Sustainable Pavement Construction

Developing a methodology for integrating environmental impact into the decision making process

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Abstract

Sustainability and specifically environmental stewardship are emerging as prominent issues in engineering decision-making. Despite this, the United States has neither a national policy on sustainability, nor a national sustainable transportation strategy. In many cases this has resulted in state DOTs basing their environmental practices on requirements set out previously by EPA regulations with little or no additional consideration of environmental effects.

A survey conducted as part of this thesis revealed that environmental stewardship is not considered part of current DOT pavement management engineers' job responsibilities, despite having duties such as pavement design and maintenance which can greatly affect the environmental impact of a project. Initial cost and engineering judgment were the most widely considered in decision-making, with LCCA also being considered at least some of the time by most respondents. Environmental impacts, on the other hand, are not often integrated into formal decision making and are more likely to be considered as a "tie breaker" when alternatives have similar costs.

The literature review also covered two distinct types of environmental decision support tools: Environmental Rating Tools and Environmental Impact Calculators. Rating Tools gather predominantly environmental impact information in order to award a score to a project. Environmental Calculators are software tools that use material or equipment inputs to estimate the amount of pollutants produced by a project. While a variety of environmental impact tools are currently available they suffer from drawbacks such as incomplete or unclearly defined LCA boundaries, consideration of only one environmental impact, subjectivity, lack of transparency, out-of-date databases, and an inability to perform probabilistic calculations. CO_2e was the only environmental factor considered by nearly all Environmental Calculators reviewed as part of this thesis and was a major focus of the Rating Tools.

The thesis proposes the framework for a tool that addresses some of the limitations of available tools and aids decision-makers in incorporating environmental factors into roadway decision-making. The proposed tool would address many of the limitations of previous environmental impact calculators and could be implemented without the need for extensive additional research. The tool would calculate emissions due to material extraction and production, emissions due to construction activities, resource consumptions, and emissions due to work zone delays. Emissions due to work zone delays are not considered by any other currently available tool. The tool would also perform probabilistic calculations and have a database which could be added to and updated by users. Additional products developed as part of this thesis are a review of currently available environmental impact tools and a Microsoft Excel workbook used to demonstrate the intended usage of the tool.

It is concluded that the development of such a tool is necessary and feasible. The proposed tool would address limitations of available tools by considering more than one environmental impact, including the previously neglected impact of emissions due to work zone related delay, pairing a user-friendly interface with an editable database, and supporting probabilistic calculations. Recommended future research includes surveying state DOT engineers to determine the barriers delaying implementation of currently available environmental impacts tools. Further benefits could be realized by programming the proposed tool and building a database that reflects the materials, mixes, and construction activities available to a specific locality.

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1 Introduction

1.1 Background

Concern for the environment both in the United States and internationally has been increasing for decades. Furthermore, with Global Climate Change and other negative effects of pollution being publicized more and more, there is reason to believe these concerns will only increase with time. While avoiding and mitigating environmental degradation is undeniably an important issue in its own right, the role of an engineer requires that the demands of economic growth and the well-being of society never be neglected. This balance of environmental, economic, and social factors is understood as *sustainability*. With growing emphasis on environmental stewardship and continuing recognition for the desirability of economic and social progress, sustainability is emerging as one of the preeminent issues in all fields of public policy, business, and engineering.

Worldwide, the implementation of sustainability strategies varies greatly. The European Union (EU) has a sustainable development strategy that includes transportation considerations, while New Zealand and the UK have specifically designed sustainable transportation strategies (*Barella, et al. 2010*). The United States has neither a comprehensive general sustainability policy, nor a national transportation sustainability strategy (*Barella, et al. 2010*). It was only within this year that the Federal Highway Administration (FHWA) released a definition of Sustainable Transportation Systems in the United States (*Harman 2010*).

Sustainability, therefore, has been prioritized (or not) by each state Department of Transportation individually. A 2009 survey of State DOTs administered by the Georgia Tech Civil Engineering program found approximately 60% of DOTs make use of some sort of environmental, social, or economic performance measure or indicator system, though only five states reported having formally implemented sustainability programs (*Barella, et al. 2010*). Many current environmental practices are based on requirements previously placed on DOTs by the Environmental Protection Agency (EPA) or FHWA, illustrating the usefulness of federal guidance in furthering sustainability (*Barella, et al. 2010*).

Economic considerations revolve around the cost to add to and maintain the transportation infrastructure system in order to meet society's growing expectations and needs. As these costs have consistently been a primary focus of decision-makers through the history of public works, economic decision support tools and techniques are more developed and more widely used than their environmental and social counterparts. Social impacts are difficult to quantify and appear in the most comprehensive tools through proxy measurements such as stakeholder involvement (public input through open hearings or other means being assumed to increase benefit to public) and access to multi-modal transportation (conventional wisdom suggests increased livability when public transportation, bicycle, and pedestrian travel is available and safe). Therefore, greater consideration of life-cycle environmental effects is the next step towards sustainable practices.

1.2 Problem Statement

In order to integrate sustainability into their current practices, governments, companies, and agencies need a new set of decision support tools. Environmental impact tools provide information on the pollution and other impacts expected from the design, construction, and maintenance of transportation projects and can be used to provide more information to transportation engineers and decision-makers. These tools are necessary to establish benchmark values and set future performance goals, track trends and monitor advancement towards or regression from desired targets, compare different design alternatives, and compare the performance between different branches within an agency (*Barella et al. 2010*). For example, the information provided by these tools can be used to justify additional funding to projects that may require greater financial commitments to achieve more sustainable results.

While there are a variety of environmental impact tools currently available, they suffer from a variety of drawbacks that have prevented them from becoming widely used in the United States. Many tools consider only one type of environmental impact. Tools that provide an environmental “rating” or “score” to a roadway project often consider multiple environmental impacts, but are either subjective or require users to input data calculated by other tools. Certain tools lack transparency and thus are not trusted by practitioners while others require very extensive inputs and are disregarded as too difficult to be useful. Currently available tools are also limited to deterministic calculations that do not clearly characterize the variability and risk associated with their outputs. Decision-makers and industry need a tool that considers multiple significant environmental impacts, is transparent, and can be used without complicated inputs. The tool should also be customizable, allowing the user to improve the quality of calculations if they choose to invest time and effort into more extensive inputs. Probabilistic capabilities would allow users to further refine their decision making and assess the confidence they have in the environmental impacts of various materials, production processes, and construction techniques.

1.3 Objective

The objective of this thesis is to develop the framework for a tool that will aid decision-makers in incorporating environmental factors into roadway decision-making and illustrate its applicability through a series of simple example scenarios. The tool should be able to be implemented without the need for extensive additional research and balance ease-of-use with relevance and value added.

1.4 Scope

This thesis made use of a survey of current practice of US state DOT and Canadian DOT and a review of existing environmental impact tools. Information gained from these sources was used to develop recommendations for a proposed new tool which addresses some of the weaknesses identified in existing tools while taking into account the needs and desires of current pavement engineers. A Microsoft Excel workbook application was also designed to serve as an example of how the proposed tool could be implemented and employed.

1.5 Significance

Environmental impact tools can provide information necessary for the inclusion of environmental considerations in the roadway construction decision-making process. The information can be used for benchmarking, tracking changes in the environmental impact of design decisions, identifying which practices or life-cycle steps have the most impact, and justifying expenditures to improve environmental performance. While various environmental impact tools have been available in the United States for many years, it seems that none have achieved widespread implementation. Implementation of the available tools may be being held back by a lack of widespread knowledge about the tools, the limited scope of many tools, the lack of transparency and trust in proprietary tools, and the time and effort required to make use of tools requiring extensive input.

The thesis provides decision-makers and pavement professionals with summary descriptions of current tools. These summaries will be useful for any individual or group who wishes to know more about what is currently available or is considering choosing a tool to be used by their company or agency. The thesis also recommends a framework and describes the necessary steps for the development of a new tool with expanded capabilities and improved usability. These two products will help decision-makers make an informed choice of how to best include environmental considerations into their plans and designs.

1.6 Thesis Overview

The environmental impact tool proposed by this thesis was developed through the study of currently available tools and examination of current decision-making practices. By studying these tools and surveying state DOT pavement management engineers, a new tool is recommended which addresses limitations present in previous tools.

Chapter 2 consists of a review of literature on life-cycle cost analysis, life-cycle assessment, and current practice in the use of life-cycle assessment. It also includes description and analysis of ten environmental impact tools currently available for use by engineers and others involved in transportation infrastructure decision-making.

Chapter 3 describes a survey conducted as part of the research. The survey itself is described and its results are reported and interpreted. The results are used to gauge interest in expanded consideration of environmental impact, as well as define the context in which a decision-support tool would be used.

Chapter 4 presents the researcher's recommendations for the development of a new tool for use by transportation infrastructure decision-makers. The proposed tool incorporates desirable characteristics from the tools described in the literature review while attempting to avoid many pitfalls that have prevented previous tools from gaining widespread usage.

Chapter 5 presents examples of uses for the proposed tool. Multiple potential uses of the tool are described, and two scenarios are described in detail. For these two scenarios user interfaces and results from the proposed tool are simulated to show how it may be integrated into the decision-making process.

Chapter 6 is a summary of the project and its conclusions. It includes recommendations for further development of decision-support tools and for the future research necessary to support such endeavors.

2 Literature Review

This literature review consists of a look at sustainability and its economic and environmental components. An overview of definitions and perspectives on sustainable development and sustainable transportation is followed by sections on life-cycle cost analysis, life-cycle assessment, and environmental impact tools. Life-cycle cost analysis and life-cycle assessment are put forward as tools for furthering sustainability in terms of economic and environmental impacts, respectively. Societal effects are not included in this literature review as they are considered outside the scope of the thesis.

2.1 Sustainability

In 1987 the Brundtland Commission defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (*WCED 1987*). In the interceding decades this has become the basis for most definitions of sustainability in many fields outside of national development. The “needs” referenced in the Brundtland Report can be understood as economic, environmental, and social factors which must be balanced in order to achieve progress without unacceptable negative results in one or more of the categories. Despite this consensus on the components of sustainability, a unified definition of sustainable transportation systems has not yet emerged.

The International Road Federations (IRF) defines transportation systems as sustainable if "through effective planning, design, construction, operation, maintenance and rehabilitation, they have the capacity to use resources efficiently during their life cycle; provide improved transport benefits for the whole community; respect the environment; and enable a range of socio-economic services (notably in terms of enhanced mobility, safety and comfort)" (*IRF 2009*).

A similar but more detailed definition was offered by the Council of the European Union which stated that a sustainable transportation system: "allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations; is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development; limits emissions and waste within the plant's ability to absorb them, uses renewable resources at or below their rates of generation, and, uses non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on the use of land and the generation of noise" (*European Council 2001*).

The Federal Highway Administration (FHWA) has recently released its own definition of sustainable transportation, putting forward that "Sustainable Transportation means providing exceptional mobility and access in a manner that meets development needs without compromising the quality of life of future generations. A sustainable transportation system is safe, healthy, affordable, renewable, operates fairly and limits emissions and the use of new and nonrenewable resources" (*Harman 2010*).

These definitions use differing language to express similar outlooks on the importance of intergenerational equity and the balance of economic, social, and environmental factors. Their level of detail, however, varies substantially. On one end of the spectrum, the 2009 IRF definition states that a sustainable transportation system "will use resources efficiently… [and] respect the environment" without addressing what constitutes efficiency or respect. The 2001 definition published by the European Council specifies that a sustainable transportation system "limits emissions and waste *within the planet's ability to absorb them*, [and] uses renewable resources *at or below their rates of generation*" (emphasis added) but the practical implications of the definition still remains unclear. This is because the thresholds for what the planet can absorb or generate, and thus what is sustainable, have been only vaguely defined (Hunkeler and Rebitzer 2005).

Furthermore, sustainability goals developed in the United States or Europe may not be practically implementable in all areas of the world. Low-, middle-, and high-income regions face different challenges and have an uneven ability to devote resources towards sustainable transportation systems (*Jeon et al. 2006)*. These socioeconomic and political differences between regions make uniform sustainability definitions standards an unrealistic goal (*Jeon et al. 2006*). Progress towards sustainability, or "movable targets" with different standards for countries at different development levels may be a more appropriate way of viewing sustainable transportation systems (*Jeon et al. 2006*).

2.2 Life-Cycle Cost Analysis

Life-Cycle Cost Analysis (LCCA) is a decision-support technique that allows for comparison of pavement alternatives with comparable structural and performance characteristics based on the overall cost each alternative. By taking into account all costs over the lifetime of the pavement asset, LCCA enhances the ability of agencies to make decisions that reflect the long-term economic effectivenes of a project. In contrast, consideration of only initial costs can result in short-term savings paired with unplanned for economic burdens in the long-term. The FHWA has been working to increase awareness and encourage use of life-cycle costing since the early 1990s (FHWA 2002).

In the Life-Cycle Cost Analysis Primer published by the US DOT in 2002, five steps are laid out for LCCA. First, alternatives with equivalent benefits are put forward. In step two, the anticipated construction, preservation, maintenance, and repair activities are identified and their expected timing planned out. The costs associated with these activities are estimated in step three. Step four requires the use of a discount rate to calculate either the present value or equivalent uniform annual value of all costs. As a final step, this total present value is used, among other variables, to compare an evaluate alternatives.

Beyond its use as an economic evaluation and decision-support technique, the documentation of LCCA for a project serves as a valuable record for recording and communicating why investment decisions were made. This is useful both for ensuring the transfer of knowledge to new employees and reporting to the public how and why their tax dollars were spent on infrastructure improvements. (FHWA 2002)

2.2.1 LCCA Best Practice

Current best practice for LCCA, as put forward by the US DOT, involves calculating both agency and user costs over the life-cycle of examined alternatives (FHWA 2002). Agency costs include all expenditures made by a DOT or other funding source during the lifespan of the project. User costs are values representing the monetary losses experienced by the public making use of the roadway, most commonly associated with vehicle operation, travel delay, and crashes (FHWA 2002). Probabilistic analysis taking into account the variability and uncertainty in cost inputs is also recommended (FHWA 1998).

It is recognized that current practice most often emphasizes agency costs over user costs when it is time for alternatives to be evaluated and compared. User costs are viewed with skepticisms because the time value of money for roadway users does not have a set market value and the relationship between agency activities, vehicle operation costs, and crashes are not completely understood. Furthermore, user costs often exceed agency costs, especially in high traffic areas where work zones produce substantial delays, and there is reluctance to make decisions based on values that are neither completely objective nor directly included in the project's budget. Even when user costs are not directly used to select an alternative, they can be used to highlight that an alternative chosen for its low agency cost has undesirable levels of user disruption which should be mitigated. (FHWA 2002)

LCCA has historically been calculated deterministically rather than probabilistically due to the complex and intense calculations necessary to fully reflect the variability and uncertainty of a project's life-cycle cost. When LCCA is being calculated deterministically, single values are provided for each input and a single value for life-cycle cost is calculated. Sensitivity analysis should be performed on multiple variables to gauge their impact on the overall cost if the input is lower or higher than estimated. While a sensitivity analysis can give some sense of the range of potential life-cycle costs, probabilistic analysis is considerably more thorough. Probabilistic analysis involves inputting a distribution of possible values for each cost variable and determining a corresponding distribution for the output life-cycle cost. With modern computing power available to all agencies, there is little reason not to follow best practice and perform probabilistic analysis using Monte Carlo simulation. (FHWA 1998)

2.2.2 RealCost Software

RealCost is a software tool which consists of a Microsoft Excel 2000 spreadsheet with user interfaces and calculations imbedded through Visual Basic for Applications coding. The FHWA developed RealCost to instruct pavement designers and decision-makers on how to perform LCCA, and to help integrate LCCA into the decision-making process through a functional tool. It follows the LCCA methodology laid out by the FHWA's 2002 LCCA Primer and 1998 LCCA Technical Bulletin. Users enter anticipated construction, preservation, maintenance, and repair costs and timings and the software converts this to a present value life-cycle cost. RealCost encourages the use of best practices by supporting probabilistic calculations and estimating user costs due to work zone delay. Probabilistic calculations are performed using Monte Carlo simulation if activity costs and timings are entered as probability functions rather than deterministic values. User costs are calculated through comparing traffic demand to the roadway's capacity during normal flow and work zone conditions. If cost inputs are entered as single values rather than probability functions, the calculations can be done deterministically. If the user does not input traffic and capacity characteristics for the roadway, the calculations will be done without user cost. (RealCost 2004)

2.3 Life-Cycle Assessment

Life-cycle assessment (LCA) is a decision-support technique that allows for comparison of products or processes based on their environmental impacts over the lifespan of the project. It evolved as a concept nearly simultaneously in the United States and Europe in the late 1960s and 1970s, existing under different names until the term LCA came into use in 1990 (Hunt and Franklin 1996). From 1990 onwards it has been the subject of an increasing number of publications, with a 1992 publication by the Centre of Environmental Science of Leiden University in the Netherlands describing the principle of LCA as having "become widely accepted, both in Europe and in the US" (Guinee et. al 1992). Though LCA was initially conceptualized as a way to track solid waste production, its applicability for monitoring energy usage was quickly recognized (Hunt and Franklin 1996) and contemporary usage is largely focused on the calculation and assessment of greenhouse gas emissions.

In 1993 the Society of Environmental Toxicology and Chemistry (SETAC) published “Guidelines for Life-Cycle Assessment – A ‘Code of Practice’” which included what has become one of the most accepted definitions of LCA (Flintsch 2007). SETAC defined LCA as “an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impacts of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use/re-use/maintenance; recycling, and final disposal” (SETAC 1993).

The International Organization for Standardization (ISO) has also become one of the most widely accepted and influential sources of information and guidance on LCA. The ISO 14000 series defines a range of environmental standards, with 14040 through 14043 dealing specifically with LCA. Flintsch describes ISO 14040 as indicating that “LCA is a technique for assessing the potential environmental aspects and impacts associated with a product (process or service) by: compiling an inventory of relevant inputs and outputs of the process, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study” (Flintsch 2007).

Four or five steps are identified in the LCA process, depending on the defining organization. ISO 14040 identifies four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation (Flintsch 2007). SETAC describes a similar process with the same first three steps but a life-cycle improvement assessment as the final step rather than interpretation (Flintsch 2007). Guinee, Udo de Haes, and Huppes include five steps in their description of an LCA in their 1992 document “Quantitative life-cycle assessment of products.” This five step LCA consists of:

1. the *goal definition* of the LCA study;
2. the *inventory* of all the different types of inputs from and outputs to the environment (environmental inputs and outputs) during the entire life cycle of a product resulting in the inventory table;
3. the *classification* converting environmental inputs and outputs into contributions to

environmental problems, resulting in the environmental profile of a product;

4. the *valuation* of the different elements constituting the environmental profiles, thus substantiating a final appraisal; and
5. the *improvement analysis*.

Bringing these LCA descriptions together, it can be seen that they all include a: definition of goal and study boundaries, inventory of all inputs and outputs (classified or unclassified) which fall within this boundary, an assessment or valuation of the anticipated impact that the inventoried inputs and outputs will produce, and an interpretation which may or may not include strategies for reducing the life-cycle impact of the product or process.

The definitions and standards put forward for LCA have formed the basis of many recently developed environmental impact tools. These tools are used primarily for the calculation of carbon footprints and while they are often described as LCA tools they make use of different boundaries for what is and is not included in the life-cycle.

2.4 Environmental Impact Tools

The environmental tools described in this thesis fall into two very distinct categories: environmental calculators and environmental rating tools. Every tool has its own set of boundary conditions and various life-cycle activities are included and omitted from each. The focus of the literature review was on tools developed and used in the United States, but two tools developed in the United Kingdom and one international tool are described for comparison.

For this thesis an environmental "calculator" is a software tool that uses material or equipment inputs to estimate the amount of pollutants produced or other environmental impacts of a project. Environmental calculators may estimate a single pollutant or environmental impact, or multiple types of pollutants and environmental impacts. The tools which fall into this category and are examined in this thesis are: MOVES2010, NONROAD, asPECT, Changer, and PaLATE.

An environmental "rating tool" is defined as a methodology that calls for the gathering of predominantly environmental impact information for a transportation project and uses this information to assign a rating or score to the project. Rating tools can be in the form of a checklist, a questionnaire, or a procedural description and may require varying levels of documentation and verification. Rating tools do not perform estimates or calculations themselves but may require the outputs of environmental calculators or other measurement systems to establish the appropriate rating. The environmental rating tools reviewed in this thesis are: Greenroads, GreenLITES, IN-VEST, I-LAST, and Ceequal.

