Applying Pavement Life Cycle Assessment Results to Enhance Sustainable Pavement Management Decision Making

James Matthew Bryce

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Civil Engineering

Gerardo W. Flintsch

Nadarajah Sivaneswaran

Ralph P. Hall

Christian Wernz

Pam M. Murray-Tuite

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Blacksburg, VA

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ABSTRACT

Sustainable pavement management implies maintaining acceptable condition of pavements while also considering the tradeoff between cost, environmental impacts and social impacts of pavement investments. Typical pavement management practices only consider economic considerations, and environmental mitigation techniques are employed after the selection of the maintenance action is complete. This dissertation presents a series of papers that demonstrate the impact of decision making on the environmental impact of the pavements both at the project and network levels of pavement management. An analysis was conducted of two models that relate pavement properties to vehicle rolling resistance and fuel consumption. These models were used, along with other tools to evaluate the impact of including the use phase of a pavement into pavement lifecycle assessments. A detailed project level lifecycle assessment was conducted, which showed it was found that the vehicles on the pavement during the use phase contribute the most to environmental pollutants by a significant margin over other phases of the lifecycle. Thus, relatively small improvements in the factors which contribute to rolling resistance may significantly influence the environmental impacts of the pavement. Building on this, a network level lifecycle assessment method was proposed to probabilistically quantify energy consumption for a given set of expected maintenance actions. This analysis showed that, although maintenance actions require a certain amount of energy consumption, this energy can be offset by improved road conditions leading to reduced rolling resistance. However, this tradeoff of reduced energy consumption also includes increased costs for a given network condition. In other words, the lowest energy consumption values did not tend to fall along the line defined by minimizing the cost divided by the pavement condition. In order to demonstrate how this tradeoff should be addressed, a novel decision analysis framework was developed, and implemented on a specific pavement network. Finally, a survey of transportation professionals was used to determine the optimal points within the solution space defined by minimizing costs and energy consumption while maximizing pavement condition. It was found that the solution space could be greatly reduced by implementing their responses using the proposed decision analysis framework.

Dedication

This dissertation is dedicated to my caring and supportive wife, Rebecca, as well as my understanding and patient son. Thank you Rebecca for providing me with the strength and encouragement to complete this work. Thank you Caleb for being obsessed with pressing the power button on my computer, which always reminds me of the importance of balance in my life.

This is also for dad Page and his mustache (praying for a safe time on tour in Afghanistan), and pops Pulse. Thank you for remaining good friends in good times and bad.

Finally, I thank God for providing me with a source of comfort and knowledge/wisdom.

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Several other people helped make this dissertation possible that I would like to acknowledge. I would like to thank my colleague and friend Joao Santos for his input into much of the work presented within this dissertation. Similarly, I would like to thank my friend and colleague Dr. Samer Katicha of VTTI for his invaluable input. Thank you to the other members of the Center for Sustainable Transportation Infrastructure for making my time there more enjoyable and informative, including: Daniel M., Akyiaa H., Lucy P. and Chris T. (among many others).

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Chapter 1.
Introduction, Objective and Background

1.1. Introduction

Pavements comprise a significant portion of the transportation infrastructure, which has a significant impact on the natural environment (Davis et al. 2010). Much of the environmental impact from pavements occurs due to the vehicles travelling along the pavement, during what is referred to as the use phase of the road. It has been established that upwards of 95 percent of the energy consumed during the lifecycle of a pavement occurs during the use phase of the road, and only 2 to 5 percent of the energy is consumed during construction, maintenance and operation (i.e., lighting and traffic controls) (EPA/EuroBitume 2004). Increased energy consumption also leads to an increase in greenhouse emissions, as well as an increase in other environmental pollutants. Examples of sources of energy consumption during the use phase include vehicle rolling resistance and pavement albedo.

Several research projects have tried to quantify the impact of pavement properties on rolling resistance. For example, an international collaboration, Models for rolling resistance In Road Infrastructure Asset Management systems (MIRIAM), investigated models to describe the energy consumption due to the tire-pavement interaction (Sandberg et al. 2011). The Highway Development and Management Model (HDM 4) has included models to characterize the impact of rough or poorly aligned pavements on the user costs (Morosiuk et al. 2006). Research has shown that in all driving conditions, an overall average of 25 percent of fuel consumption is expended on rolling resistance leaving 75 percent to overcome air drag and inertia (Izevbekhai 2012). Thus, if the rolling resistance of a pavement were reduced, the vehicle fuel consumption along that pavement would be reduced. For the effect of albedo, simulations in the city of Los Angeles predict that increasing the albedo of 1,250 km (777 miles) of pavement by a value of 0.25 (on a 0 to 1 scale) could save an amount of cooling energy worth $15 million per year (ACPA 2002).

