> *2. There are computational activities, related to transforming or combing data items into a certain result. For instance, emission data are related to the functional unit, aggregated over all unit processes in the system, multiplied with appropriate characterization factor and so on.*
> *3. There are activities that are related to the procedural embedding of an LCA project. Depending on the topic of study and the intended application, different stakeholders may be involved in certain ways. For certain applications, critical review by an independent expert is essential.*
> *4. There are activities that are related to the planning of the LCA. For instance, one can start with a small-size LCA, to explore the potentials and bottlenecks, and then to reiterate the steps in a more complete way. Uncertainty analyses can give rise to further reiterations.*
> *5. There are activities related to the reporting of an LCA. All types of requirements on what to report and how to report can be imposed to obtain transparent and reproducible reports."*

The ISO-standards for LCA do not clearly separate these different types of activities and are lack of concrete mechanism concerning the implementation of the standards into specific product and system, like pavement in this dissertation.

There are three approaches to perform an LCA study, including process LCA, economical input-output LCA (ECO-IO), and hybrid LCA. The third one combines the advantages of and is designed to alleviate the shortcomings inherent to the first two approaches on which they are based. Detailed discussion of the strength and weakness of each of the three approaches will be presented in the following sections.

A1.2 Process Approach

A process model approach bases primarily on the standard recommendations of the Society of Environmental Toxicology and Chemistry (SETAC). In the process-based LCA (P-LCA), one itemizes the inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) for each step in producing a product.

The prominent advantage of P- LCA model is its target-oriented. Each step in the process is discretized and careful explored so that the results are detailed and process specific. With P-LCA results, one can answer questions like:

1. What are the most significant contributors to energy consumption of a product among all the examined ones?
2. What's the most effective way to improve a product in terms of lessening its environmental burdens?
3. Where is the advantage of one design compared with the alternatives?

Ironically, the strength of P-LCA is also where the weakness lies. The most notorious criticize of P-LCA model may be the truncation error that is inherent to its birth. A system boundary is mandatory for P-LCA model which considers only a portion of the complete system, with the completeness depending on the broadness of the boundary. Theoretically, one step can be traced about the upstream origination and the associated energy consumption and environmental metrics infinitely, known as indirect influence.

The system boundary of P-LCA is drawn with the assumption that the inputs of any further upstream stages have negligible effects on the total inventory for the product or process studied, and thus introduces truncation error since this assumption is frequently invalid.

The magnitude of the truncation error varies with the type of product or process and depth of the study, but can mount up to 10% according to Boustead and Hancock (1979) or even to 50%, according to Lave et al. (1995), Lenzen (2000, 2001a) and Lenzen and Treloar (2003). Although these examples are raised from building construction field, it does demonstrate the existence and significant influence of truncation error in P-LCA models.

A1.3 ECO-IO Approach

ECO-IO LCA, as abbreviated to be IO-LCA in the following contents, is an approach using aggregate sector-level data to qualify the amount of environmental impact that is directly attributed to each sector of the economy and the amount that is purchased from other sectors in producing its outputs. This approach combines life cycle assessment and national economic input-output table, and is based on the work of Wassily Leontief (1936).

IO-LCA relies on sector-level averages that may or may not be representative of the specific subset of the sector relevant to a particular product. On the case that the goods or service of interest is representative of the sector, IO-LCA model can provide fast estimation of full supply chain implications. To perform the IO-LCA study, one needs the national level input-output (IO) table. The latest version of IO table in the U.S. is formed with 2002 economic data, and consists of 430 economy sectors.

A1.3.1 Pros and Cons

To overcome the truncation error born to P-LCA, the IO LCA has been adopted to minimize the cut off error due to the incompleteness of upstream stages associated with the P-LCA approach. Different from a limited inclusion of upstream contributors for P-LCA approach, typically with three or four upstream stages, IO approach assesses an infinite number of upstream stages, includes a full range of direct and indirect inputs into the product or process, and thus avoids the truncation errors thoroughly (Lenzen, 2002).