2.4.1 Calculators

Objective assessments form the backbone of engineering. Environmental calculators estimate emissions, leachate, and material use based on databases, values entered by the user, or a combination of default values supplemented by user inputs. These values can be used to set benchmarks, track trends, and compare project alternatives. Quantitative data produced by such tools provide a substantial advantage in justifying the inclusion of environmental factors in decision making.

Outputs are often in the form of raw numbers which may be difficult for laypeople, politicians, and non-technical decision makers to understand, make use of, and market. Additionally, both database and user input systems suffer from drawbacks. Publicly available databases may not be properly maintained and can become out-of-date or contain inaccuracies. Proprietary software makes use of databases and calculations that may not be transparent to the user. When user input is used rather than a database, the heavier burden of time and effort put on the user to gather up-to-date and accurate data may discourage use of the tool.

MOBILE/MOVES

The MOBILE model for estimating emissions of vehicles was first developed by the EPA in the late 1970s and was revised many times in the following decades. The last version, MOBILE6.2 is being phased out in favor of the MOVES2010 model (*EPA 2009*). MOVES2010 models the production of volatile organic compounds (VOCs), nitrogen oxides (NOx), carbon monoxide (CO), direct particulate matter (PM10 and PM2.5), various mobile source air toxics (MSATs), and other pollutants and pollution precursors emitted from cars, trucks, motorcycles, and buses (*EPA 2009*). This can be used to compute CO_2 equivalent (CO_2e) or broader inventories of emitted pollutants.

MOVES2010 estimates only those emissions produced by vehicles travelling on roadways and is not able to be applied in a meaningful way to construction projects. Social and economic factors are not considered. MOVES2010 is intended for modeling the emissions of entire systems, but as environmental assessments of construction processes become more thorough, similar vehicle emission models may be used to calculate the currently unconsidered increase in emissions due to work zone related traffic delays.

NONROAD

NONROAD is a model developed by the EPA in the mid 1990s when the organization began regulating nonroad vehicles and equipment emissions. The software models hydrocarbon, NOx, carbon monoxide, carbon dioxide, sulfur oxides, and particulate matter of recreational vehicles, logging equipment, agricultural equipment, construction equipment, industrial equipment, and lawn and garden equipment (EPA 2005). A wide range of construction equipment, including excavators, graders, material mixers, pavers, and seal coating equipment are included in the tool's databases (EPA 2005). The databases include both national and local estimates for equipment inventories as well as rates of new equipment acquisition and retirement (EPA 2005).

NONROAD calculations can potentially be used to estimate emissions from road construction at a systems level, though it would be difficult to apply at the project level. Social and economic factors are not considered.

asPECT

The asphalt Pavement Embodied Carbon Tool (asPECT) developed by the United Kingdom's Transportation Research Laboratory (TRL) is an asphalt pavement-specific life-cycle carbon foot-printing tool that is currently in a beta usage phase. When completed it is anticipated that the tool will be compliant with the Publicly Available Specification (PAS) 2050 released by the British Standards Institution (BSI) in 2008 (TRL 2009). This PAS specifies the requirements for LCA of GHG emissions due to the production of goods and the provision of services and is intended to build on the methods put forward in BS EN ISO 14040 and BS EN ISO 14044.

asPECT divides the asphalt pavement life-cycle into 10 stages: raw material acquisition, raw material transport, raw material processing, processed material transport, road component production, material transport to site, installation, scheme specific works, maintenance, and end of life (Wayman et al. 2010a). A version capable of calculating carbon equivalent emission productions for the first 7 stages of the pavement lifecycle was released for Beta testing and evaluation in October 2009. After review and modification a second Beta version which also covers the first 7 stages was released in October 2010, and a complete version is scheduled for completion in 2011 (TRL 2010).

The asPECT tool is a freely downloadable software application, available from http://www.sustainabilityofhighways.org.uk/ (TRL 2010). The program has a limited database of materials with associated emission factors for their extraction and processing. New materials can be added to the database in two ways. The user can input previously calculated or researched emission factors (Wayman et al. 2010b). Alternatively, the tool can calculate the emission factor when the user inputs the tons of raw material extracted and processed in a year, along with the energy used by the extraction and processing facilities and equipment in a year, and the mix of electricity and fuel used to provide the facilities and equipment with energy (Wayman et al. 2010b). A similar process is used to generate emissions factors for pavement mixtures produced by production plants – tons of mixture produced, energy used, and mix of electricity and fuel used over the course of the previous year is input and the tool calculates an emission factor (Wayman et al. 2010b). Inputting hauling distance and tonnage is required for transport calculations. Laying and compacting activities are assumed to result in 4 kg CO_2e/ton of material laid unless otherwise specified (Wayman et al. 2010b).

asPECT estimates the global warming potential of emissions and omits emissions that do not contribute to global warming as well as other types of pollution. Social and economic factors are also outside the scope of the tool. asPECT does not provide estimates for emissions due traffic caused by construction activities, though this is described as a desired addition to future versions of the tool (Wayman et al. 2010b).

Changer

The International Road Federation (IRF) has developed propriety software called "Changer" (Calculator for Harmonised Assessment and Normalisation of Greenhouse gas Emissions for Roads) which calculates GHG emissions generated by the pre-construction, on-site, material, and machinery activities involved in roadway construction (IRF 2010). Changer was designed in conjunction with external technical partners and the databases and calculations used by the program have been evaluated and validated by the Swiss Federal Institute of Technology (IRF 2010). The tool currently has pre-construction and construction modules, and an additional maintenance module is planned for future release (IRF 2010).

Changer estimates the global warming potential of emissions and omits emissions that do not contribute to global warming as well as other types of pollution. Social and economic factors are also outside the scope of the tool. Changer does not provide estimates for emissions due to material extraction or traffic caused by construction activities. Greenroads, a rating tools described in the following section, specifies Changer outputs as an acceptable form of carbon emission documentation for fulfillment of its life-cycle inventory (LCI) requirement (Anderson and Muench 2010).

PaLATE

PaLATE is a freely distributed Microsoft Excel worksheet based tool with the capability to estimate both life-cycle costs and environmental impacts of multiple pavement alternatives (Natham 2009). Users input the pavement design, the pavement design life, and the equipment that will be used during construction and PaLATE calculates net present value, emissions, and leachate information (Horvath 2003). Emissions considered include CO_2, NO_x, PM10, SC_2, and CO (Horvath 2003).

The program is designed to be easily modified, making it adaptable enough to be used by many companies and agencies (Natham 2009). PaLATE outputs could be used as inputs for a rating system used to compare different alternatives (Chan and Tighe 2010). A modified version of PaLATE is one of the tools specified as adequate to justify environmental impact points in the Greenroads rating system (Anderson and Muench 2010).

The tool is sensitive to the data quality of its material and equipment emissions/pollution database, which tends to become out of date as technologies and techniques evolve (Natham 2009). If the tool becomes more widely used, it is reasonable to believe that the database will be better maintained and the quality of data would improve (Natham 2009).

2.4.2 Rating Tools

In order to recognize and reward sustainable decision-making, numerous rating schemes have been developed in different fields. In the United States most of the transportation rating systems currently in use are modeled after the Leadership in Energy & Environmental Design (LEED) certification program for building construction, modified to be appropriate for transportation systems (Barella et al. 2010).

Rating systems, especially those which include certifications reflecting different levels of performance, have the benefit that they can be easily understood by laypeople, politicians, and non-technical planners. This allows rating tools to be used to encourage sustainable practices and discourage decision-making that neglects sustainability concerns. Rating tools can also be used to highlight areas that many projects perform well in and other areas that need more effort and development.

The corresponding drawback is that sustainable practices not captured by the system are not rewarded and may be neglected in favor of techniques that will increase the project’s score. If a rating system is not comprehensive enough, or not flexible enough to incorporate emerging sustainable practices, the motivation to produce the most sustainable product may be subverted by the motivation to produce the highest-scoring product. Many rating tools incorporate a certain number of unassigned credits to be awarded to innovative or otherwise unspecified practices.

Greenroads

Greenroads is a point-based sustainability rating system similar in style to the LEED certification program (Muench 2009). It was developed by the University of Washington in conjunction with CH2MHill. There are 11 Project Requirements that must be met to receive any level of Greenroads certification and additional 118 voluntary credits that can be earned in the categories of Environment & Water, Access & Equity, Construction Activities, Materials & Resources, Pavement Technologies, and Custom Credit (Anderson and Muench 2010). A project can be ranked as certified (32+ credits), silver (43+ credits), gold (54+ credits), or evergreen (64+ credits) (Anderson and Muench 2010). Documentation proving that each credit is truly deserved must be provided to Greenroads, which then officially awards the appropriate certification level.

Though the emphasis of the rating system is environmental impacts, 30 voluntary credits are dedicated to the Access & Equity category and one of the Project Requirements is that a life-cycle cost analysis (LCCA) is performed for the project (Anderson and Muench 2010). Activities that protect or enhance water quality or local ecology and habitat can be awarded points in the Environment & Water category. Greenroads limits its consideration of emissions to their global warming potentials and does not call for other forms of air pollution to be reported. Two environmental calculators described in this paper, PaLATE and Changer, are specified by Greenroads as fulfilling their documentation requirements for performing the required LCI of GHG emissions (Anderson and Muench 2010). Other tools and techniques may be permissible, but must be approved by Greenroads personnel (Anderson and Muench 2010)

The effects of material extraction are not directly examined, though they may be included if the project performs a LCA, worth 2 points in the Materials & Resources category. Material production impacts are also not fully considered by the Greenroads rating system, though 3 points can be earned in the Pavement Technologies category through the use of Warm-Mix Asphalt and a LCA with appropriate boundaries will capture the material production process. The environmental effects of work zone related traffic disruption are not considered, though user costs due to traffic delay may be considered within the required LCCA.

Greenroads is limited by its inability to take many life-cycle effects like maintenance, preservation, and traffic emissions into account since certification occurs at substantial completion (Muench 2009). While points can be earned for maintenance and operation plans that provide economic or environmental benefits, it is outside the abilities of the rating system to enforce accountability or modify the awarded certification based on the extent to which agencies follow through on these plans.

GreenLITES

GreenLITES (Leadership In Transportation and Environmental Sustainability) is a rating system in many ways similar to Greenroads which was developed by the New York State Department of Transportation. The first version of the system was released in September of 2008 and supported the rating of project designs. Since then, a maintenance/operations plan spreadsheet has been developed (April 2009) and a regional pilot program has been initiated (March 2010) (NYSDOT 2010b). The two available spreadsheets are separate rating systems; the first applies to project designs which are certified before going to bid (NYSDOT 2010a) while the second rates the performance of state and regional agencies in charge of maintaining roadways and other transportation infrastructure (NYSDOT 2009). Unlike Greenroads, GreenLITES was developed primarily as an internal monitoring and assessment system (NYSDOT 2010a, NYSDOT 2009). It is a self-assessment and self-certification tool without external auditors confirming the score, though projects and groups achieving the highest ratings of gold or evergreen are reviewed by a Main Office review team (NYSDOT 2010a, NYSDOT 2009). Random checks will also be performed to ensure quality (NYSDOT 2010a, NYSDOT 2009). GreenLITES is widely used on NYDOT projects and will continue to be modified to include emerging technologies and techniques as well to be applicable to an increasing variety of projects and networks (NYSDOT 2010b). The Office of Operations awards plaques and publish GreenLITES results each year (NYSDOT 2009).

By adding a Maintenance and Operations rating system GreenLITES has gone further towards covering the life-cycle effects of transportation infrastructure than many other programs. Social and equity concerns are addressed in the form of points awarded for public outreach, landscape and local feature preservation, and increases in multi-modal transportation access. It does not, however, require any economic analysis to be performed as part of the certification.

The GreenLITES module which rates designs considers material choice through measures such as awarding points for recycled material, but it does not directly cover material extraction or production impacts. It also does not strongly rate the impact of construction activities which may vary based on factors such as the choice of equipment or equipment fuel. The environmental effects of work zone related traffic disruption are also not considered.

IN-VEST

The Federal Highway Administration has released a Beta version of its sustainability rating tool under the working title: IN-VEST (Infrastructure Voluntary Evaluation Sustainability Tool) (Shepherd 2010). There are three categories that can be rated by IN-VEST: system planning and processes, project development, and transportation systems, management, operations, and maintenance (Sustainable Highways Self-Evaluation Tool 2010). System Planning and Processes consists of 140 possible points evenly distributed over 14 goals (Sustainable Highways Self-Evaluation Tool 2010). Project Development is divided into 39 goals worth from 1 to 10 points each, adding up to a total of 124 possible points (Sustainable Highways Self-Evaluation Tool 2010). Transportation Systems, Management, Operations, and Maintenance consists of 150 possible points evenly divided amongst 15 goals (Sustainable Highways Self-Evaluation Tool 2010). Each category is rated separately and points earned in one cannot be counted toward the score of a different category (Sustainable Highways Self-Evaluation Tool 2010). Project rankings are determined based on percentage of the total points are achieved. The possible rankings are bronze (>=30%), silver (>=40%), gold (>+50%), and platinum (>+60%) (Sustainable Highways Self-Evaluation Tool 2010). Neither FHWA nor a third-party agency certifies these rankings (Sustainable Highways Self-Evaluation Tool 2010).

The beta versions of IN-VEST includes initial weighting for points in the Project Development category, while all goals in the System Planning and Processes and Transportation Systems, Management, Operations, and Maintenance categories are all given equal weight. Weights are intended to reflect the potential of each goal to impact the overall sustainability of the system, project, or operations/maintenance plan being rated. Some activities which are already required due to federal regulations receive a relatively low weighting even if they are expected to have substantial impacts because there is little room for voluntary action. Activities which the federal government wants to encourage are assigned higher weight than they may otherwise have been awarded. In general, highest weights (5 – 10 points) are assigned to safety-related credits, environmental credits are worth 3 points, equity credits are worth 2 points, and economic credits are worth 1 point, though there are variations from this due to credits affecting multiple forms of impact and credits that are intentionally incentivized or de-emphasized due to regulatory overlap. All of these weightings will be adjusted as the tool is reviewed and refined. (Sustainable Highways Self-Evaluation Tool 2010)

The effects of material extraction are not directly examined, though they may be included if the project performs a LCA, worth 2 points in the Project Development rating phase. Reducing material extraction impacts is also listed as a rationale for awarding points for use of recycled materials (worth up to 5 points) and will also be effected by reuse of materials (worth up to 5 points). Material production impacts are considered through the Reduced Energy Materials credit, which awards up to 3 points for reducing fossil fuel use and/or emissions at the asphalt or cement plant, or reducing worker exposure to emissions at the work site. The environmental effects of work zone related traffic disruption are not considered, though user costs due to traffic delay may be considered if a LCCA is performed. (Sustainable Highways Self-Evaluation Tool 2010)

IN-VEST includes a rating phase for systems planning and system maintenance which expands its ability to capture all life-cycle phases of pavement projects. Social and equity concerns are addressed in the form of points awarded for public outreach and education, preservation of scenic views and historical or cultural landmarks, travel demand management, and increases in multi-modal transportation access. It also allows points to be earned for economic analysis in the form of LCCA and Cost Benefit Analysis as well as advanced financial planning at the systems planning level.

I-LAST

The Illinois Department of Transportation partnered with the Illinois Joint Sustainability Group, the Illinois Road and Transportation Builders Association, and the Illinois branch of the American Council of Engineering Companies to develop a sustainability advisory tool called Illinois - Livable and Sustainable Transportation Rating System and Guide (I-LAST). I-LAST is a checklist of activities associated with highway design and construction that are considered sustainable. These activities are divided into the broad categories of Planning, Design, Environmental, Water Quality, Transportation, Lighting, Materials, and Innovation. It is recognized that not all items on the checklist will apply to every highway project and thus direct comparison between two projects making use of I-LAST is not recommended and no awards levels are specified. The scoring system is designed to be simple and require minimal time and effort while still giving the highway industry a way to identify and acknowledge sustainable practices. (*I-LAST 2010*)

Social and equity concerns are addressed in the form of points awarded for public outreach and increases in multi-modal transportation access. I-LAST does not, however, award any points for economic analysis. Points are awarded for material choice activities such as the inclusion of local or recycled material, but environmental impacts due to material extraction and production are not considered. Construction-related activities such as techniques which would reduce equipment fuel usage or emissions are not considered, nor are the environmental effects of work zone related traffic disruption. Water quality and plant/animal habitat concerns are considered. Emissions or emission-cutting techniques are not directly rated by this tool, but its guide does describe potential emission reductions as the rationale behind points awarded for actions such as use of recycled materials and cut/fill balancing.

Ceequal

The Civil Engineering Environmental Quality (Ceequal) system is an assessment and awards scheme developed in the UK by a team led by the Institution of Civil Engineers (ICE). It is currently managed by CIRIA and Crane Environmental. Ceequal is flexible enough to be used on a wide range of civil engineering projects, including transportation, water and wastewater, and energy infrastructure. (Ceequal 2008)

Much like Greenroads, GreenLITES, and I-LAST, Ceequal is a credit-based system which awards points for sustainable practices in 12 different categories of design and construction for civil engineering projects (Campbell-Lendrumand and Feris 2008). The 12 categories, project management, land use, landscape, ecology and biodiversity, the historic environment, water resources and the water environment, energy and carbon, material use, waste management, transport, effects on neighbors, and relations with the local community and other stakeholders (Ceequal 2008) represent different aspects of social and environmental sustainability. Questions that do not apply to the project are not considered as part of the total possible points and scoring is based on percentage of possible points available for the project (Campbell-Lendrumand and Feris 2008). This differs from the previously described rating systems which rely on the absolute score of each project for either the final score or the assignment of the ranking. A project can be ranked as Pass (>25% of possible points are awarded), Good (>40% possible points), Very Good (>60% possible points), or Excellent (>75%) (Ceequal 2008).

The Ceequal awards scheme can be applied exclusively to the design of a project, exclusively to the manner in which construction was carried out, or to the entire project from design to completion. To ensure quality of results, Ceequal scoring is done through a two-step process. An assessor employed by the company managing the project determines which questions apply to the project and which of these applicable points has been earned. The assessor then submits the score and documentation to an independent verifier who reviews the evidence of each point the assessor claims and awards the official level of certification. When evidence cannot be produced to prove that an action was taken or that it was truly beneficial, no points are awarded, making quality documentation through the project critical. (Campbell-Lendrumand and Feris 2008)

The roughly 200 questions that make up the Ceequal rating system cover a broad range of environmental and social topics, but cost and other economic issues are not directly dealt with. The life-cycle approach put forward by Ceequal means that all aspects of a project, from material extraction to maintenance and operations, must be examined.

2.4.3 Tool Evaluation

Life-cycle assessments should ideally cover all impacts from “cradle-to-grave” of a project. For a project as large and complex as the construction or reconstruction of a highway section, this is generally not seen as practical and assessment tools address a limited number of impacts and activities seen as feasible and particularly significant. Boundaries for what is going to be included in an assessment are often drawn based on either a set of critical activities or a set of critical impacts. These two types of boundaries are used to compare the scopes of tools reviewed in this paper.

Comparison by activity

To aid comparison between tools in this review, the life-cycle activities of a transportation project have been divided into discrete categories called: Material Choice, Material Extraction, Material Production, Material Transport, Construction Activities, Traffic during Construction, and Maintenance Activities. Material Choice occurs at the design stage and may encompass decisions such as whether to incorporate recycled materials and in what amounts. Material Extraction refers to the physical activities required to obtain raw materials. Material Production includes those operations necessary to process and combine raw materials into a product such as a batch of asphalt or concrete. Material Transport includes hauling materials from extraction sites to production sites, from production sites to construction sites, and from extraction sites to construction sites. All impacts caused by equipment or materials at the construction site are included in Construction Activities. Traffic During Construction encompasses all emissions or other impacts resulting from vehicular traffic disrupted by roadway speed or capacity changes in the work zone. All activities performed after initial construction is complete (preventative maintenance, routine maintenance, corrective maintenance, repair, renewal, rehabilitation) are grouped under the category Maintenance Activities. Table 1 presents a comparison of the tools based on the life-cycle activities each considers.