In light of extensive research that has shown that pavement characteristics have a significant impact on vehicle fuel consumption and that the vehicle fuel consumption contributes significantly to the energy consumption during the pavements lifecycle, recent literature has proposed an extension of the typical LCA for pavements to include the use phase (Wang et al. 2012, Bryce et al. 2014). Several impacts resulting from the pavement use phase have been identified, such as increased fuel consumption as a function of pavement roughness, heat island effect of the pavement, effect of pavement albedo and others (Santero et al. 2011b). However, the impact of the pavement condition on vehicle fuel consumption remains to be the best defined in literature (Chatti and Zaabar 2012). An expected benefit of including the use phase into the LCA process is the ability to better evaluate the environmental sustainability of the pavement over its entire lifecycle, as opposed to during only its material and construction phases (Wang et al. 2012).

1.2. Objective

The objective of the research presented in this dissertation is two fold; (1) expand the boundaries of pavement LCA to include the use phase and assess the impact of this on pavement management decision making, and (2) develop a decision analysis methodology that assists engineers and planners when including environmental factors into asset management decision processes.

This dissertation focuses on evaluating techniques to include environmental factors into pavement management decision processes. However, it is important to recognize that environmental and economic factors are only two legs of the three legged stool of sustainability. The third leg, social equity, must also be recognized for a truly sustainable transportation network. Whereas environmental impacts of infrastructure have been well documented, the social factors resulting from investment in infrastructure management are less developed. Some research has shown the extent of a society's well-being has been directly correlated to the extent of that society's infrastructure (Chamorro & Tighe 2009). The interconnected systems of highways, bridges, pipelines and dams have made the changes in social behaviors possible by providing mobility, safe drinking water, waste management, and stable structures. The presence of an extensive road network allows people in rural areas to have access to health care and financial resources that are typically more prevalent in urban areas, and clean drinking water is a basic need for the health of all people. Although the main focus of this work will be to include environmental factors into sustainable decision processes, the decision processes proposed are expected to also be applicable when social factors are included into the decision analysis procedure.

1.3. Research Approach

The following tasks were completed in order to achieve the overall objectives of the dissertation.

A. Literature Review: An extensive review of technical papers and books in order to acquire a deeper knowledge of the most recent advances in the topics, which will be summarized in the following sections of this chapter. The review suggested that although a great quantity of relevant articles is available about costs and performance analysis of road pavements over the life cycle, only a small number of papers cover the topic of including the use phase in the environmental life cycle assessment of roads. However, recent models have made the inclusion of this phase more feasible.

While conducting the literature review, it became apparent that contributions could be made to both project level and network level pavement management. Therefore, three needs were identified for which this dissertation could contribute. The needs, linkages back to pavement management, contribution to the objectives, and corresponding chapters within this dissertation are summarized in Figure 1-1.