However, IO-LCA should not be regarded as superior than P-LCA because many weaknesses also pertain to the IO approach due to its nature of macro-economic level aggregation instead of project level itemization. Several following concerns and assumptions plague the application of IO-LCA model, including data source uncertainty, homogeneity assumption, use of national averages, capital equipment, and sector classification/aggregation, to name a few.

Information used to compile IO-LCA model is originated from surveys and forms submitted by industries to government for national statistical purpose. The uncertainty in sampling, response rate, missing/incomplete data, estimations to complete forms, etc. from the original data remain as underlying uncertainty in the IO tables computed by the agency. Homogenous assumption of sector production is one of the major limitations to the utility of IO-LCA model, which stipulates a single output by each economic sector, whether the output is in either fixed proportion or can be inter-substituted. Bitumen is a byproduct of petroleum refinery sector in the US IO table, with other products such as gasoline, diesel, wax, etc. Makeup of these productions varies due to property differences of imported oil from different regions, technology improvement or instrument update of refining process, market dollar fluctuation of the products, and so on. Neglecting these possible changes, IO tables fix the bitumen (and other products) production portion in the sector and evaluate the environmental burdens proportionally.

In a specific project, project level or regional level data is preferred while this requirement cannot be satisfied by using IO tables. Cement production in the cement manufacturing sector of the IO table uses a national level environmental discharges associated with unit cost of cement production while cement manufacturing costs of manufacturers vary significantly due to the purchases of limestone sources (transportation distances, transportation mode, energy consumption during extraction, etc.), quality of the materials, production technologies, to name a few. Thus, a simple treatment to use national level data instead of project level introduces the accuracy concern of LCIs.

IO tables do not consider the purchase/input of capital equipment by sectors, such as asphalt drum mix in the plant, but rather as outputs of the economic system (Lenzen, 2001b). The initial investment on the drum mix is apportioned over the life time so that questions such as determination of the left life of the equipment and its replacement periods further complicate the problem of interests.

High extent of sector aggregation is also criticized for IO tables. Due to the aggregation, the number of sectors in current IO tables is too limited. For instances:

> “*Cement manufacturing sectors comprise establishments primarily engaged in manufacturing portland cement concrete, natural, masonry, pozzalanic, and other hydraulic cements; cement manufacturing establishments may calcine earths or mine, quarry, manufacture, or purchase lime”* (IO Table 2002)

A certain type of cement needs to share room with all its counterparts, making the specific evaluation of the energy consumption and environmental pollutant release barely impossible.

Although the values given by IO tables have a large variance, IO tables are still regarded as a useful tool to be a complement to the P-LCA model, and in this sense, a hybrid LCA model forms.

A1.4 Comparison between P-LCA and IO-LCA

Based on the previous discussion, a summary table is compiled to more clearly state the advantage and disadvantage of these two models by Hendrickson et al. (2006). It is found that the advantage and disadvantage of these two methodologies are mutually complementary. The P-LCA suffers from truncation error mainly while provides concrete, detailed results; the EIO-LCA eliminates truncation error efficiently while is plagued by significant extent of uncertainty in the data and results. It is nature to combine these two methods together, namely hybrid LCA.

A1.5 Hybrid LCA

The weakness of P-LCA model and IO-LCA model has been recognized and result in the development of hybrid technique of LCA model. Regarding the basic rationale underlying, hybrid LCA can further be divided as Tier-based hybrid LCA (called P-based hybrid LCA for consistency in the following contents) and IO-based hybrid LCA.

A1.5.1 P-Based Hybrid LCA

The concept of P-based hybrid analysis was raised in 1970s by Bullard and Pillati (1976) and Bullard et al. (1978) who combined process analysis based on flow charts with IO tables to calculate the environmental impacts of a product or process. P-based hybrid analysis can be performed simply by adding IO-based LCIs to the P-based LCIs but needs to remove double counting issue since P-based results are already counted.