Table 1: Comparison of Tools by Life-Cycle Activities

	Tool	Material Choice	Material Extraction	Material Production	Material Transport	Construction Activities	Traffic during Construction	Maintenance Activities
Calculators	MOVES2010						X	
	NONROAD					X		X
	asPECT	X	X	X	X	X[a]		planned
	Changer	X		X	X	X	planned	planned
	PaLATE	X		X	X	X		X
Rating Tools	Greenroads	X	X[a]	X[a]	X[ab]	X		X[c]
	GreenLITES	X			X[b]			X
	I-LAST	X			X[b]			
	Ceequal	X	X	X	X	X	X[d]	X

a - Life-Cycle Activity is reflected indirectly if a life-cycle inventory or life-cycle assessment is performed

b - Material transport is reflected indirectly through points awarded for activities that result in reduced material transport (i.e. local materials, cut-fill balance).

c - Points are awarded for maintenance plans, but no monitoring is performed.

d - Ceequal considers Tranffic distruptions caused by construction equipment, material transport vehicles, and commuting construction employees, but does not specify lane closure effects.

The Environmental Calculators examined required inputs that were directly associated with activities throughout the life-cycle of the project, making it simple to determine which activities were considered by each tool. MOVES2010, which was designed for traffic emissions modeling rather than for roadway construction, is only directly applicable to the emissions produced by traffic in the work zone. It is the only tool reviewed which has the capability to model traffic emissions during construction. NONROAD, which models only the emissions of nonroad equipment such as graders and pavers, can only be applied to construction activities. asPECT, Changer, and PaLATE all have mechanisms for estimating the effects of material choice, material production, material transport, and construction activity. PaLATE can be used to analyze maintenance activities, while the designers of asPECT and Changer are currently developing updates that will add this capability to their tools. asPECT appears to be the only tool reviewed which directly includes calculations of material extraction effects though Changer and PaLATE databases likely include extraction emissions in their material emission factors.

In the case of Rating Tools, divisions based on life-cycle activity were less clear and it became apparent that many of these activities overlap. For example, the choice of material will significantly affect the material production facility chosen, the amount and distance of material transport, and potentially the construction equipment and techniques used. In order to allow comparison between rating tools, these related effects are not considered and only items which are directly considered are marked for each tool.

Ceequal requires consideration of all of the categories of life-cycle activities examined in this review. Its consideration of traffic during construction includes increased traffic due to equipment, material, and worker transportation, but does not specifically consider delays caused by capacity or speed reductions in work zones. Greenroads considers material choice, activities with direct impacts on material transport, construction activities, and reported maintenance plans. Material extraction and production are considered if the user performs a life-cycle inventory. GreenLITES considers material choice and activities with direct impacts on material transport, and has a separate module which rates the performance of agencies tasked with maintaining transportation systems. IN-VEST includes points awarded for material choice, material extraction, material processing, construction activities, and activities with direct impacts on material transport. It also has a separate rating system for maintenance and operations. I-LAST focuses on material choice and activities with direct impacts on material transport.

Comparison by impact

In order to form a full picture of tool capabilities, it is important to also examine which impact(s) each tool calculates or considers. In this review, impacts have been grouped together as GHG Emissions, Non-GHG Emissions, Non-Emission Pollution, Material Usage, Other Environmental Factors, Economic Factors, and Social/Equity Factors. GHG Emissions and Non-GHG Emissions refer to air pollution. Material Usage refers to the quantity and type of material used in a project. Other Environmental Factors refers to a broad range of less quantifiable impacts including plant and animal habitat impacts, noise, and light pollution. Economic Factors pertains to direct consideration of monetary investment or economic stimulation within the tool. Social/Equity Factors can include consideration of public outreach in the decision making process, livability measures such as access to multiple safe and affordable modes of transportation, and sensitive treatment of items of local value such as landscapes and historically or culturally significance structures or landmarks. Table 2 presents a comparison of the tools based on the environmental impacts each considers.

Table 2: Comparison of Tools by Environmental Impact

	Tool	GHG Emissions	Non-GHG Emissions	Non-Emission Pollution	Material Usage	Other Env. Factors	Economic Factors	Social/Equity Factors
Calculators	MOVES2010	X	X					
	NONROAD	X	X					
	asPECT	X						
	Changer	X						
	PaLATE	X	X	X	X		X	
Rating Tools	Greenroads	X		X	X	X	X	X
	GreenLITES	X	X	X	X	X		X
	I-LAST	X[a]	X[a]	X	X	X		X
	Ceequal	X	X[b]	X	X	X		X

a - I-LAST does not directly award points for emission reductions, but describes the rationale behind many of its awarded activities as their potential emission reductions.

b - Ceequal puts a clear emphasis on GHG emissions but air pollution in general and VOCs as they pertain to human health are mentioned and presumably examined.

Four of the five environmental calculators considered can be more specifically termed “emissions calculators.” As such, they use energy and efficiency data provided by either a database or the user to estimate the gaseous emissions for a project and Material Usage, Other Environmental Factors, Economic Factors, and Social/Equity Factors are outside of their scope. These four calculators are MOVES2010, NONROAD, asPECT, and Changer. MOVES2010 and NONROAD considers both GHG and Non-GHG Emissions while asPECT and Changer calculate only GHG Emissions. The fifth calculator, PaLATE, calculates GHG Emissions, Non-GHG Emissions, Non-Emission Pollution in the form of material leachate estimates, and quantity of material used. It also estimates the life-cycle cost of the project based on the material types and quantities specified.

Greenroads limits their emission considerations to GHG emissions. Greenroads integrates Economic Factors through mandating that each evaluated project carry out a life-cycle cost analysis. IN-VEST awards points for GHG Emissions, Non-GHG Emissions, Non-Emission Pollution, Material Usage, Economic Factors, and Social/Equity Factors. GreenLITES, I-LAST, and Ceequal all award points either directly or indirectly for GHG Emissions, Non-GHG Emissions, Non-Emission Pollution, Material Usage, and Social/Equity Factors. Economic Factors are not integrated into these tools. I-LAST does not directly award points for emission reductions, but does describe potential emission reductions as its motivation for rewarding points in other areas.

2.5 Summary

The concept of sustainability has been evolving over the past three decades or more. While there is widespread agreement that sustainability consists of a balance of economic, environmental, and social factors, a single definition of sustainable transportation has not yet emerged. Despite this lack of consensus on the definition of sustainability, the growing number of definitions and publications indicates ongoing interest and commitment to developing the concept into practice.

Life-cycle evaluations of economic factors are now being incorporated in decision-making, especially for projects with especially large budgets. This represents a shift towards the intergenerational timescale of sustainability in economic considerations. Though LCCA best practice involves the inclusion of both agency and user costs as well as probabilistic calculations, most agencies still consider only deterministically calculated agency costs. Life-cycle assessment of environmental factors is also being increasingly considered, though it is often less formally integrated into the decision-making process than LCCA. Social factors are less understood and more difficult to quantify and as such are not yet incorporated into decision-making in a substantial way.

The range of environmental tools developed or under development by government agencies, organizations, and corporations demonstrates a strong and increasing interest in integrating the environmental impacts of transportation projects into the decision making process. Greenhouse gas emissions are the most widely calculated environmental impact as well as the most widely considered impact in rating tools, reflecting growing concern about Global Climate Change. Though many of these tools omit one or more life-cycle stages, the emission estimates provide valuable information that decision makers can begin using immediately. As with economic analysis best practices, environmental analysis should ideally cover a full range of impacts over the life-cycle of a transportation project.

The usefulness of already available environmental calculator tools is held back by their limited adoption as well as inadequate LCA boundaries and concerns about usability and data quality. Lessons can be learned from these limitations and a new tool designed which will address some of these issues and provide yet more valuable information to engineers and decision makers.

3 Survey

The survey was conducted with the objective of examining decision-making current practice of US state DOTs and Canadian DOTs. Of special interest was the balance of economic, environmental, and social aspects considered as part of the decision-making process and the extent to which different agencies employed long-term or life-cycle evaluations in each of these areas. This information, once interpreted, would reveal how close agencies are to integrating sustainability into their decision-making process.

It was also hoped that information could be gained about which specific environmental factors were being considered and which were not currently considered but were of particular interest to the agencies being surveyed.

3.1 Description / Methodology

3.1.1 Respondents

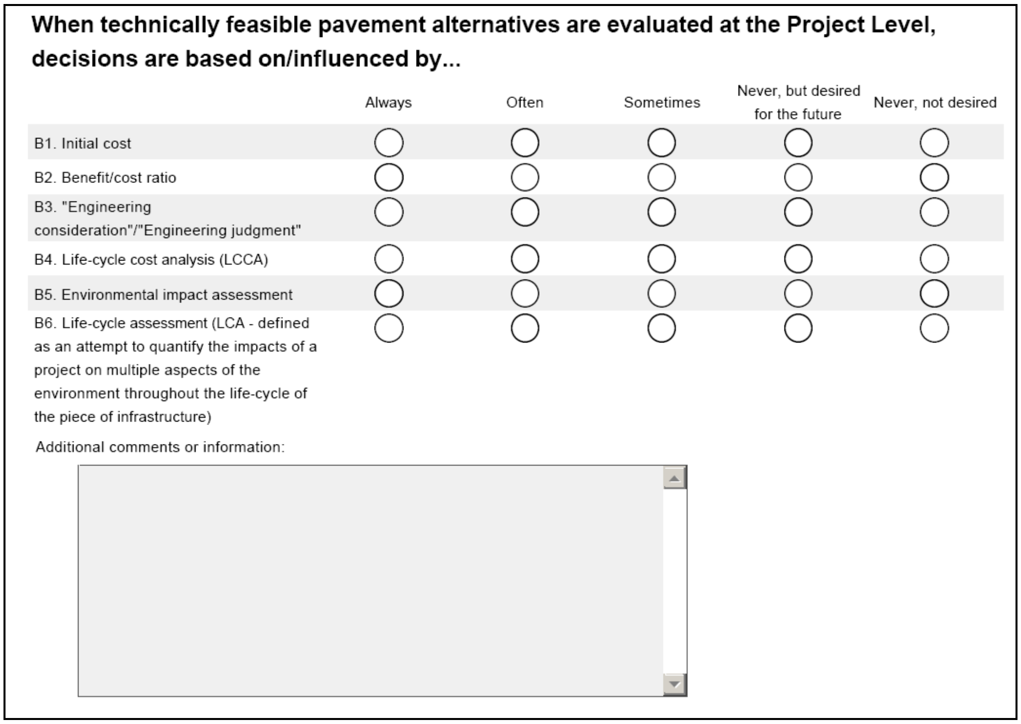
The survey invitation was sent to individuals identified as pavement management engineers from the 50 United States Departments of Transportation (DOTs), Washington D.C., Puerto Rico, and 7 of the Canadian provinces and territories. Respondents described their job duties as including material selection, research, modeling, energy, road inventory, GIS, asset management, construction and preservation project programming, as well as pavement design, testing, evaluation, maintenance, and management. Based on these responses it is believed that the target group of engineers was reached.

Responses were received from 36 United States DOTs and 6 Canadian provincial and territorial Transportation Authorities. This is an overall response rate of 71%, or 69% from the United States DOTs and 86% from Canadian transportation authorities.

3.1.2 Format

Participants were invited to take part in the survey through an email containing a short description of the project and a link to the survey. The entire survey was administered online through the website SurveyMonkey.com. Respondents could choose to respond or not on a question-by-question basis. Many respondents answered all questions themselves, while others sought input from coworkers or forwarded the survey to colleagues who were better able to answer the questions.

The majority of questions asked respondents to rate whether his or her agency uses a certain decision-making criterion “Always,” “Sometimes,” “Often”, or “Never.” Never was divided into two further options: “Never, but desired for the future” if the agency would like to implement the criteria given appropriate resources or “Never, not desired” if this is not a priority for the agency. This division proved objectionable to certain respondents, resulting in these being combined into a more simple “Never” response for analysis of most questions. Comments and additional information were also solicited for each set of questions. Figure 1 presents a representative excerpt from the survey



When technically feasible pavement alternatives are evaluated at the Project Level, decisions are based on/influenced by...

	Always	Often	Sometimes	Never, but desired for the future	Never, not desired
B1. Initial cost	○	○	○	○	○
B2. Benefit/cost ratio	○	○	○	○	○
B3. "Engineering consideration"/"Engineering judgment"	○	○	○	○	○
B4. Life-cycle cost analysis (LCCA)	○	○	○	○	○
B5. Environmental impact assessment	○	○	○	○	○
B6. Life-cycle assessment (LCA - defined as an attempt to quantify the impacts of a project on multiple aspects of the environment throughout the life-cycle of the piece of infrastructure)	○	○	○	○	○

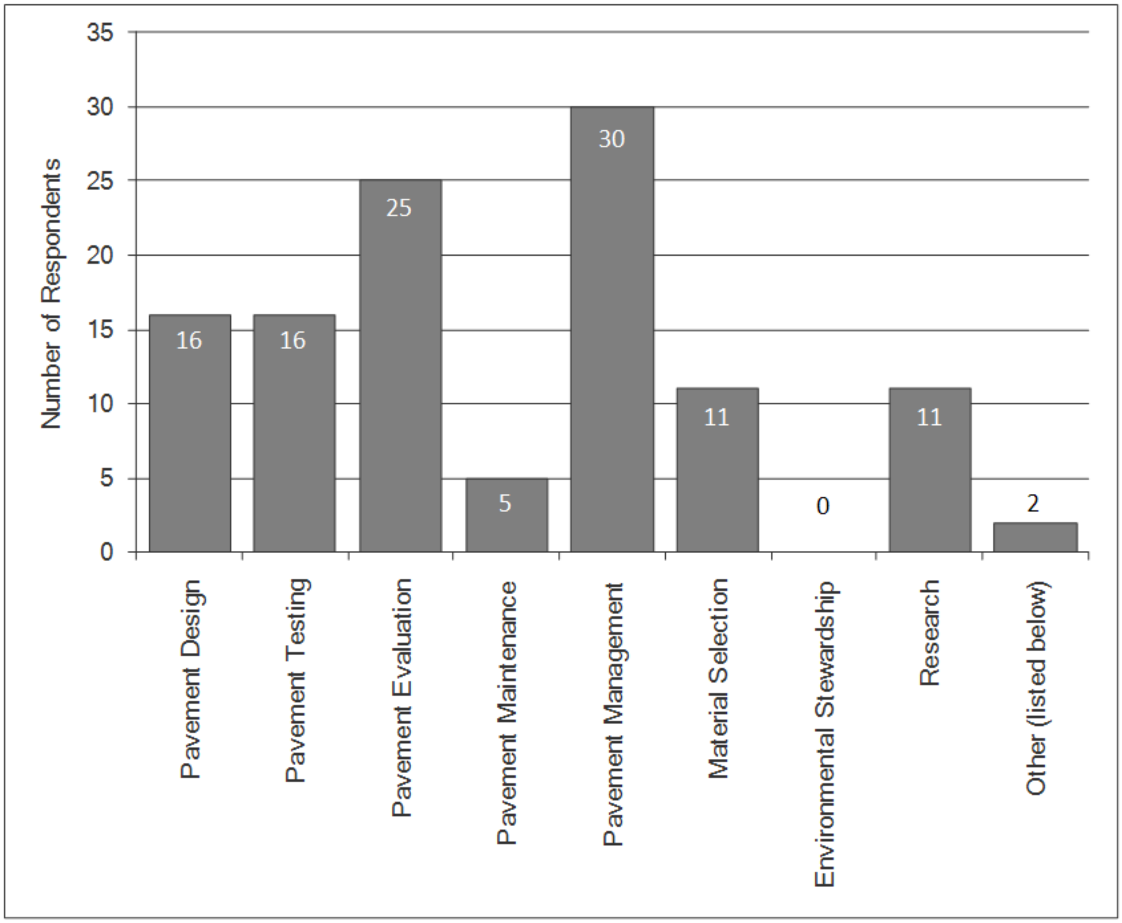
Additional comments or information:

Figure 1: Typical Survey Question

3.2 Results

3.2.1 Job Duties

In order to insure that the proper group of pavement management professionals had been reached by the survey, respondents were asked to report their job duties. A list of expected job duties was supplied and respondents selected as many from the list as applied, and indicated any unlisted job duties by selecting “Other” (Figure 2). Respondents chose between 1 and 7 job duties, with the majority selecting between 1 and 3 job duties. Thirty Respondents (79%) indicated that pavement management was one of their job duties.



Other: modeling, energy, road inventory, GIS, asset management, construction and preservation project programming

Figure 2: Job Duties (please choose all options that fall under your current job responsibilities)

Despite the ability to choose multiple job duties, no respondents indicated that they considered Environmental Stewardship as one of their responsibilities. In some cases, this likely reflected that the agency lacked a formal environmental assessment policy, or that the engineers surveyed were unaware of their agency's environmental policies. This assessment was substantiated by comments from respondents such as "No formal environmental impact assessments are currently performed" and "Environmental impact is not assessed as part of the pavement decision making process." Other agencies do perform assessments of environmental impact, but the pavement management engineers surveyed were not involved in performing the evaluations and sometimes not aware of what went into these assessments. Some respondents described a separate division which handled such evaluations, or indicated that such evaluations were conducted in the planning phase and not considered in the design or management phase. Comments to this effect included:

> "The EIA process is handled by our Planning Office. Unfortunately, I couldn't get in touch with anyone to discuss what activities are considered during the assessment,"[1]
>
> "We consider some of these environmental issues but this consideration is divided among many different units, mostly in planning, rather than as part of pavement selection," and
>
> "Pavement Type Environmental Impact Assessments are not conducted by the Materials Branch (Pavement Management and Design Programs)"[1]

These combined with the universal lack of Environmental Stewardship being viewed as a job duty strongly demonstrates a lack of integration of environmental impact and pavement management in the respondent's agencies. Considering the large potential environmental impact of decisions involving pavement design, material selection, and pavement maintenance (selected as job duties by 16, 11, and 5 respondents respectively), this lack of integration shows a fundamental disconnect between current practice and the widespread desire to increase environmental sustainability in the field of pavement infrastructure.

3.2.2 Economic Assessment

The importance of economic responsibility is well recognized within the pavement engineering profession and economic considerations form the traditional basis for deciding between different technically feasible design alternatives. LCCA is more thorough than assessment methods that include only initial costs due to its incorporation of on-going funding requirements associated with the project over its lifetime. Additionally, assessment methods which include user costs capture a fuller range of economic impacts than those which only take into account agency costs and can also be seen as more responsive to the desires of the population. The idea of including environmental impact as a cost has been considered but is not widely accepted or advocated and is viewed as inappropriate and controversial by some groups.

Participating engineers were asked how often their agencies' project-level decisions were influenced by initial cost, engineering consideration, LCCA, benefit/cost ratios, environmental impact assessment, and LCA. Responses revealed that while initial cost is still a dominant factor in decision making, with all respondents reporting that it was the basis or an influencing factor in their decision at least some of the

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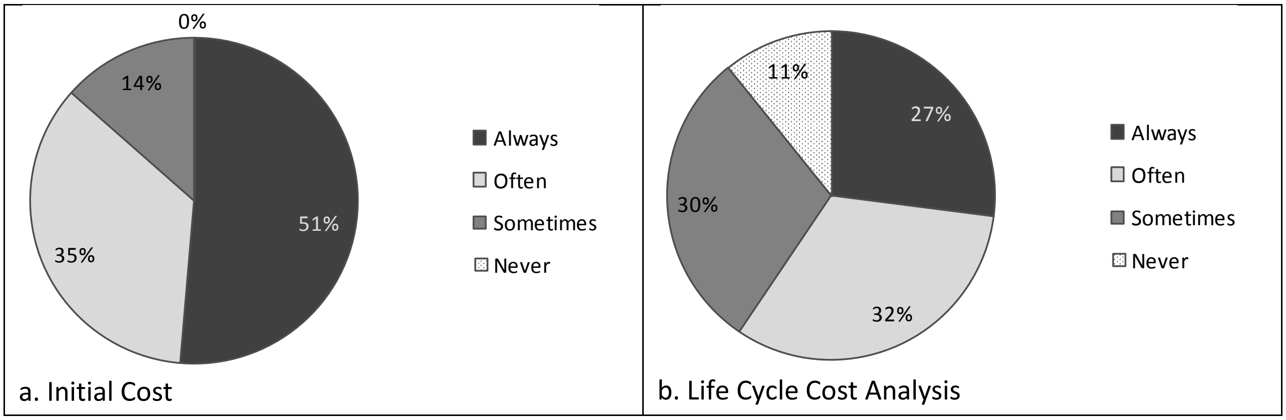
[1] Edited, original text available for review upon request.

time and approximately half reporting that it is always a part of the decision. LCCA is also used by a large majority of responding agencies with only 11% of respondents indicating that their agency never used LCCA as part of their project-level decision making. Figure 3 displays what percentage of respondents indicated that their agencies' project-level decisions were Always, Often, Sometimes, or Never based on/influenced by initial cost and LCCA.



a. Initial Cost

b. Life Cycle Cost Analysis

Figure 3: Economic Assessment Techniques

When performing a LCCA, current best practice involves the calculation of both agency (state DOT) and user (motorist) costs (FHWA 2002). It is also desirable to calculate the expected performance of the pavement and the cost of the project probabilistically (FHWA 1998). Probabilistic analysis involves integrating variability and risk into the calculations and outputting a range of potential results. This contrasts deterministic calculations which output a single value which does not reflect the level uncertainty or risk associated with the project. Monetizing environmental impacts and including them in LCCA is not recommended but has been considered (FHWA 2006).

The survey asked how often an agency's usage of LCCA included consideration of only agency costs, agency costs and some user costs, probabilistic cost variability, probabilistic performance variability, and environmental costs. Most common was the practice of calculating only agency costs, which almost half of respondents reported was always done by their agency. Approximately half of the respondents put forward that their agency calculated both agency and user costs at least sometimes, while only 16% reported that their agency always included both factors. Performance and cost variability were at least sometimes considered by 33% and 30% of agencies respectively. Environmental costs were not described as "always" or "often" being considered by any respondent and only 25% of respondents reported that these costs were sometimes included. Figure 4 summarizes survey participants' responses.

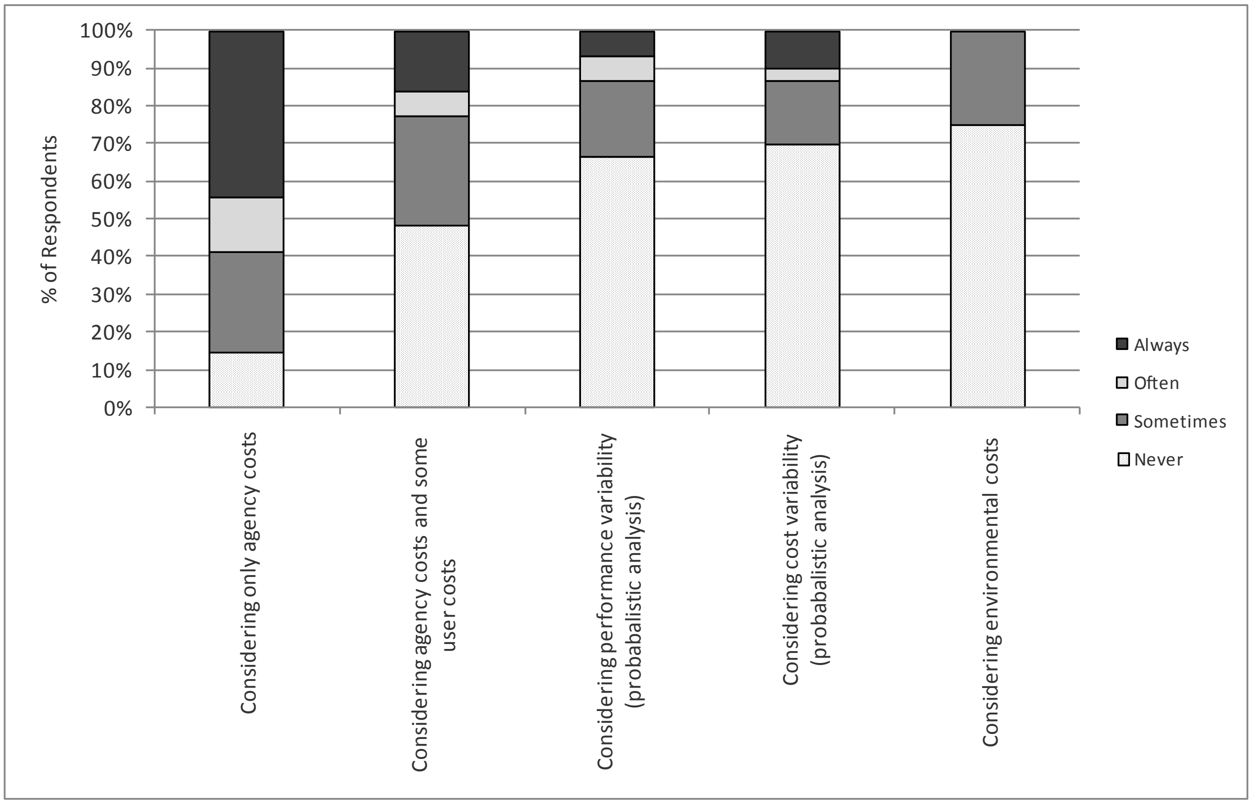
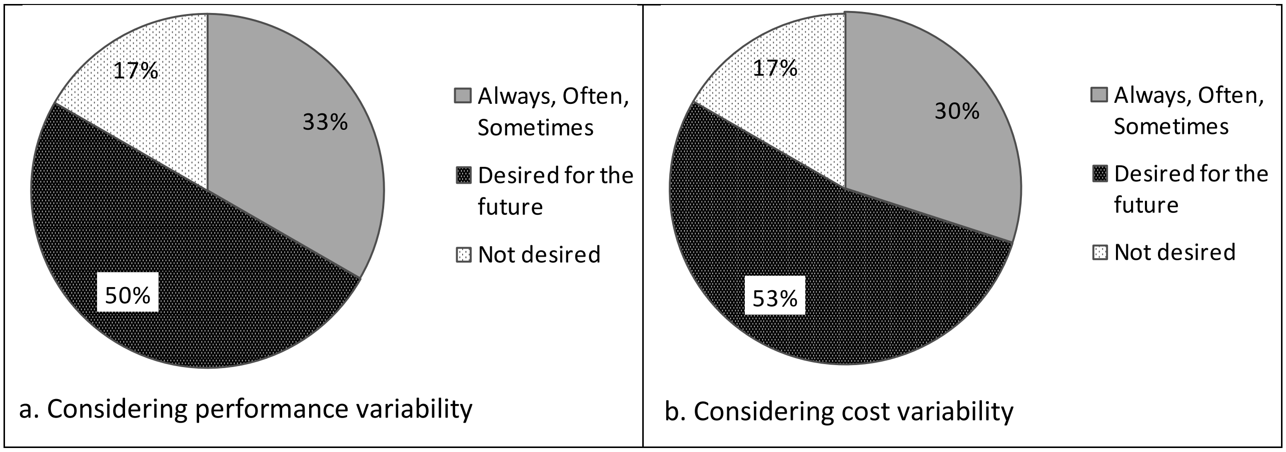


Figure 4: Factors included in project-level LCCA

Four respondents commented that their agencies used FHWA's RealCost software to calculate LCCA. DARWin, PerRoad, and Deighton Software were also identified by respondents as being used for LCCA while one respondent stated that "analysis is mostly by hand." Aggregate conservation, asphalt millings, mitigation of environmental damage, and noise abatement were listed as environmental costs considered by those agencies which sometimes consider environmental impacts. One respondent clarified "Environmental impacts are considered as a tie breaker when the life cycle costs of two alternatives is nearly the same."

From the same question, more information can be learned about the participating agencies' use of probabilistic analysis. Responses to this question indicate a definite interest in adding probabilistic examination of variability in both performance and cost calculations. About a third of the respondents indicated that their agencies currently perform probabilistic analysis, and half reported that it was desired for the future. Figure 5 presents these responses.



a. Considering performance variability

b. Considering cost variability

Figure 5: Probabilistic Considerations in LCCA

When asked which, if any, user benefits or costs were included in their agencies' LCCA, responses clearly showed that user delay during construction was the most commonly considered cost. Respondents indicated that user delay was considered at least some of the time by 66% of represented agencies while all other listed factors were considered by less than 40%. Figure 6 displays the full range of responses to this question.

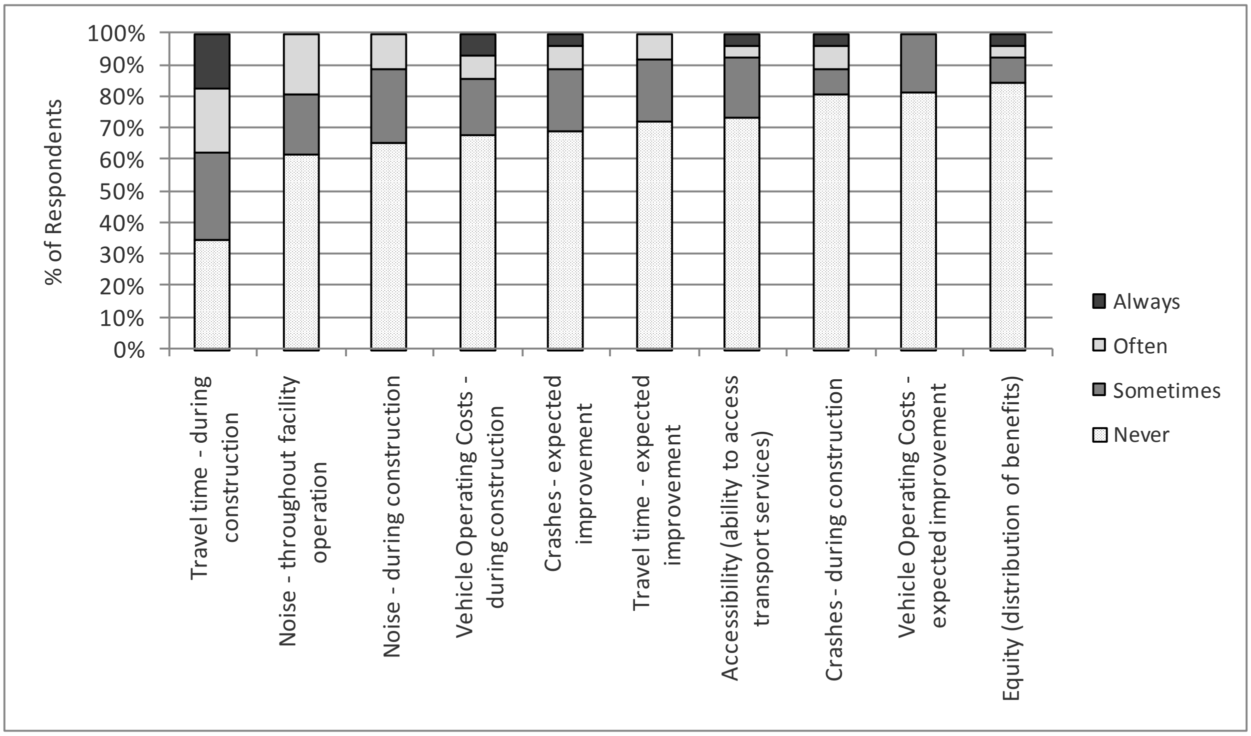


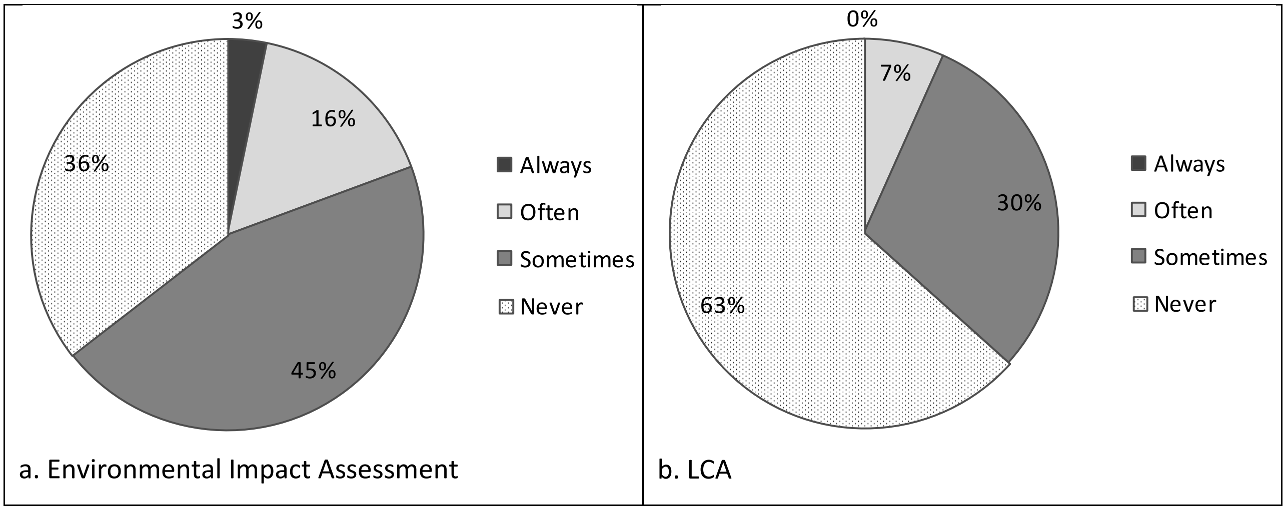
Figure 6: User benefits/costs evaluated include...

Differences in what is included in an LCCA can be due to agency priorities, the relative ease or difficulty of measuring and monetizing a factor, or other complicating factors. Noise, for example, is considered an environmental impact by certain agencies and may be handled separately from costs. Equity, the factor least likely to be considered by the respondents' agencies, is a factor without a universally adopted indicator system or form of measurement that is likely to be considered qualitatively rather than quantitatively if it is considered at all.

3.2.3 Environmental Assessment

The next step towards sustainable design and maintenance practices is a greater consideration of currently overlooked and disregarded environmental factors. For the purposes of the survey, an environmental impact assessment was meant as any calculation and consideration of a single environmental impact or a set of environmental impacts over any time frame. LCA is defined in the survey question as an attempt to quantify the impacts of a project on multiple aspects of the environment throughout the life-cycle of the piece of infrastructure. Using this interpretation of the two terms, LCA more fully reflects the intergenerational nature of sustainability.

Survey participants were asked how often environmental impact assessments and/or LCA was the basis of or an influence in their agencies' decision-making process. While environmental impact assessments were reported to be at least sometimes performed by 65% of respondents' agencies, LCA was only performed by 37%. The greater usage of environmental impact assessment than LCA likely reflects NEPA regulations which require assessment of environmental damage but do not require consideration of life-cycle effects. Figure 7 displays what percentage of respondents indicated that their agencies' project-level decisions were Always, Often, Sometimes, or Never based on/influenced by environmental impact assessments and LCA.



a. Environmental Impact Assessment

b. LCA

Figure 7: Environmental Assessment

In order to evaluate what potential impacts were being considered, participants were asked what construction activities were included in environmental assessments. The activity most commonly reported as included in environmental assessments was material selection, which over two-thirds of participants marked as a consideration. End-of-life activities were the least likely to be considered. The lack of inclusion of end-of-life conditions is likely due to where an agency draws the boundary of their assessments. Since most pavement projects are overlays or reconstructions of existing pavement structures, the disposal of roadway materials is often evaluated as the first phase of new project rather than the last phase of the old. Figure 8 presents the full range of responses to this question.

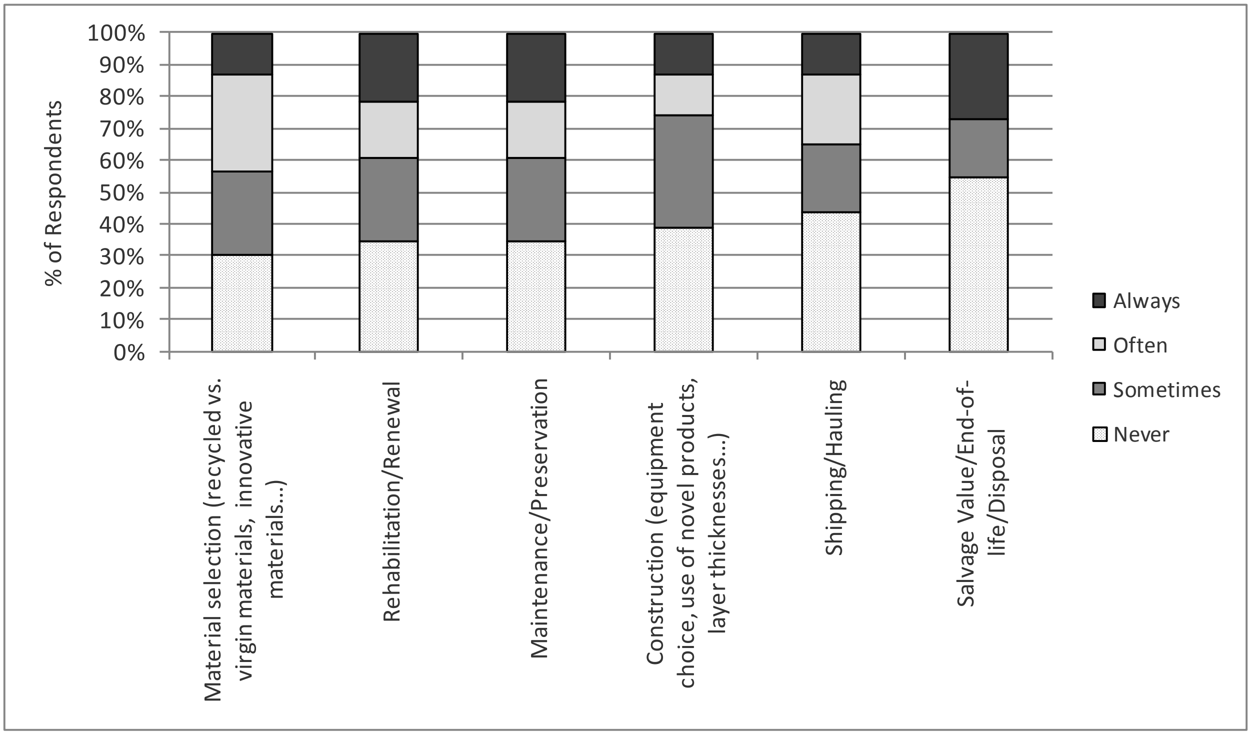


Figure 8: If an Environmental Impact Assessment is performed, activities considered in the assessment include...

When asked what environmental impacts their agencies considered, respondents indicated that habitat impact, land use, contamination of soil during construction, noise, and water use were frequently assessed, with each of these being considered at least some of the time by between 65% and 75% of agencies. Water quality during construction and depletion of resources were also evaluated by more than 50% of agencies. Surprisingly, air quality and toxicological stress are the least likely impacts to be evaluated despite their seemingly high importance. Figure 9 displays the responses for all environmental impacts included in the survey.