P-based hybrid LCA model can produce satisfactory complete and efficient inventory results compared with P-based LCA model. However, several aspects must be attended properly to assure a successful operation of the model (Suh and Huppes 2002):

1. Great attention shall be paid to the border selection between P-based LCA and IO-based LCA to avoid significant errors introduced by important process modeled by aggregated IO information.
2. Be cautious of double counting issue in P-based hybrid LCA model. The commodity flows of the P-based system are already considered in the IO tables and need to be subtracted away about that portion.
3. P-based hybrid model deals with the P-based system and the IO-based system in a separate way, so that the interaction between them cannot be assessed in a systematic way.

P-based hybrid LCA model, however, has similar limitations to P-based LCA since the same mechanism is behind these two methods, with the former one eliminating portion of truncation error due to the substitution of P-based data with IO-based data.

A1.5.2 IO-Based Hybrid LCA

IO-based LCA is complete and less labor and time intensive compared with P-based LCA. The direct input to the product or process of the model is calculated using process level data and substitutes the corresponding IO values of the IO model without altering the upstream processes or truncating the system boundary and avoids truncation error consequently (Treloar et al. 2003).

Treloar et al. (2000) have proposed and developed the methodology for IO-based hybrid LCA model and outlined the possible steps to obtain data for LCA models using hybrid techniques, as follows:

1. Formulate an IO-based LCA model.
2. Extract the most important paths of the appropriate sector.
3. Derive case specific process LCA data for the product or process being studied.
4. Substitute the case specific process LCA data into the IO model.

This approach is straightforward to understand and convenient to manipulate and thus has been applied to pavement field (Treloar et al. 2004). Although process level data has been employed to substitute the IO data, which in a certain extent eases the critique of IO-based LCA model, it still carries the same attributes and suffers the same shortcomings.

There are very limited LCA studies using hybrid techniques in pavement field till date so that the P-based hybrid LCA and the IO-based hybrid LCA will not be differentiated and given a uniform name: hybrid LCA.

A demonstration figure about the PCC pavement construction is presented to visualize the principle and process of applying hybrid technology to LCA study. Specifically, process data is substituted by the IO data, which on one hand, captures the truncation error associated with cement concrete production, and on the other hand utilizes the project specific data to improve the reliability of the LCIs.