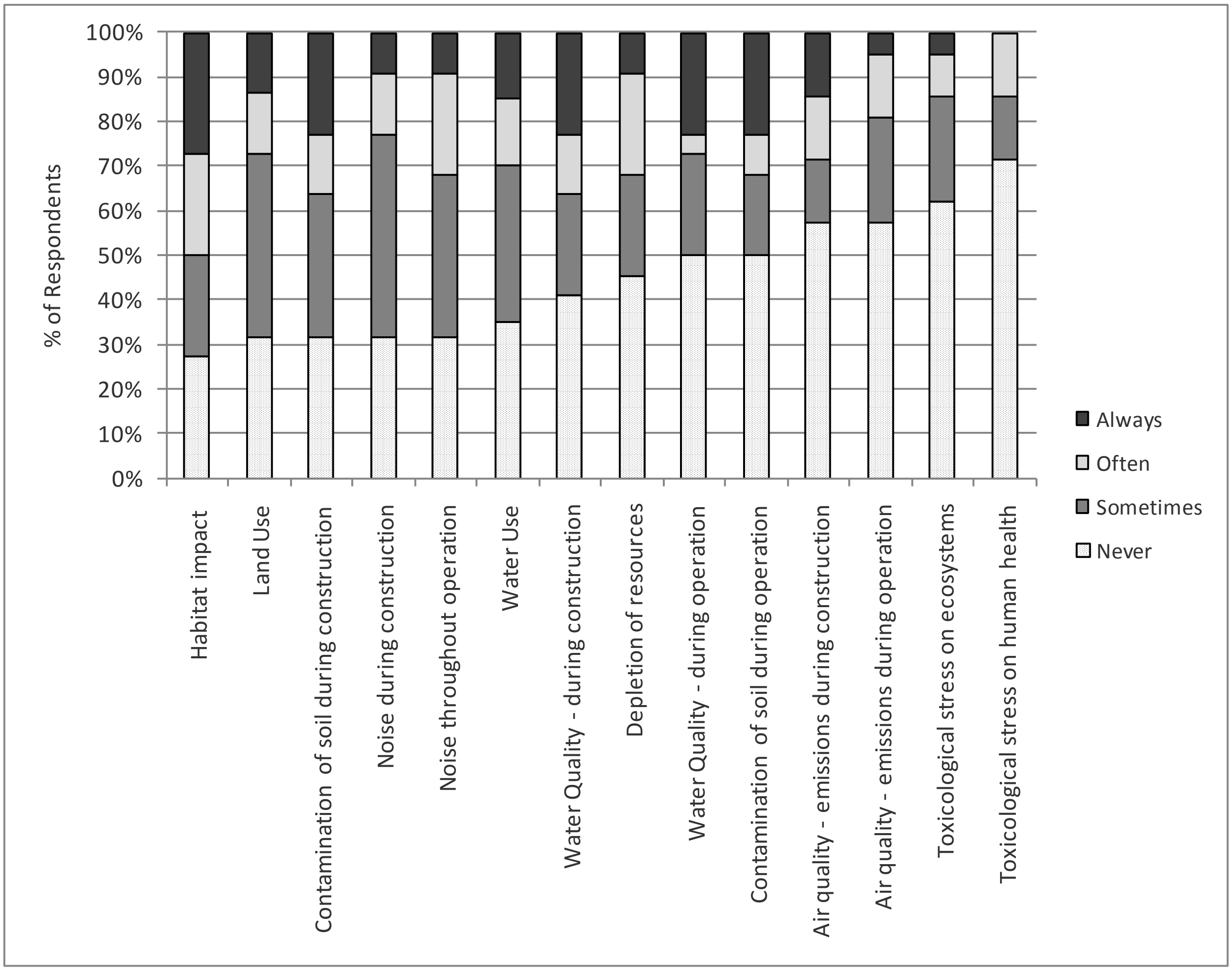


Figure 9: Environmental benefits/costs evaluated in an environmental impact assessment and/or LCA include...

A number of factors likely come into play in influencing which impacts an agency evaluates. Regulatory obligations, overlapping economic impacts, and ease or difficulty of calculation can all have a role in encouraging or discouraging the consideration of an environmental impact separate from the agencies intended priorities or its value to the environment itself. Habitat impact and land use in particular are subject to specific federal regulations regarding endangered species and protected geographic features such as wetlands and historical sites. Noise is also subject to regulation when roadways are located near residential areas and may be connected to obligations to put up sound barriers. Water use may be considered an especially important environmental concern in areas with arid climates or a lack of large aquifers, but may be assessed by agencies in other areas simply because specific water contents are important for proper pavement mix design for structural reasons.

Air quality, both during construction and operation of the roadway, is considered by only 43% of responding agencies despite growing concern over the emission of carbon dioxide and its potential effects on global climate. This could be partly due to difficulty in quantifying emissions from construction activities and operational traffic and likely reflects a lack of regulations requiring such calculations.

3.2.4 Economic and Environmental Comparison

Figure 10 shows that Initial Cost and Engineering Judgment are currently the most commonly used factors in pavement infrastructure decision-making.

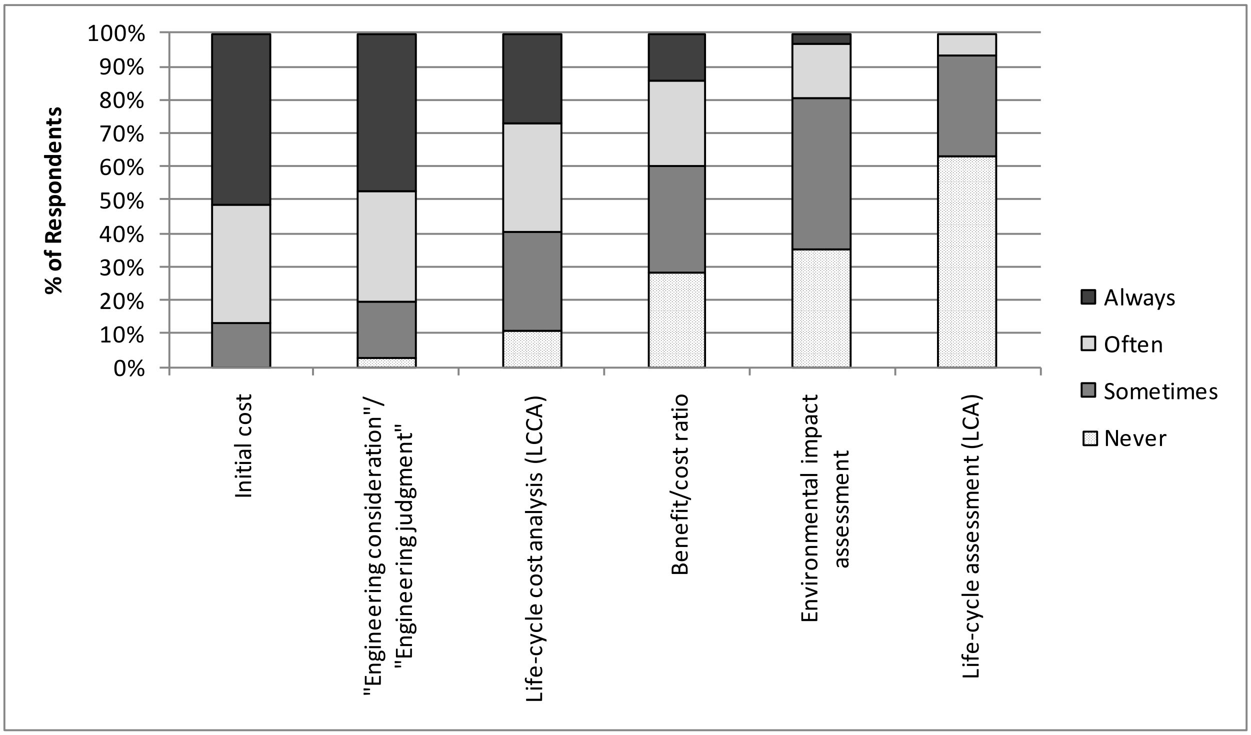


Figure 10: When technically feasible pavement alternatives are evaluated at the Project Level, decisions are based on/influenced by...

All respondents reported that initial cost was a factor at least sometimes and over half report that it is the basis or an influence in all evaluations of technically feasible alternative designs. LCCA is the basis or an influence in decision-making at least some of the time in 89% of respondents' agencies, and always a consideration in 27%. In contrast, LCA is considered by only a third of the respondents' agencies, with no agency reporting that it is always an influencing factor. This demonstrates that cost considerations are still the dominant factor in deciding between technically feasible alternatives. Though initial cost and engineering judgment are still the most relied upon factors in decision-making, LCCA is also widely used. Environmental assessment techniques are much less likely to factor into decision-making despite the growing popularity of sustainability and sustainable design.

3.3 Conclusions

The survey proved useful for capturing current state-of-the practice of the weight assigned to economic and environmental impacts in pavement infrastructure decision-making. Specific findings include:

- Environmental stewardship is not integrated into the job duties of pavement management professionals
- Initial cost and engineering judgment are the most commonly considered factors in pavement infrastructure decision making
- LCCA is considered at least sometimes by the majority of responding DOTs
- Most agencies performing LCCA calculations consider only agency costs
- Respondents report infrequent use of probabilistic calculations, but a desire to perform these calculations in the future
- The most commonly considered environmental impacts are habitat impact, land use, contamination of soil during construction, noise, and water use
- The least commonly considered environmental impacts are air quality and toxicological stress

3.4 Observations

Interpretation of the survey responses was complicated by various factors. From issues that arose from this survey, I would make the following observations:

- Surveys done early in research can miss relevant topics
- Response options may alter a respondent's willingness to answer a question
- Long surveys can result in incomplete responses

This survey was administered early in the research process with the intention of providing a basis for decisions regarding the development of a new framework or tool. Because of this, the questions asked were generic and failed to provide in-depth understanding of current use and understanding of environmental impact tools. A better approach would have involved a survey later in the project, when a knowledge gap had been definitively identified. The later survey could have been performed in place of the generic survey, or in addition to it. For this research topic, a more specific survey asking engineers what environmental decision-support tools they were familiar with and why they did or did not use these tools would have added relevant results.

Another aspect of the survey that potentially caused problems was the wording of the questions and response options themselves. The inclusion of two “Never” responses – “Never, but desired for the future” and “Never, not desired” – seemed to make respondents uncomfortable. Respondents’ reluctance to respond “Never, not desired” may have led to them to skip entire questions, potentially skewing the results of the survey. If this had been anticipated, skipping questions may have been disallowed, or the wording may have been altered to make respondents more comfortable with their options.

While the first question had 38 responses, the final question had only 24. This was at least partially due to the length of the survey. If a survey is overlong its scope should be carefully reviewed. If no sections can be completely abandoned options such as breaking the survey into multiple questionnaires should be considered.

4 Proposed Tool

Developing a new decision-support tool presents many challenges. The tool should provide new information, the information should be relevant, and the information should be reliable. Additionally, the tool cannot be so complicated that roadway engineers and planners refuse to use it. A tool which lacks these four characteristics will be trivial and will not be adopted for use by agencies or companies. This makes the choice of which new factors to include in the tool critical. There must be interest in the factors chosen, there should be widespread understanding of the importance of the factors, and there should be data which supports the legitimacy of the tool's outputs. The tool's usability must also be taken into consideration, and the scientific rigor of the tool balanced with simplicity to allow for reasonable ease-of-use.

Through the literature review, many tools for calculating life-cycle economic and environmental impacts were examined. These tools have different input, output, and calculation requirements as well as interface formats offering varying degrees of customizability and ease-of-use. These diverse features serve as a base on which the proposed tool is built. Suitable and complementary elements from various sources are integrated into the proposed tool while elements which did not match the goals and purposes of the new tool are altered or omitted.

RealCost takes in provided cost values and outputs life-cycle cost and its probabilistic distribution. If this technique were applied to construction emissions, users would input their expected emissions and the tool would output them with little or no modification. This does not add value to the user and therefore cannot be the direction taken when developing this factor.

Tools such as PaLATE require inputs of pavement layers, materials, and equipment which allows the program to perform calculations based off of a large database of equipment, technologies, and material sources in order to output a range of gas emissions, leachate, and other environmental impact factors. Results are often considered unreliable or too variable due to the requirement of very specific inputs which agencies may not know how to provide as well as the heavy dependence on a database which may become out-of-date quickly or fail to include certain equipment, materials, or process information. Privately developed software such as Changer developed by the International Road Federation may have more rigorously maintained databases, but are often less transparent and their reliability more difficult to judge.

A third style of input is employed by asPECT, developed in the United Kingdom by the Transportation

Research Laboratory. Users of asPECT input detailed energy usage and material production data for individual material sources and production facilities. These are used to calculate emission factors that are temporally and geographically specific to the users of the tool in a very transparent manner. The burden placed on tool users to gather such a large amount of detailed data lessens the usability of this input style and makes it inappropriate as the default form of input for the proposed tool.

To implement a non-trivial but also trusted tool, the following is proposed:

1) Limit calculations to emissions and resource usage. These are the most commonly studied effects and data will be more available and reliable.

2) Integrate probabilistic capabilities. Each material and production plant should have both an emission factor and a probabilistic distribution associated with it. If users choose to add materials or plants without an associated distribution, calculations will be deterministic and should be supported by a sensitivity analysis.

3) Supply a default database for easy and immediate use, but allow for extensive customization. Default emission factors and probabilistic distributions should be provided for a variety of common materials and production plants, but users will be encouraged to provide their own data if it is available.

4) Provide a notification advising the users of the broad nature of the estimates if they are left on default values. Such default values can provide general guidance on the impacts of various materials and processes, but calculations should not be viewed as project specific unless the users are providing their own data and probability distributions.

It is important to note that a project-level environmental impact tool should be used as part of a larger environmental impact or sustainability strategy. Higher level evaluation should take place, examining how potential roadway projects are expected to impact the environment and the sustainability of the transportation system and interconnected sectors as a whole. After this evaluation has taken place and a decision has been made to move forward with a project, a tool such as the one proposed can be used to compare the environmental impacts of various alternative designs and construction strategies.

4.1 Environmental Factors Included in Tool

The envisioned tool should consider four factors believed to be the most practical and useful in providing environmental impact information for use in a decision support capacity. These four factors are: emissions due to material extraction and production, emissions due to construction activities, resource consumption, and emissions due to work zone-related travel delay. The justification for inclusion in the tool, the necessary inputs, and the planned outputs for each factor are summarized in Table 3.

Table 3: Summary of Environmental Factors Recommended for Inclusion

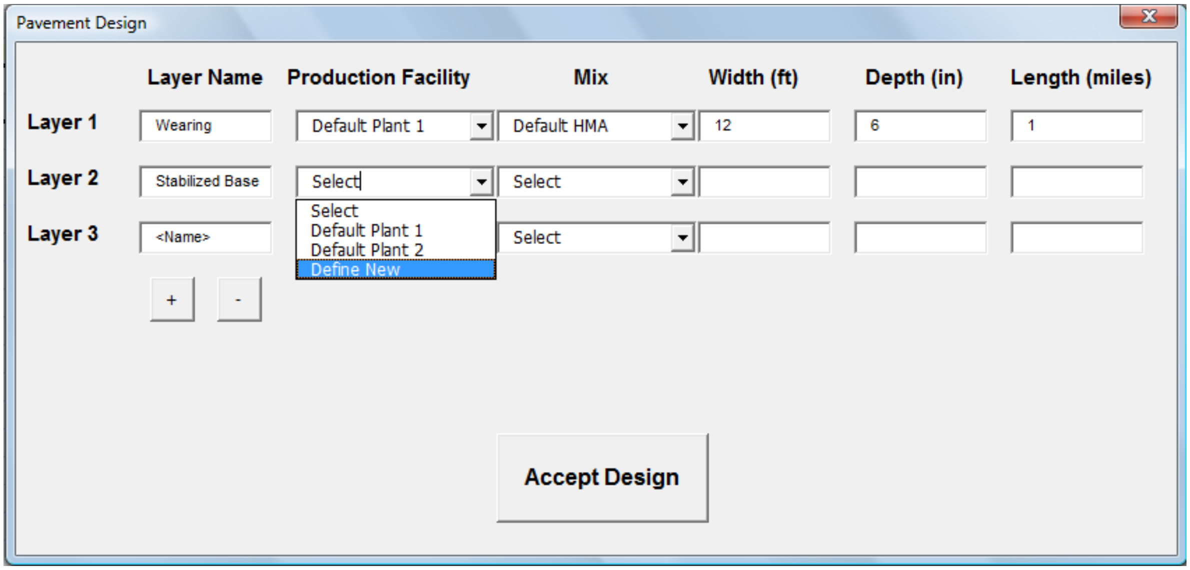
Factor		Justification	Inputs	Outputs
Emissions due to Materials	Material Extraction	Necessary for comparison of different materials and production facilities.	Material Type Tons of Material	Tons - emissions
	Hauling (Extraction Site to Production Facility)		Tons of Material Miles from material source	Tons - emissions
	Material Production		Tons of Material Facility characteristics	Tons - emissions
Emissions due to Construction	Hauling (Production Site to Project Location)	Necessary for comparison of different construction. technologies and techniques.	Tons of Material Miles from production facility	Tons - emissions
	Laydown		Tons of Material Process Used	Tons - emissions
Resource Consumption		Allows comparison based on varied design. Allows comparison of recycling and resuse plans.	Pavement design - material layers and depths. Percent recycled or reused materials in each layer (broken into Aggregate, Binder, Admixtures)	Tons of total material Tons of virgin material Toxicity Warning (admixtures)
Emissions due to Work-Zone Related Travel Delay		Large emissions impact. Not included in other tools. Immediately implementable.	Standard operations capacity and speed. Work zone capacity, speed, and duration. AADT, Hourly traffic mix	Tons - emissions

4.1.1 Emissions due to Material Extraction and Production

Variations in material source, shipping distances, and production facilities can affect the emissions of a road construction project; these variations are reflected by the Materials section of the tool. Users will be able to observe the effects of their material and production facility choices, and compare specific material sources (i.e., quarries for aggregates or refineries for binder) and production plants that they have added to the database.

To estimate material extraction and production effects, users will select a production facility and mix design from the database. Mix designs will be associated with specific production facilities and consist of a collection of materials, their percentage by weight in the mix, and their individual hauling distances from extraction sites to the production facility. Each material will have an emission factor and probabilistic distribution stored in the database which will be accessed when the mix is selected. Production plants will also have an associated emission factor and probabilistic distribution.

Many options can be presented in the form of a menu with a mix of pull down lists of predefined facilities and mix design. A proposed interface is shown in Figure 11.



	Layer Name	Production Facility	Mix	Width (ft)	Depth (in)	Length (miles)
Layer 1	Wearing	Default Plant 1	Default HMA	12	6	1
Layer 2	Stabilized Base	Select	Select			
Layer 3	<Name>		Select			

Figure 11 Material Inputs

Figure 11 shows how production facility and material mixes will be chosen. The layer dimensions can be used to calculate the volume of each mix required. This will allow the material amount to be multiplied by the associated emission factors stored in the database to calculate the emissions impact of the material extraction and production. One of the items in each pull down list should be “Define New Production Facility” or “Define New Mix.”

When “Define New Production Facility” is chosen, the user will be prompted to enter either an already calculated emissions factor or the energy consumption, energy sources, and the amount of material produced by the facility over a set period of time. The energy sources, generally electricity from a grid and fuels will have emissions factors stored in the database. Inputting energy consumption, energy sources, and the amount of material produced will call on the tool to use these inputs to calculate the emissions factor for the new facility. Equation (1) states that the emissions factor of a production facility is the sum of the amount of energy used from all energy sources multiplied by the emissions factor for the corresponding energy source, divided by the total amount of material produced by the facility. The resulting emissions factor has units of tons of emissions over tons of material produced.

$$EF_{pr} = \frac{\sum_{i=1}^{n}(E_{pr,i} * EF_{es,i})}{A_{pr}} \tag{1}$$

Where,

EF_{pr} = Emissions factor for a production facility (tons emissions/ton of material)

$E_{pr,i}$ = Energy Amount of type i used by the production facility over a known time span (kwh, gallons…)

$EF_{es,i}$ = Emissions factor for energy type I (tons emissions/kwh, gallons…)

A_{pr} = Amount of material produced over same time span (tons)

An addition option of "Define New Material" should be available. If this option is chosen users will enter a name, description, and either an already calculated emissions factor or the energy consumption, energy sources, and the amount of material extracted over a set period of time. The new material will then become a permanent item in the user's database and can be chosen for all future mix designs. Equation (2) states that the emissions factor for a material's extraction is the sum of the amount of energy used from all energy sources multiplied by the emissions factor for the corresponding energy source, divided by the total amount of material extracted. The resulting emissions factor has units of tons of emissions over tons of material produced.

$$EF_{ex} = \frac{\sum_{i=1}^{n}(E_{ex,i} * EF_{es,i})}{A_{ex}} \tag{2}$$

Where,

EF_{ex} = Emissions factor for a material's extraction (tons emissions/ton of material)

$E_{ex,i}$ = Energy Amount of type i (electricity grid, gasoline, diesel…) used by the extraction facility over a known time span (kwh, gallons…)

$EF_{es,I}$ = Emissions factor for energy type I (tons emissions/kwh, gallons…)

A_{ex} = Amount of material extracted over same time span (tons)

When “Define New Mix” is chosen, a new menu will open allowing the user to pick from materials in the database. The new mix will be defined by the materials chosen and their percentage by weight in the mix and will be associated with a production facility in the database.

4.1.2 Emissions due to Construction Activities

Emissions due to construction activities will be based on hauling distance from production facilities to the project site in addition to site preparation and laydown activities. Users will indicate the hauling distance for each material layer and select a “construction profile,” which will be the emission factor for the project. A construction profile will consist of a single emission factor representing all anticipated preparation and construction activities for a project, or a set of emission factors which each represent a single preparation or construction activity. A single construction profile will be provided in the default database and users will be encouraged to add new profiles reflecting their specific activities and equipment.

Users will be able to create construction profiles in much the same way as they add production facilities, mixes, and materials to the database. As with material extraction and production, the user will be able to either enter an already known emissions factor or input energy usage, energy mix, and a material amount in order to have the tool calculate an emission factor. In the case of most construction activities, these inputs should be drawn from the fuel usage of previous projects.

This feature of the tool will help users distinguish the differences that may come about through choosing production facilities at varying distances from the project site. If users create construction profiles that reflect specific combinations of construction activities and equipment it will also be useful for comparing these choices.

4.1.3 Resource Consumption

Many agencies have already adopted a “resource conscious” stance on the use of pavement materials. This can have both economic and environmental benefits, and supporting the ability of agencies to make resource conscious decisions will be a valuable addition to a LCA tool. The resource consumption feature will help justify decisions on whether or not to make use of recycled (RAP, RCA,…) and reused (fly ash, blast furnace slag,…) materials. It will also support comparison of design alternatives and processes that may require different amounts of material.

Engineers and contractors can reasonably estimate the amount of recycled and reused materials they intend to include in a design. Simple inputs of layer depths, widths, and lengths will be combined with this data to allow the tool to create resource usage tables that can be used to compare the total and virgin material use of different designs, processes, and material sources.

The output tables will display the amount of total aggregate and binder used in the design, measured in tons, as well as total virgin aggregate and binder tonnage. If an admixture has potentially harmful effects, such as the use of sulfur in an asphalt mix, a warning should be displayed ensuring that the user is aware of the risk.

4.1.4 Emissions due to Work Zone Related Delay

Work zone related travel delay is a significant source of emissions in the road construction process (Huang, Bird, Bell 2009). Standard gasoline engines burn least efficiently during deceleration, acceleration, and idling. The slow speeds and reduced capacity of a work zone necessitate such decelerations and accelerations, as well as often creating traffic delays that extend the effects outside of the construction area. Despite the clear impact construction activities have on local traffic and therefore on the associated emissions, these emissions are not currently considered as a part of the construction process (Santero and Horvath 2009). It was not included in any Environmental Calculator tool reviewed during this study, though the most recent documentation associated with asPECT lists it as a desired addition for future versions of the tool (Wayman et al. 2010a). This feature of the tool will allow agencies to make informed decisions on construction timing and traffic management strategies in order to balance conventional practice and agency cost measures with user costs and emission impacts.

In addition to being a critical aspect of construction-caused pollution, the calculation of these emissions is easily implementable. RealCost currently requires the input of traffic data as well as capacity during normal operation and construction conditions in order to calculate user cost due to delay. These delay calculations, paired with an already developed emission model such as MOVES, can yield the full range of gaseous and particulate emissions or a CO_2e value depending on the chosen settings. Variability in these calculations is well enough understood that a full implementation with default values can and will be trusted by the majority of decision-makers and practitioners. A proposed input screen, based on the interface used in the RealCost software, is shown in Figure 12.

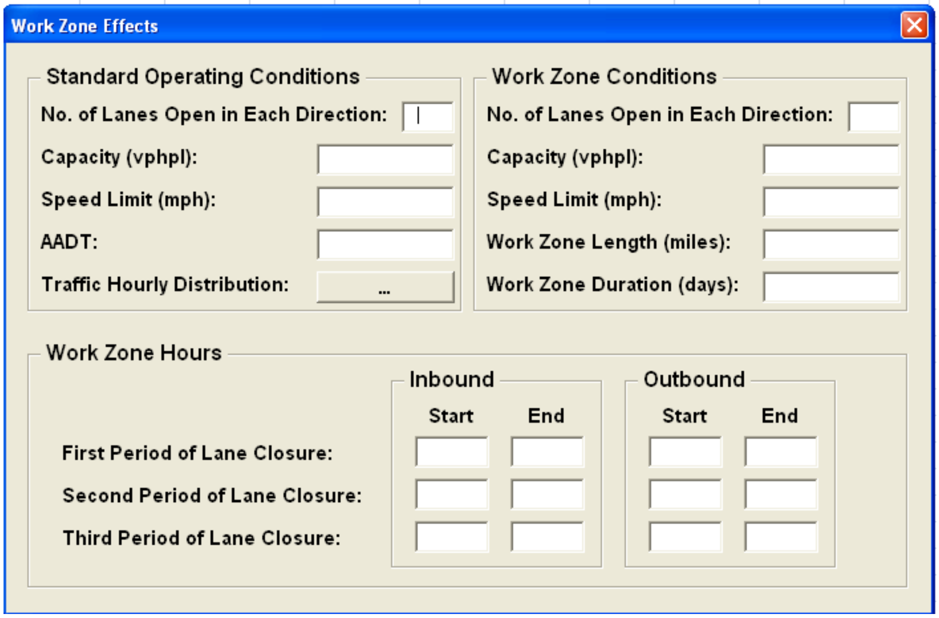


Figure 12: Work Zone Inputs

Figure 12 shows a user interface that prompts users to enter standard operation and work zone data. This data is necessary for calculating traffic conditions during construction for comparison with normal roadway operation. In RealCost, this comparison is used to show variations in User Cost between different alternatives and work zone strategies. The proposed tool will use the comparison to calculate emissions due to work zone related traffic congestion.

4.2 Factors of Interest Excluded from Tool

The four factors chosen for the proposed tool are not intended to represent the full range of environmental impacts from roadway construction. Two further factors that state transportation agencies have expressed interest in are the effects of transportation construction on water quality and air quality during the road's use phase. These factors *are not* recommended for inclusion in the proposed tool despite current interest because they require more research before reliable models can be developed.

Water quality impacts that should be considered for future addition to an environmental impact tool include the effect of sediment washed into waterways during construction activities and run-off from road surfaces during the use phase. The effects of sediment are not considered for the proposed tool because the effect of sediment is a factor of the sediment control systems employed, which is not within the scope of the tool. Run-off during use phase is most closely linked to vehicles rather than infrastructure design, though material choice, maintenance strategy, and road profile can play a role.

More information on the effect pavement design has on run-off is needed before this can be implemented into a design decision-support tool.

It is believed that vehicle emissions during the road’s use phase may be significantly affected by the rolling resistance of the road (Santero and Horvath 2009). Currently this relationship is not well enough understood for inclusion in the proposed tool but as studies on the subject are carried out and it becomes better understood, pavement surface quality/deterioration modeling can be used to add this as a factor to environmental decision-support tools.

4.3 Customization

4.3.1 Define New Material, Mixture, Production Facility

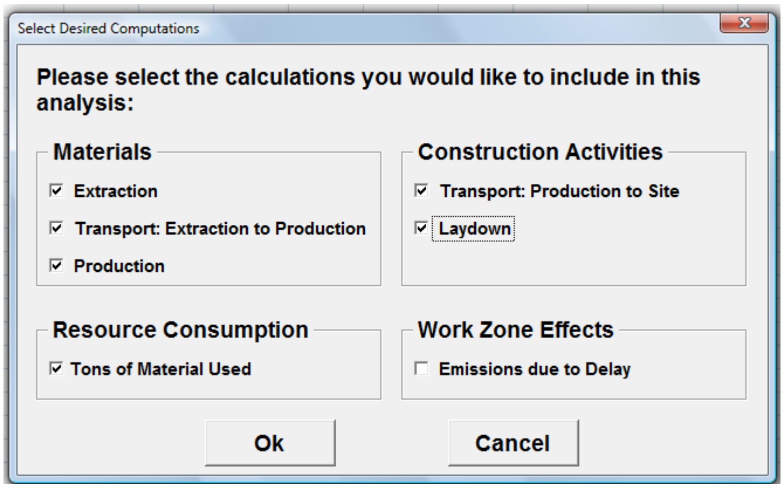
While a limited database of default values should be provided with the tool, these values will inevitably fail to cover certain equipment, techniques, and materials and go out-of-date as new equipment, techniques, and materials are developed. For anything beyond general guidance on the impacts of various materials and processes, users should be encouraged to provide their own data if it is available.

The input format of asPECT is very well suited for complete customization of material extraction and production emissions. In the same style as asPECT, users of the proposed tool should be able to characterize the specific material sources (i.e., quarries) and pavement production facilities they may choose to use. Users will either enter an emission factor that they have independently calculated or pulled from literature, or they will input the yearly energy usage, fuel and electricity mix, and material output of the facility. The new material source or production facility will then become a permanent entry in the user’s database and can be drawn on for all future designs. Furthermore, users will be able to group materials into mix designs associated with a production facility, allowing them to easily specify all of the components of a pavement layer through a single selection.

4.3.2 Calculations and Outputs

The proposed tool will have the capability to calculate and output substantially large amounts of information, which may be more than needed or desired by the agencies that will make use of it. The sheer amount of data may require large calculation times and in some cases could potentially confuse the decision-making process rather than support it. It is thus important to provide users a clear way to simplify the calculations and display of outputs to meet their needs.

This will be implemented through an initial screen prompting the user to choose which environmental factors are being examined. Users will be encouraged to omit factors which can be assumed to stay the same between the alternatives or processes being considered. A potential interface for these selections is shown in Figure 13.


Select Desired Computations

Please select the calculations you would like to include in this analysis:

Materials
☑ Extraction
☑ Transport: Extraction to Production
☑ Production

Construction Activities
☑ Transport: Production to Site
☑ Laydown

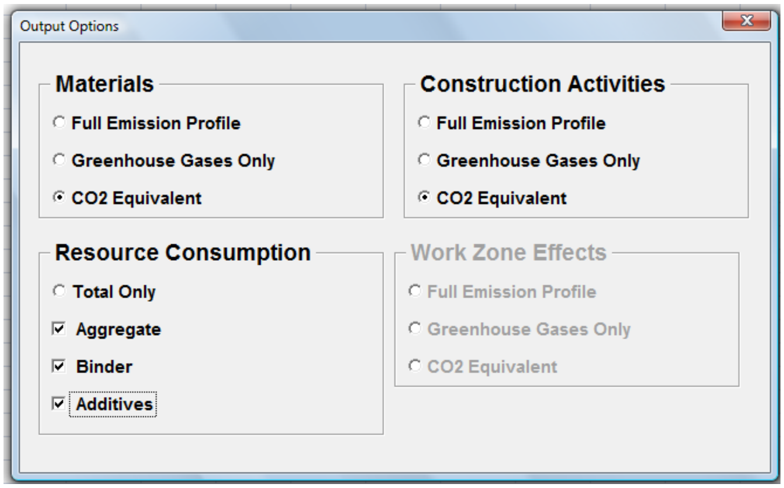
Resource Consumption
☑ Tons of Material Used

Work Zone Effects
☐ Emissions due to Delay

Figure 13 Desired Calculations

Figure 13 shows a possible user interface for selecting which calculations will be performed by the tool. In this figure the user has chosen to calculate emissions due to material extraction and production, emissions due to construction activities, and resource consumption, but is not interested in the emissions due to work zone effects.

Users will also be able to select different levels of output aggregation or disaggregation, such as examining emissions as a range of gases and particulates or having the program reduce this to a CO_2e value. An interface for making this selection is shown in Figure 14.


Output Options

Materials
○ Full Emission Profile
○ Greenhouse Gases Only
● CO2 Equivalent

Construction Activities
○ Full Emission Profile
○ Greenhouse Gases Only
● CO2 Equivalent

Resource Consumption
○ Total Only
☑ Aggregate
☑ Binder
☑ Additives

Work Zone Effects
○ Full Emission Profile
○ Greenhouse Gases Only
○ CO2 Equivalent

Figure 14 Output Options

Figure 14 indicates that the user has chosen to display a CO_2e value for Material and Construction Activities. For Resource Consumption the tool will output the virgin and recycled/reused tons of material divided for its component parts of Aggregate and Binder separately and notifications will be displayed if there are warnings associated with the additives. Work Zone Effects does not have an output selected because the user has previously indicated that these calculations should not be run.

4.4 Deterministic and Probabilistic Calculations

Each material, production facility, construction profile, and hauling distance should be able to be entered either as a single number (deterministically) or as an expected value with an associated distribution function (probabilistically). Users will be able to choose uniform, normal, truncated normal, triangular, or truncated triangular distribution. If users run a deterministic analysis, or an analysis in which some values are deterministic while others have probabilistic distributions, the proposed tool should be able to perform a sensitivity analysis by varying the deterministic variables a set amount above and below their input values.

5 Example Applications

The proposed tool could be used to compare many different types of projects and design alternatives. It will be equally applicable to new construction and maintenance or repair activities such as seal coats and overlays. It will be useful for comparing the environmental impact of alternatives using different material types, material sources, production facilities, hauling distances, recycling regimens, construction techniques, or work zone lane closure strategies and schedules. The results that will be produced by this tool should be used alongside economic and social analysis methods deemed most appropriate by decision-makers.

Examples of possible comparisons include, but are not limited to:

1) Use of virgin or recycled material

Choosing between virgin materials and recycled materials can affect the material extraction, material production, and hauling emissions. It can also affect construction emissions if the recycled material has to be handled differently than the virgin material. Additionally, resource consumption characteristics will vary substantially depending on the amount of recycled material included in a project. The tool will be able to be used to compare alternatives based on both their emissions and resource consumption.

2) Differing lane closure strategies

Depending on roadway traffic conditions, the delay caused by lane closures can be a substantial source of emissions. The choice of an appropriate lane closure strategy can reduce traffic delay, user inconvenience, and vehicle emissions. This tool will use roadway capacity and speed limit information along with traffic distribution to estimate traffic delay and relate this to increased emissions by comparing the delay and emissions within the work zone to standard operating conditions. This feature can then be used to compare different work zone schedules and lane closure strategies to identify which cause the least delay and emissions.

3) Examining the difference between hot-mix asphalt and warm-mix asphalt

Producing asphalt at a lower temperature than standard hot-mix asphalt has the potential to produce less emissions. This reduction is largely due to the reduced amount of energy required to raise the material to the necessary temperature and maintain that temperature. The database of the proposed tool will be ideal for characterizing the variety of materials known collectively as "warm-mix asphalt" based on their production energy needs. Once the materials are in the database, alternatives making use of these materials can be compared to each other and to alternatives making use of hot-mix asphalt.

The tool could also be used to examine a scenario where it is desirable to locate an asphalt plant as far from an urban area as possible without increasing overall construction emissions. The use of warm-mix asphalt both decreases emissions and allows a longer time period of material workability, increasing the distance it can be hauled before placement. However, increasing the distance between the production facility and potential work sites increases the emissions due to hauling. The proposed tool would enable an interested party to calculate at the distance at which the emission reductions from the production of warm-mix asphalt would be balanced by the greater hauling emissions.

4) Choosing a local material or a more distant material

At times there may be multiple sources available to meet the needs of an alternative design. These materials may have different prices, or require slight adjustments to the pavement design such as an aggregate which is known to absorb more water than an alternative aggregate. By calculating both hauling emissions and material consumption, this tool will be able to add environmental impact as a consideration to be weighed alongside cost and functionality.

In order to aid in understanding the usefulness of the tool and its customizability, the first two examples have been developed further in a Microsoft Excel workbook and are described in the following sections. Numerical values used in the examples are for demonstration of theoretical comparisons only and do not represent true project values. The displayed results represent a concept of how the data may be displayed rather than the outputs of a completed tool.

5.1 Example 1: 100% Virgin Material vs. 20% Recycled Asphalt

This scenario describes a situation where recycled asphalt pavement (RAP) is used as 20% of the material in the wearing course of a new asphalt pavement road section. It is assumed that work zone effects and emissions due to construction do not significantly differ between the two cases.

This example highlights several functions of the tool. First, it is assumed that while a standard asphalt mix and other necessary materials are already part of the database, RAP must be defined as a new material and integrated into a new mix. Therefore the example demonstrates how this material and mix could be defined. Secondly, the example shows how two alternatives using different materials may have different resource usage and emission profiles, and presents a possible output format for the tool.

5.1.1 Procedure

This example calls for the analysis of two alternatives using the proposed tool. Each alternative will have the same three layers, with the only difference being that the wearing course for one will consist of an HMA made of 100% virgin materials while the other will be 80% virgin materials and 20% RAP. The virgin HMA will already be a part of the database while the RAP will not, requiring the user to define the new material and define a new mix containing it.

The user will first run the tool for Alternative 1: 100% Virgin Material. After starting a new project file, the user will be presented with options to select calculation, select output options, input pavement design, input work zone conditions, edit the database, and run the calculations.

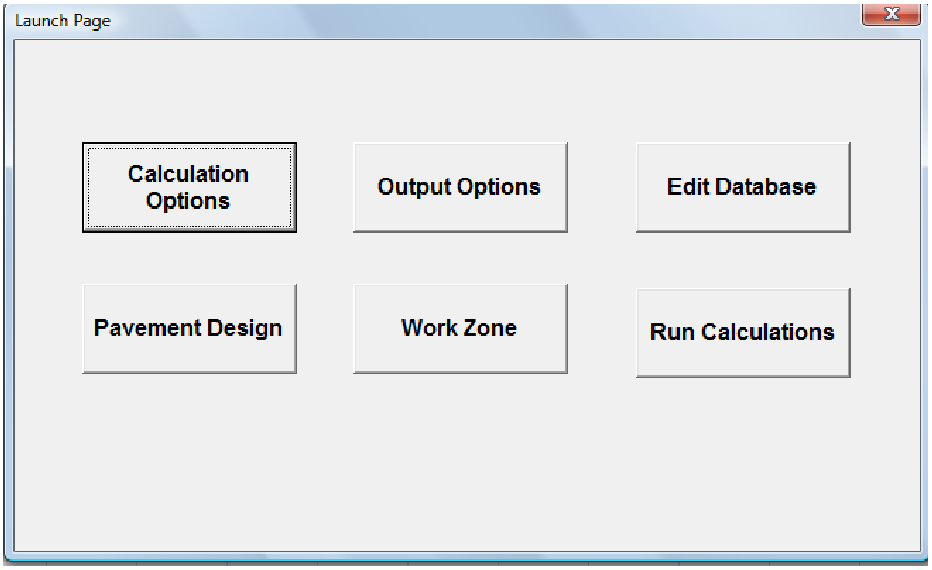
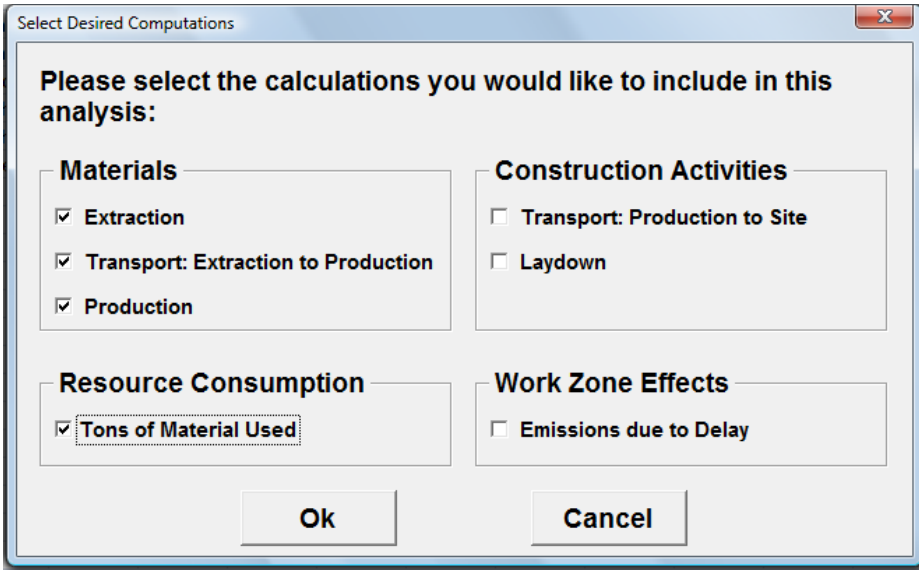


Figure 15: New project launch page

The user will start by entering the desired Calculation Options. For this example the user will want to consider material extraction, transport, and production as well as resource consumption. The other features of the tool are not selected because they will remain the same between the two alternatives.