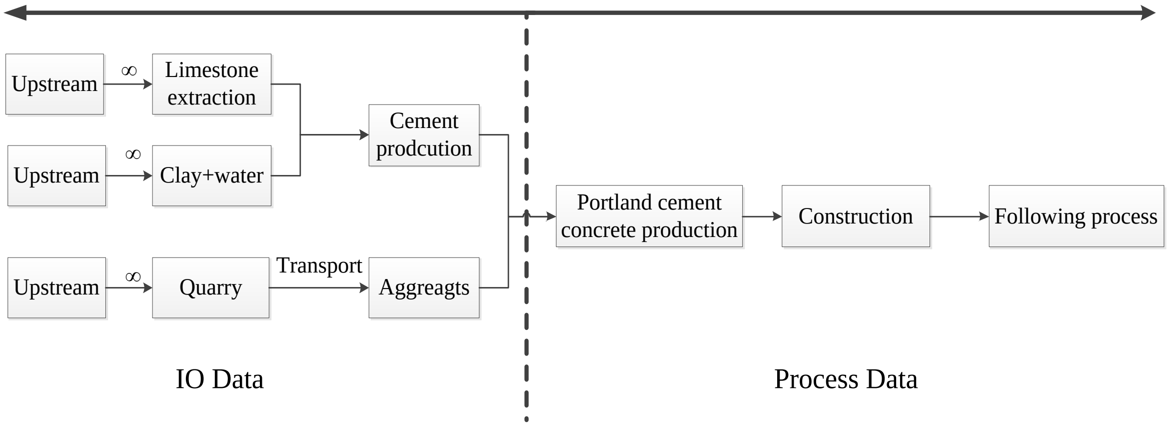

Figure A1.1 Hybrid LCA Approach Applied to PCC Pavement

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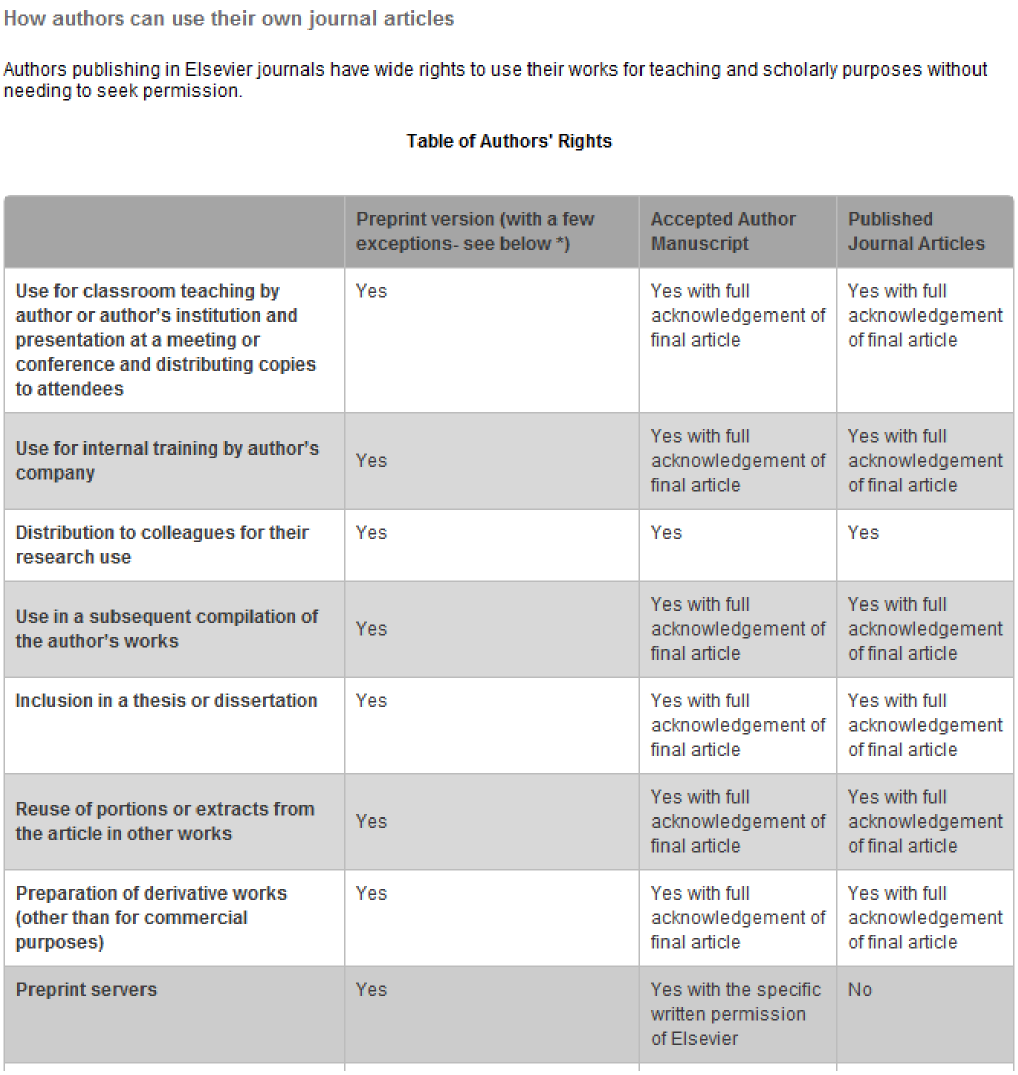

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