Select Desired Computations

Please select the calculations you would like to include in this analysis:

Materials
- ☑ Extraction
- ☑ Transport: Extraction to Production
- ☑ Production

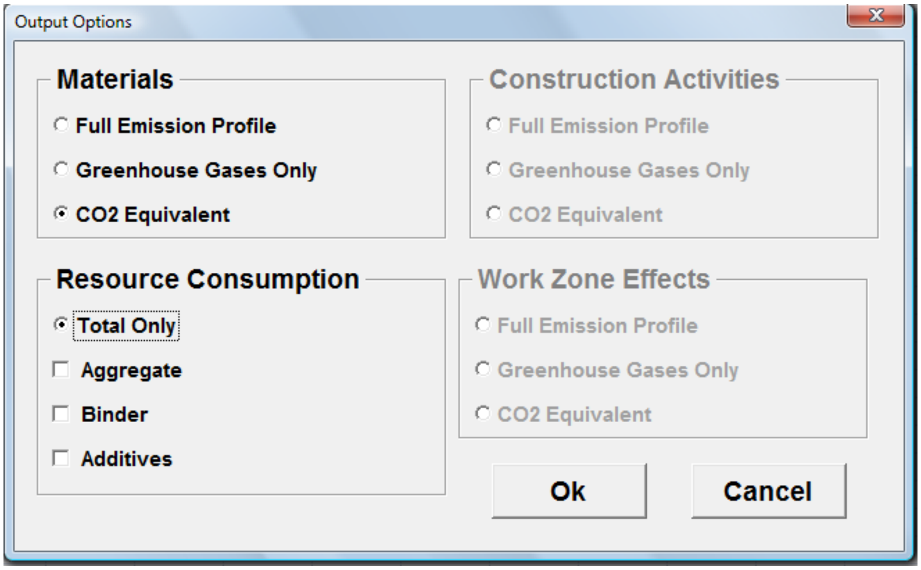
Construction Activities
- ☐ Transport: Production to Site
- ☐ Laydown

Resource Consumption
- ☑ Tons of Material Used

Work Zone Effects
- ☐ Emissions due to Delay

Figure 16: Example 1 - User selects desired calculations

The user will then select the output options he prefers. For this example, the emissions due to material extraction, transport, and production will be output as a CO_2e value and the resource consumption will be reported as tons of total virgin and recycled material. Due to the user's previous selection to omit construction and work zone emissions, these output options will not be available.



Output Options

Materials
- ○ Full Emission Profile
- ○ Greenhouse Gases Only
- ● CO2 Equivalent

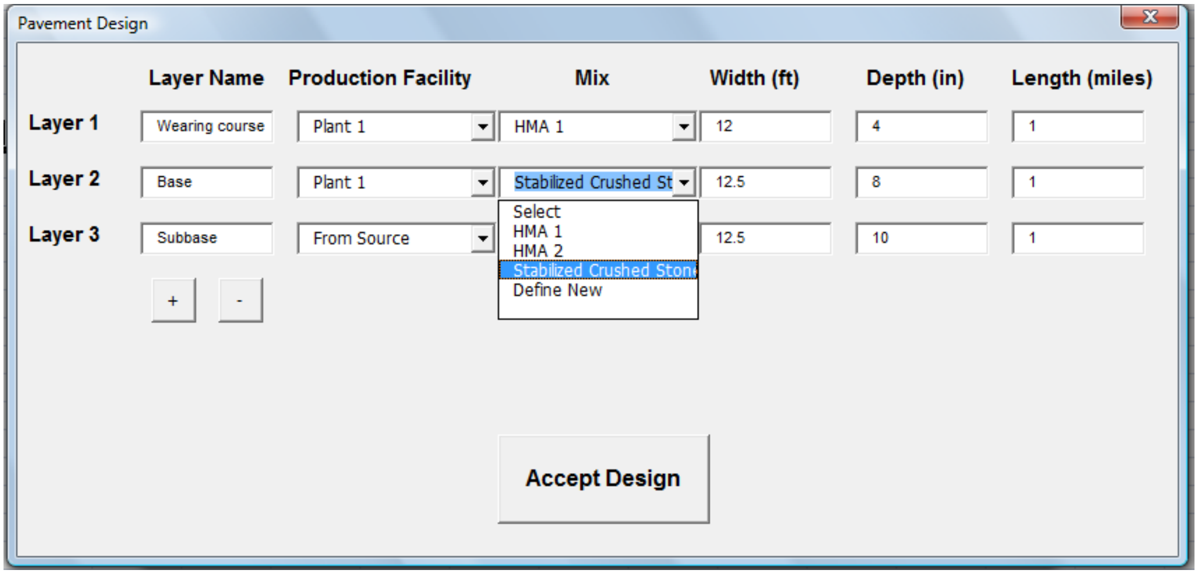
Construction Activities
- ○ Full Emission Profile
- ○ Greenhouse Gases Only
- ○ CO2 Equivalent

Resource Consumption
- ● Total Only
- ☐ Aggregate
- ☐ Binder
- ☐ Additives

Work Zone Effects
- ○ Full Emission Profile
- ○ Greenhouse Gases Only
- ○ CO2 Equivalent

Figure 17: Example 1 - User selects desired outputs

After selecting the desired calculations and outputs, the user will input the pavement design. For Alternative 1 all of the materials and mixes are already in the database and can be selected through pull-down menus. It can be noted that the mix needed for Alternative 2, HMA + 20% RAP, is not in the list of mixes. When the design has been accepted the user may run the calculations and their output will be displayed in an Excel worksheet.

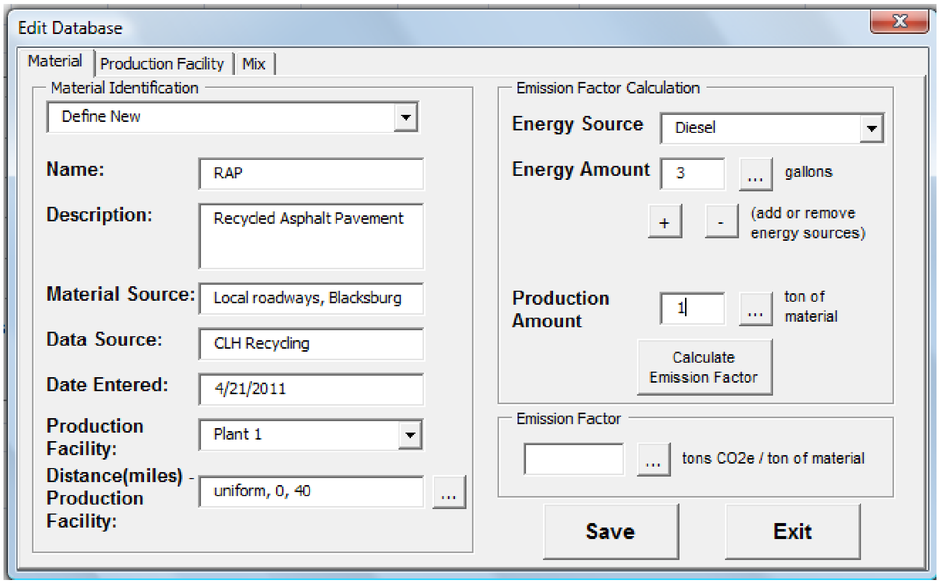


	Layer Name	Production Facility	Mix	Width (ft)	Depth (in)	Length (miles)
Layer 1	Wearing course	Plant 1	HMA 1	12	4	1
Layer 2	Base	Plant 1	Stabilized Crushed St	12.5	8	1
Layer 3	Subbase	From Source		12.5	10	1

Figure 18: Example 1 - User inputs Alternative 1 design

The first steps for Alternative 2: HMA + 20% RAP will be to define the RAP material and then create a mix made up of 80% virgin materials and 20% RAP. The user interface designed to illustrate the tool has two pathways to add materials, mixes, and production facilities to the database. The first is by selecting "Edit Database" in the new project launch page. The second is by selecting Define New as either a production facility or a mix as part of the Pavement Design. Either option will take the user to a page which lets them modify or add items to the database.

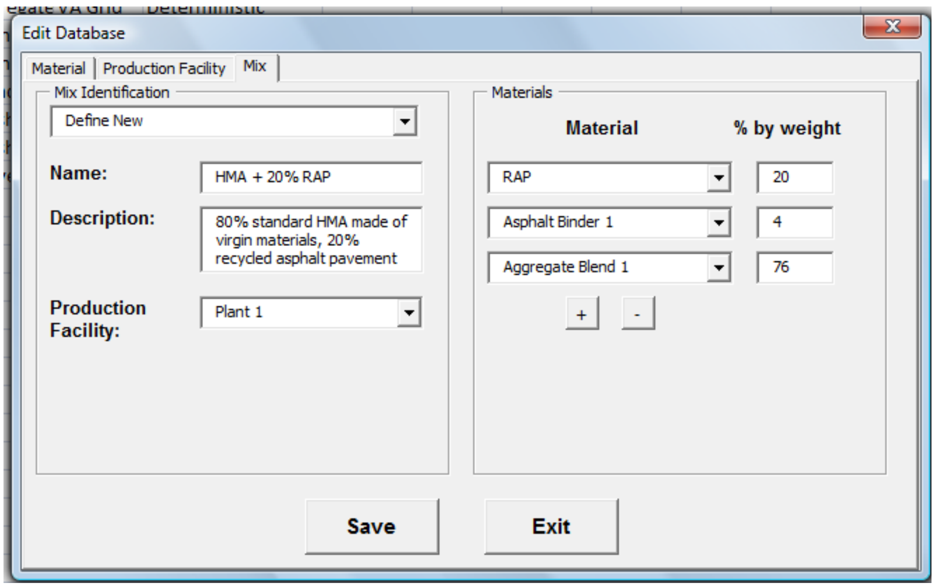
When adding a new material to the database, users will enter information about the new material such as the name, description, extraction source, the source of their extraction data, the date the data was obtained, which production facility the material will be associated with, and the distance from the extraction site to the production facility. The user will then have two options for determining the extraction emissions. The first option is to enter the energy source, energy amount used, and the amount of material produced. This information would be used by the tool to calculate an emission factor. If the user has already calculated or researched an emission factor for the material, they will be able to input it directly without having the tool calculate it. For this example, the new RAP material is being processed by an already defined production facility labeled "Plant 1," so a new production facility will not have to be defined in order to calculate the emissions due to material production. If a new production facility were being defined the user could similarly input either an energy source, energy amount, and amount of material produced by the facility or input an emission factor.



Define New
Name: RAP
Description: Recycled Asphalt Pavement
Material Source: Local roadways, Blacksburg
Data Source: CLH Recycling
Date Entered: 4/21/2011
Production Facility: Plant 1
Distance(miles) - Production Facility: uniform, 0, 40
Energy Source: Diesel
Energy Amount: 3 gallons
Production Amount: 1 ton of material
tons CO2e / ton of material

Figure 19: Example 1 - Define New Material, RAP

Once the material extraction emission factor has been calculated and saved, the new material will be able to be integrated into mix designs. For this example, a new mix named “HMA + 20% RAP” is defined. Additional mixes making use of different percentages of RAP could be defined if the user wished to examine a range of recycling options.



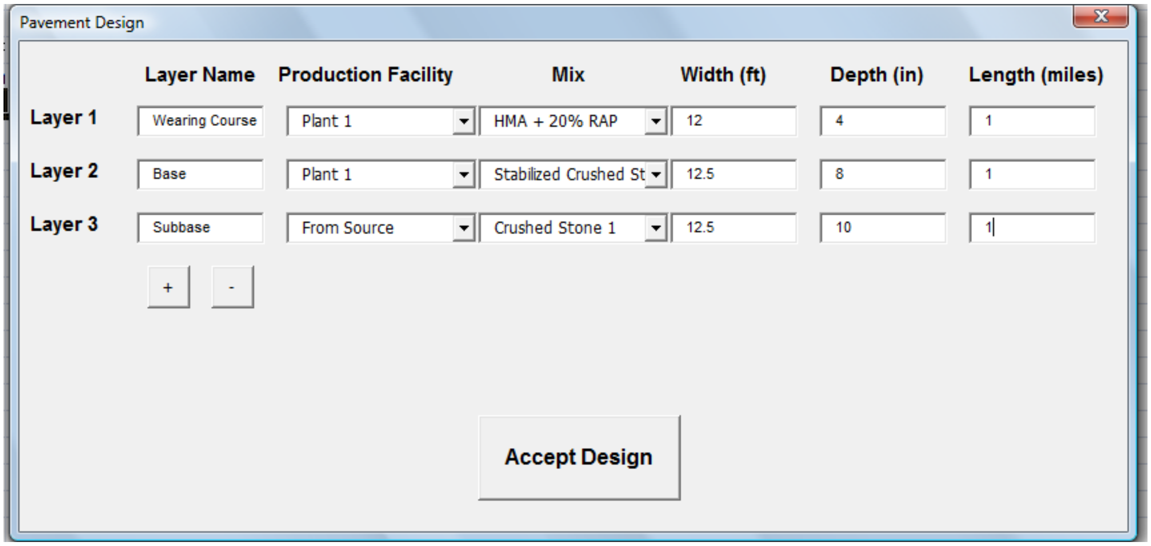
Define New
Name: HMA + 20% RAP
Description: 80% standard HMA made of virgin materials, 20% recycled asphalt pavement
Production Facility: Plant 1

Material	% by weight
RAP	20
Asphalt Binder 1	4
Aggregate Blend 1	76

Figure 20: Example 1 - Define New Mix, HMA + 20% RAP

The new material and mix have now been added to the database and will appear as options in the

Pavement Design page. This is the final step of Example 1. After the user inputs the Alternative 2 design (Figure 21) and runs the calculations, its output will be displayed in an Excel worksheet.



	Layer Name	Production Facility	Mix	Width (ft)	Depth (in)	Length (miles)
Layer 1	Wearing Course	Plant 1	HMA + 20% RAP	12	4	1
Layer 2	Base	Plant 1	Stabilized Crushed St	12.5	8	1
Layer 3	Subbase	From Source	Crushed Stone 1	12.5	10	1

Figure 21: Example 1 - User inputs Alternative 2 design

5.1.2 Outputs

Based on the calculation and output options chosen for this example, the tool would produce tables and figures reporting the emissions produced by material extraction, material transport from extraction site to production facility, and material production for each alternative. Additionally, the material usage of each alternative would be reported. Table 4 displays a potential output for the total amount of CO_2e emissions produced by the activities which were chosen for this example.

Table 4: Example 1 - Material Emissions

	Alternative 1: 100% Virgin Material		Alternative 2: 20% RAP	
	Emissions (tons CO_2e)	Standard dev.	Emissions (tons CO_2e)	Standard dev.
Total	**424**	**21**	**393**	**27**
Material Extraction	227	10	202	11
Material Transport: Extraction to Production	85	3	79	4
Material Production	112	6	112	6[2]

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[2] These numbers are loosely based on GHG Emissions per Cubic Meter values provided by ATHENA 1999. Numerical values used in the examples are for demonstration of theoretical comparisons only and do not represent true project values.

It would also be useful for the tool to create a visual display the probabilistic distribution of potential outcomes. This is shown in Table 4 through mean and standard deviation values and presented in Figure 22 graphically.

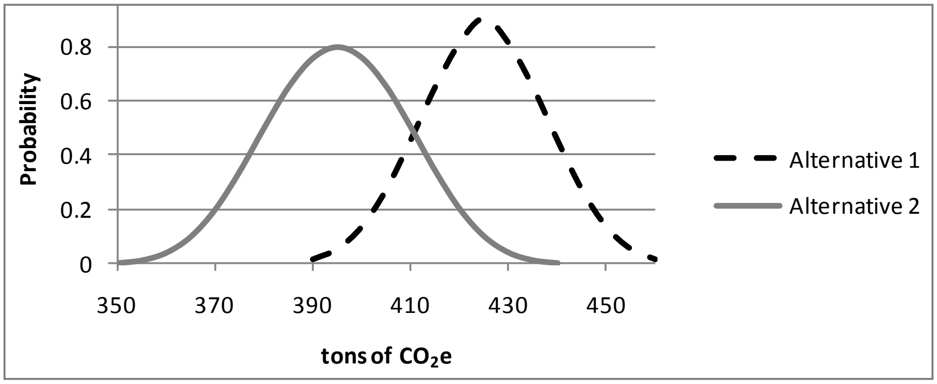

Figure 22: Example 1 - Material Emissions Distribution

Table 5 shows a potential output for the tons of total material and the tons of virgin material used in each alternative. If more detail were desired, the user could choose to have the tool produce a Resource Consumption table that would show material usage for aggregate and binder, as well as any notices associated with admixture usage.

Table 5: Example 1 – Resource Consumption

	Alternative 1: 100% Virgin Material		Alternative 2: 20% RAP	
	Total Material (tons)	Virgin Material (tons)	Total Material (tons)	Virgin Material (tons)
Mean	9943	9943	9852	9007
Standard Dev	450	450	464	464
Minimum	9268	9268	9156	8311
Maximum	10632	10632	10562	9717[3]

This example compares a conventional pavement design to an alternative which incorporates a recycled material. The output tables show modest reductions in emissions due to a reduction in material extraction energy and a reduction in usage of virgin material. Users of the proposed tool would consider this information alongside other criteria such as cost when choosing an alternative.

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[3] These numbers are based on the assumption that the HMA, stabilized base, and subbase densities are 145pcf, 185pcf, and 150pcf respectively. Numerical values used in the examples do not represent true project values.

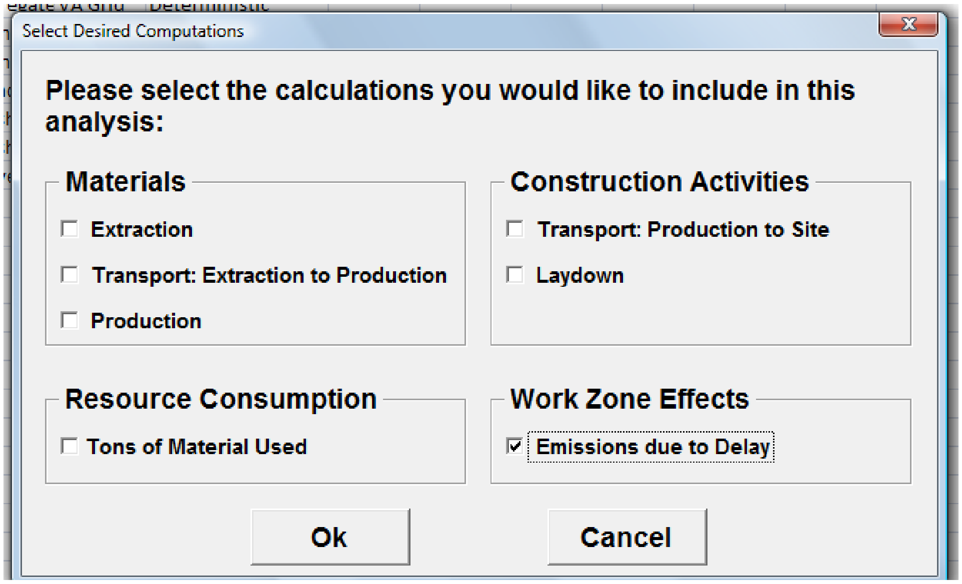
5.2 Example 2: Lane Closure Strategy

Even when pavement design and processes remain constant, different work zone strategies can affect the environmental impact of a project. Depending on road usage characteristics, it may be appropriate to close lanes during all non-peak hours, close lanes only at night, or close the necessary lanes continuously until construction is complete. This example show how the proposed tool could be used to compare the work zone related emissions of three strategies while all other factors remain constant.

The significance of this example lies in its illustration of an environmental impact not considered by other currently available tools: emissions due to work zone related delay.

5.2.1 Procedure

This example does not involve differences in pavement designs or construction activities, so the only calculations necessary are the emissions due to work zone effects. For that reason no other calculations will be selected in the initial Computation Selection screen.



Please select the calculations you would like to include in this analysis:

Materials
- ☐ Extraction
- ☐ Transport: Extraction to Production
- ☐ Production

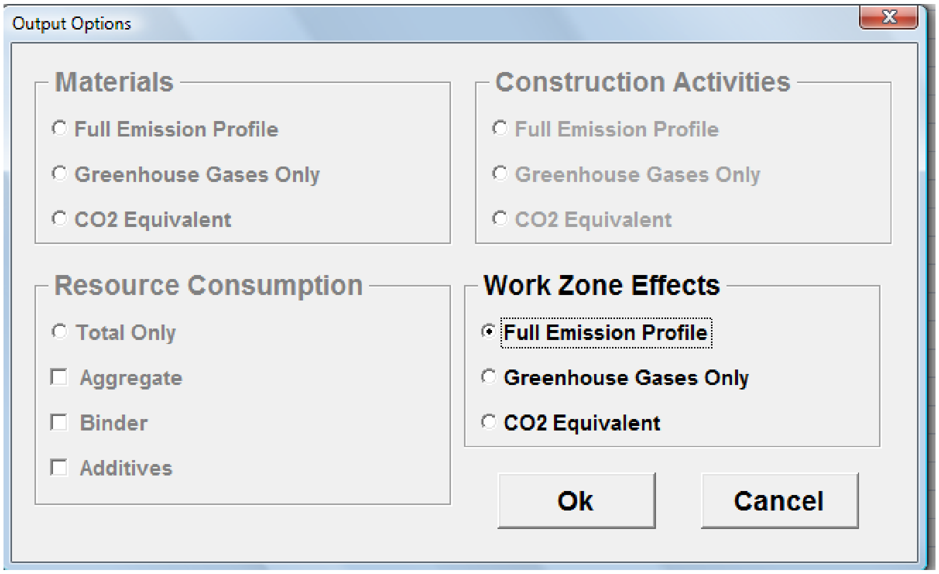
Construction Activities
- ☐ Transport: Production to Site
- ☐ Laydown

Resource Consumption
- ☐ Tons of Material Used

Work Zone Effects
- ☑ Emissions due to Delay

Figure 23: Example 2 - User selects desired calculations

The user will then select his output options. In this case, only work zone emissions are being calculated so no other sets of output options will be available. For this example, the user chooses to display the outputs as a full emission profile. This means that a range of emissions will be reported, including CO_2, NO_x, and SO_x.



Materials
○ Full Emission Profile
○ Greenhouse Gases Only
○ CO2 Equivalent

Construction Activities
○ Full Emission Profile
○ Greenhouse Gases Only
○ CO2 Equivalent

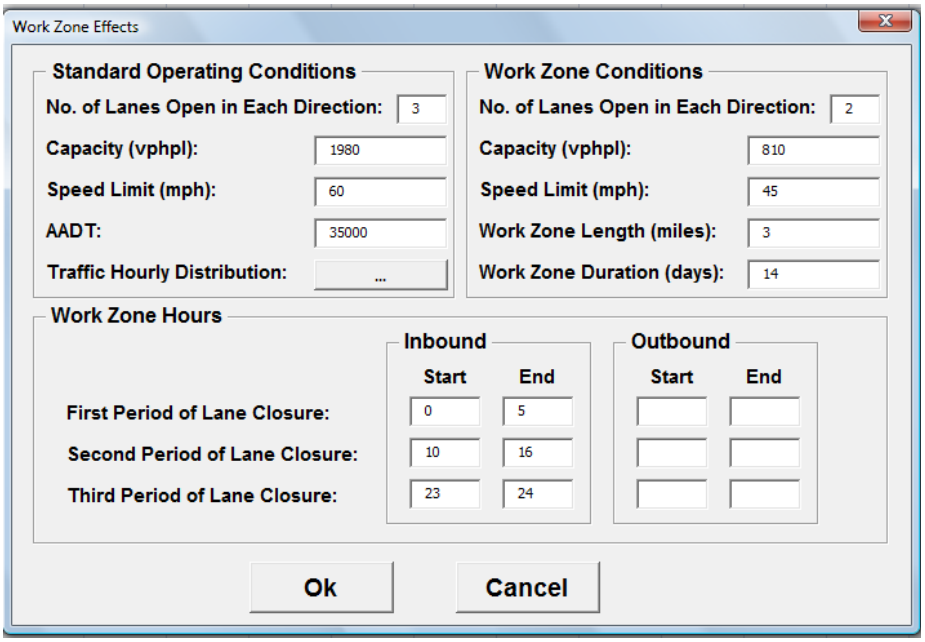
Resource Consumption
○ Total Only
☐ Aggregate
☐ Binder
☐ Additives

Work Zone Effects
● Full Emission Profile
○ Greenhouse Gases Only
○ CO2 Equivalent

Figure 24: Example 2 - User selects desired outputs

Rather than selecting Pavement Design as in the previous example, the user will select Work Zone from the launch page. For each alternative, the user will need to enter the standard operation and work zone characteristics of the roadway's traffic. This is likely to include the number of lanes open in each direction, the capacity, the speed limit, the hourly traffic distribution, and the annual average daily traffic (AADT). The length of the work zone in miles, the work zone duration, and the hours of each day that the work zone will be in place will also be required.

Alternative 1 calls for one lane of a 3 lane highway to be closed during all non-peak hours. This may be practical for a roadway which is used primarily by commuters and experiences very low volume during non-peak hours. For the roadway in this example, non-peak hours are from 11:00pm (23:00) to 5:00am (5:00) and from 10:00am (10:00) to 4:00pm (16:00). With this schedule the construction will be completed in 14 days.



Standard Operating Conditions
No. of Lanes Open in Each Direction: 3
Capacity (vphpl): 1980
Speed Limit (mph): 60
AADT: 35000
Traffic Hourly Distribution: ...

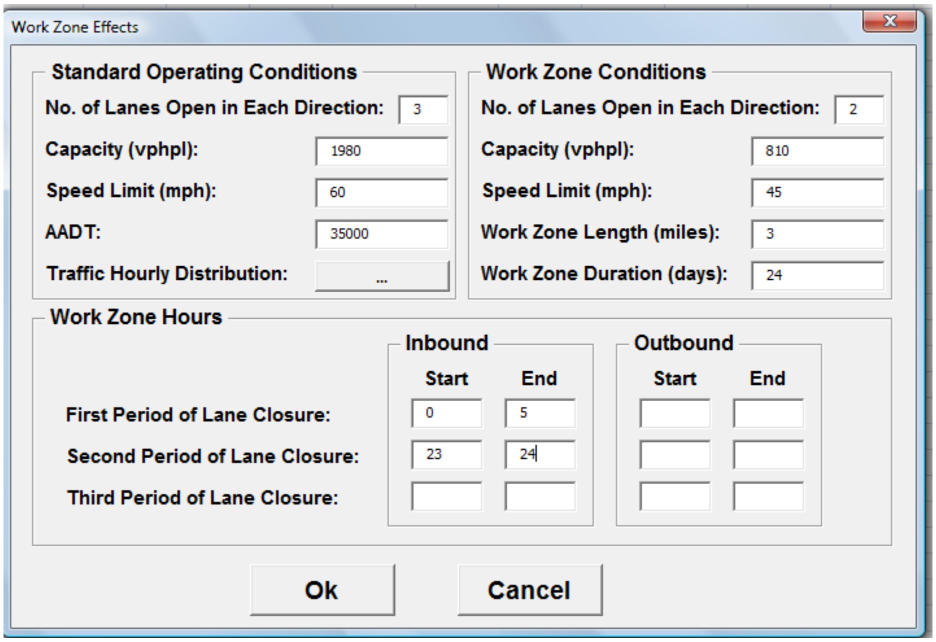
Work Zone Conditions
No. of Lanes Open in Each Direction: 2
Capacity (vphpl): 810
Speed Limit (mph): 45
Work Zone Length (miles): 3
Work Zone Duration (days): 14

Work Zone Hours

	Inbound Start	Inbound End	Outbound Start	Outbound End
First Period of Lane Closure:	0	5		
Second Period of Lane Closure:	10	16		
Third Period of Lane Closure:	23	24		

Figure 25: Example 2 - Alternative 1, Off-peak lane closure

Alternative 2 calls for the lane to be closed only between 11:00pm and 5:00am so as not to disrupt any daytime traffic. This closing schedule may be best suited for roadways without large volume fluctuations through the day or which operates close to capacity during all daytime hours. With this schedule, construction will be completed in 24 days.



Standard Operating Conditions
No. of Lanes Open in Each Direction: 3
Capacity (vphpl): 1980
Speed Limit (mph): 60
AADT: 35000
Traffic Hourly Distribution: ...

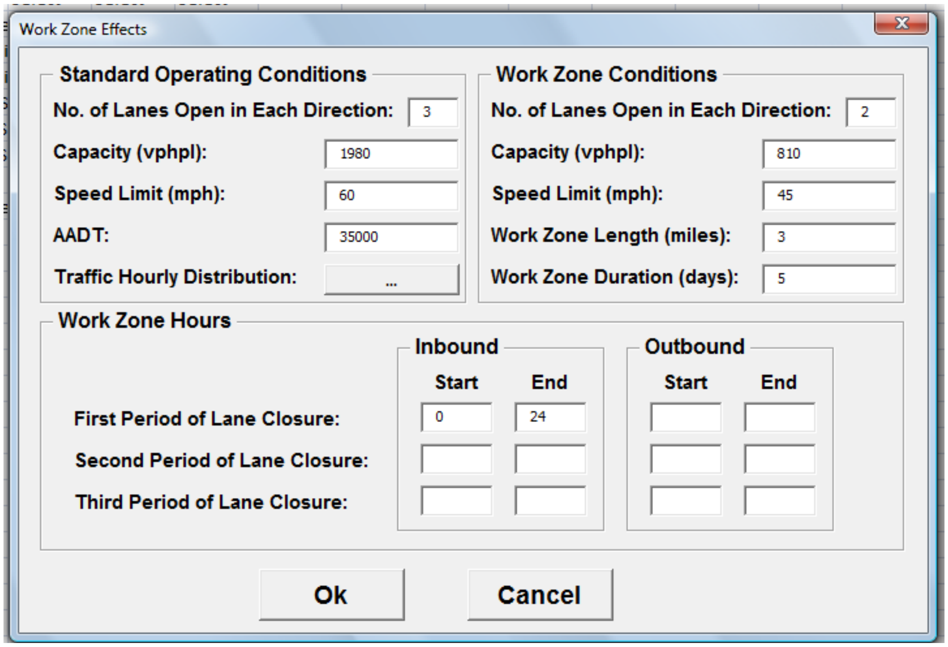
Work Zone Conditions
No. of Lanes Open in Each Direction: 2
Capacity (vphpl): 810
Speed Limit (mph): 45
Work Zone Length (miles): 3
Work Zone Duration (days): 24

Work Zone Hours

	Inbound Start	Inbound End	Outbound Start	Outbound End
First Period of Lane Closure:	0	5		
Second Period of Lane Closure:	23	24		
Third Period of Lane Closure:				

Figure 26: Example 2 - Alternative 2, Night lane closure

Alternative 3 calls for the lane to be closed continuously until construction is complete. This creates the greatest traffic disruption during construction, but allows construction to be completed in 5 days. A schedule like this may be most appropriate for a roadway with alternative routes that can absorb additional traffic.


Work Zone Effects

Standard Operating Conditions
No. of Lanes Open in Each Direction: 3
Capacity (vphpl): 1980
Speed Limit (mph): 60
AADT: 35000
Traffic Hourly Distribution: ...

Work Zone Conditions
No. of Lanes Open in Each Direction: 2
Capacity (vphpl): 810
Speed Limit (mph): 45
Work Zone Length (miles): 3
Work Zone Duration (days): 5

Work Zone Hours

	Inbound		Outbound	
	Start	End	Start	End
First Period of Lane Closure:	0	24		
Second Period of Lane Closure:				
Third Period of Lane Closure:				

Figure 27: Example 2 - Alternative 3, Continuous lane closure

5.2.2 Outputs

Based on the calculation and output options chosen for this example, the tool would produce a table reporting the emissions produced by work zone related delay for each alternative. These emissions would be presented as a list of emissions and their relative amounts, and summarized with a CO_2e value. Alternatively, users could choose to have the tool output only greenhouse gases, or only a CO_2e value.

Table 6 displays how this information would look in a proposed output format. While this example shows an emissions reduction for employing a strategy where lanes are closed only at night, different traffic characteristics and work zone requirements may make other strategies preferable.

Table 6: Example 2 - Emissions Due to Work Zone Delay

	Alternative 1, Off-peak land closure	Alternative 2, Night lane closure	Alternative 3, Continuous lane closure
Emissions due to Work Zone Delay, Tons CO_2e	**134.3**	**60.5**	**120.6**
Tons, CO_2	88.5	39.7	79.4
Tons, CO	3.68	1.66	3.30
Tons, CH_4	0.87	0.40	0.78
Tons, N_2O	0.09	0.04	0.08
Tons, NO_x	2.41	1.08	2.16
Tons, SO_x	1.01	0.46	0.91
Tons, VOC	2.24	1.01	2.01
Tons, PM	7.73	3.48	6.94

[4]

Agencies would be able to use this data to guide choices between multiple work plans. The information that could be provided by the tool would be considered alongside other criteria such as cost when choosing an alternative.

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[4] These numbers are loosely based on g/day traffic emission values provided by Huang 2009. Numerical values used in the examples are for demonstration of theoretical comparisons only and do not represent true project values.

6 Summary and Conclusions

With climate change and other negative effects of pollution gaining increasingly more public attention, sustainability and specifically environmental stewardship is emerging as a preeminent issue in engineering decision-making. Despite this, the United States has neither a national policy on sustainability, nor a national sustainable transportation strategy. Without national guidance, state DOTs have been left to decide how fully to integrate environmental effects into the decision-making process. In many cases this has resulted in DOTs basing their environmental practices on requirements set out previously by EPA regulations with little or no additional consideration of environmental effects.

A survey of current DOT pavement management engineers revealed that environmental stewardship was not considered part of their job responsibilities, despite having job duties such as pavement design and maintenance which can greatly affect the environmental impact of a project. Initial cost and engineering judgment were the most widely considered in decision-making, with LCCA also being considered at least some of the time by most respondents. Environmental impacts on the other hand were most likely to be considered as a "tie breaker" when alternatives are found to have similar costs.

In order to integrate sustainability into their current practices, pavement decision-makers need a set of environmental decision support tools. The literature review covered two distinct types of environmental decision support tools. Rating tools gather predominantly environmental impact information in order to award a score to the project. Environmental calculators are software tools that use material or equipment inputs to estimate the amount of pollutants produced by a project. While a variety of environmental impact tools are currently available they suffer from a number of drawbacks which serve as barriers to their implementation.

This thesis proposed a tool which addresses many of the limitations of previous environmental impact tools. The proposed tool will calculate multiple environmental impacts, including emissions due to work zone delays which are not considered by any other currently available tool. The tool will also perform probabilistic calculations and will have a database which can be added to and updated by users.

6.1 Findings

Major findings of this research included:

- CO_2e is the focus of most environmental impact tools
- Currently available environmental impact tools do not perform probabilistic calculations
- Pavement management engineers do not consider environmental stewardship one of their job

duties

- Cost and engineering judgment are the most common factors influencing pavement decisions
- Probabilistic calculations are desired, but not often performed as part of LCCA
- User costs are not frequently included in LCCA
- When user costs are included in LCCA, the most commonly considered cost is travel time/delay

The literature review and survey performed as part of this thesis showed that while LCA's have been being performed for decades, their application to pavement engineering is not widespread. Environmental impact tools currently being used to analyze pavement infrastructure projects have a heavy emphasis on CO_2e, often to the exclusion of all other impacts. The tools reviewed for this thesis are universally deterministic in their calculations, without consideration of uncertainty or risk.

The tools also do not appear to be being widely used, as not a single of the surveyed pavement management engineers reported that environmental impact was one of their job duties. The survey also showed that initial cost and engineering judgment are the most common factors used in decision-making. LCCA is also considered at least some of the time by a majority of responding agencies, while examination and inclusion of environmental impacts is substantially less common. Respondents reported that LCCA is most commonly performed deterministically and considering only agency costs. When user costs are included, the most commonly considered user cost is increased travel time (delay) during construction.

6.2 Conclusions

The literature review and survey uncovered that despite growing concern for the environment and a selection of environmental impact tools already available, environmental impact is not extensively integrated into pavement infrastructure decision-making. Currently available tools are not being used and decision-makers do not see environmental stewardship as part of their job responsibilities. The currently available tools suffer from drawbacks such as incomplete or unclearly defined LCA boundaries, consideration of only one environmental impact, subjectivity, lack of transparency, out-of-date databases, and an inability to perform probabilistic calculations. There is a need for a new tool to be designed which avoids these shortcomings. Furthermore, many of these drawbacks can be addressed without the need for extensive additional research, making the development of a new environmental impact tool immediately feasible.

6.3 Products

The objective of this thesis was to develop a framework for a software tool that will aid decision-makers in incorporating environmental factors into roadway decision-making. In order to achieve this, two products were developed:

1) A review of currently available environmental impact tools, describing their scopes and capabilities
2) A proposal for a new environmental impact tool, including its recommended scope, inputs, outputs, and a potential user interface

The review of environmental impact tools can be used to help familiarize decision-makers with the strengths and limitations of already available tools. If an individual or group is considering adding an environmental impact tool into their decision-making process, the review will serve as a starting point for deciding if an available tool aligns with their company or agency's needs and goals.

Reviewing existent tools and considering the current needs of pavement engineers and decision-makers led to the conclusion that significant gaps could be filled by a new environmental impact tool. The proposed tool will calculate resource usage and a wide range of emissions rather than just CO_2e. It will have a database which allows for immediate employment of the tool and this database can be fully customized through additions by the user. This would provide both ease of use and the assurance that the database can be kept up-to-date and made relevant to the region in which it is being used. A significant life-cycle impact not covered by other tools, emissions due to work zone related traffic delay, will be included. The proposed tool will also have probabilistic capabilities, allowing users to take risk and uncertainty into account in their decision-making. All of these features were chosen such that the tool can be developed immediately, without the need for extensive additional research.

Additionally, a Microsoft Excel workbook with a visual and interactive representation of the proposed tool was developed as part of this thesis. This workbook is capable of demonstrating the proposed tool's intended functionality and usability.

6.4 Recommendations for Tool Development and Implementation

While this thesis provides a full conceptual description for the proposed tool, the database and programming is left to future engineers. Development of the tool can be divided into two phases:

1) Build an initial database from literature

2) Program the tool using Microsoft Excel VBA or other appropriate platform

The first step involves data-mining for already developed emissions factors. Emissions factors will be needed for material extraction, material processing, material hauling, construction activities, power plants, and fuels. Material extraction, material processing, material hauling, and construction activities values will be in the form of kilograms or tons of emissions produced per ton of material. Power plant values will take the form of kilograms or tons of emissions produced per kilowatt-hour. Each fuel will be associated with a value of kilograms or tons of emissions produced per unit of fuel burned. These values are available from numerous sources, though care should be taken in noting where and when the values were calculated. Multiple values will be available for many of the materials and energy sources desired for the database; these can form the beginning of a probabilistic distribution of the database entry.

Programming of the tool will take many forms. For many of the calculations, the tool will simply need to access the database and multiply the emissions factor by the amount of material. The two methods of adding items to the database require two distinct programmed pathways. For the first, a user will input an already calculated emission factor and the program will save this value as a database entry. For the second method, users will input energy consumption and material production. The tool will then access the applicable power and fuel source data in order to calculate an emissions factor and store this in the database.

After the proposed environmental impact tool is developed, a database specific to a chosen locality should be developed. This should be achieved through working with local material sources and production facilities to determine their energy usage and material production. Variation in energy use and material production over the time period the database is being built can be used to generate probabilistic distributions specific to individual material and mix providers. The value of such geographically and temporally specific data will eclipse the general database and should be used to perform case studies demonstrating the usefulness of the tool.

6.5 Recommendations for Future Research

The incorporation of environmental impacts into pavement infrastructure decision-making could be aided by the following research:

- Develop an independent Emissions Due to Work Zone Delay calculator
- Survey of DOT engineers on barriers to using environmental impact tools:

    - Which environmental impact tools are they familiar with?
    - Which tools, if any, do they use?
    - What do they see as the greatest barriers to use?
      (i.e., time/effort required, cost to purchase software or license, lack of confidence in results, lack of knowledge of options, environmental impacts not a priority)
- Expanding review into a more comprehensive guide

Emissions due to work zone delay can be a significant source of construction-related emissions and is not currently considered by any tool examined as part of this thesis. The calculations necessary for modeling queuing, delay, and their resultant emissions are already well understood and could immediately be developed into an independent tool or add-on for an existing tool. Therefore, even if programming of the proposed tool is not pursued, this element should be focused on for continuing research and development.

While this thesis designed an environmental impact tool which filled gaps left by other tools, the reasons currently existent tools are not more widely known have not been fully established. Finding out the biggest barriers to use of environmental impact tools would help guide future researchers in attempts to increase integration of environmental considerations into the decision-making process.

The review of tools included in this thesis covers ten environmental impact tools that relate either directly or indirectly to transportation and pavement design. This review could be expanded into a more comprehensive guidebook. Such a guidebook could be used by pavement infrastructure decision-makers who are considering selecting a tool for use by their company or agency.

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