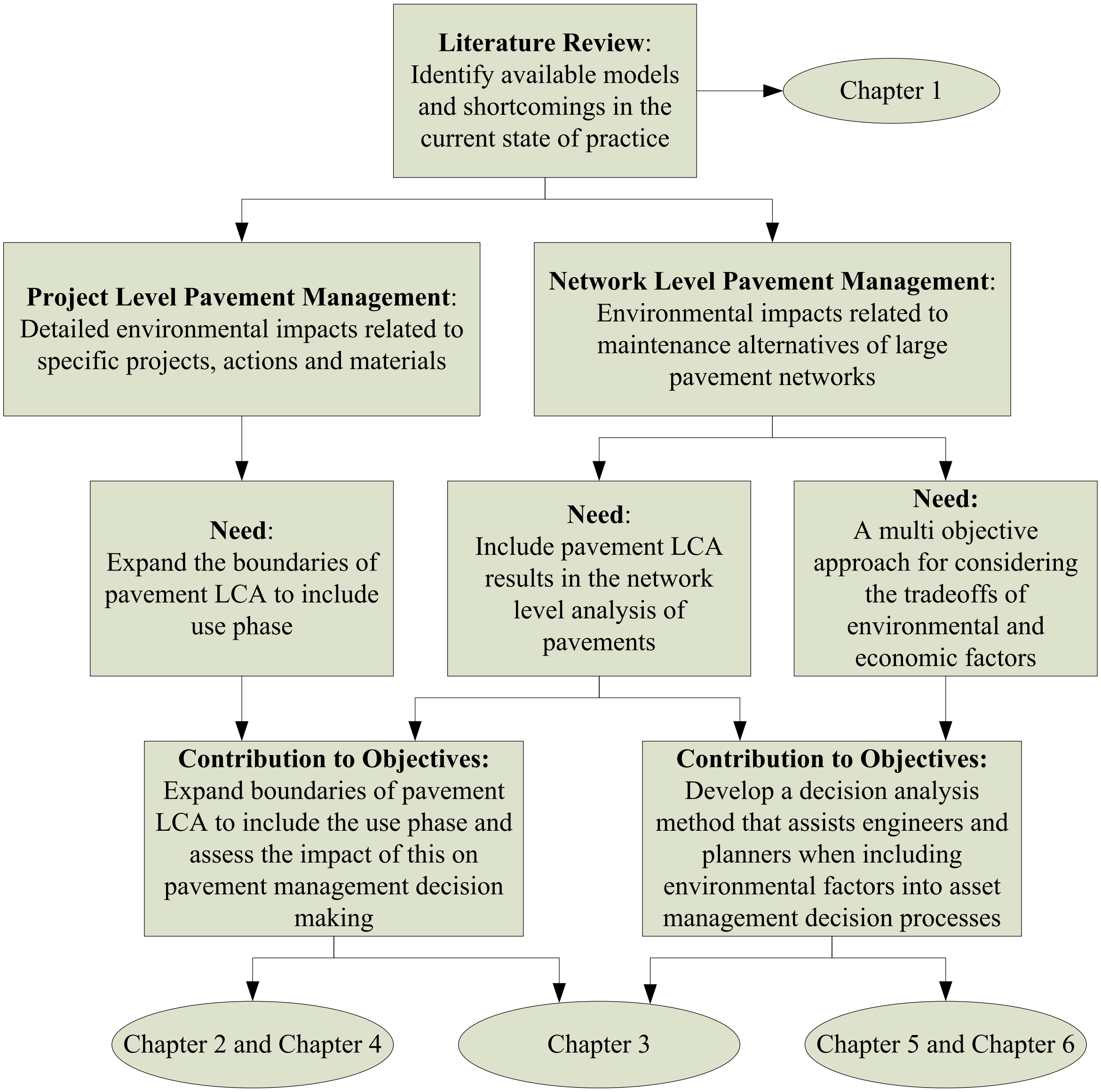

Figure 1-1. Results from Identifying Needs throughout the Literature Review

B. Analysis of Recently Developed Rolling Resistance Models: In order to contribute to the state of knowledge about the environmental impacts of pavements, a review was conducted in order to determine the extent to which recently developed rolling resistance models can be implemented into environmental life cycle assessment. Two recently developed models were evaluated, and a sensitivity analysis was conducted to determine the most important variables to reducing energy consumption. Also, a methodology was introduced to determine the impact of increased rolling resistance on vehicle emissions and other environmental pollutants. It was also noted that the range of energy consumption for typical interstates in the United States is dominated by aerodynamic resistance such that reducing the vehicle speed by a small amount accounts for the additional energy consumption due to poor pavement conditions.

C. **Expansion of Pavement LCA to Include the Use Phase:** This task was completed to both contribute to the state of current knowledge about a pavements environmental impact, as well as contribute to the objective of proposing techniques to enhance sustainable decision making. Methodologies to account for the pavement use phase in an LCA were introduced at the project level and at the network level. The project level methodology was introduced by conducting a detailed LCA on a project conducted in Virginia, and the impact assessment covered many environmental pollutants defined by the US Environmental Protection Agency. The project level evaluation represents the most detailed assessment of the environmental impacts of a pavements lifecycle when compared to the current literature.

The network level methodology was introduced as a way to allow agencies to account for total energy consumption when allocating resources. Energy consumption was selected as the environmental indicator because it can be used to predict the production of other environmental pollutants as in Patrick and Arampamoorthy (2010). A model was developed to predict the relationship between energy consumption, cost and condition resulting from pavement management decisions, and the model was coded into MATLAB™ to obtain results.

D. **Evaluating the Potential of Implementing Results into Network Level Pavement Management Practices:** This task was undertaken in order to develop a decision analysis methodology for including environmental factors into more sustainable multi-criteria asset management decision processes. A review of decision analysis techniques, as well as various decision theories, was conducted to determine the most appropriate way to implement the results from a life cycle assessment into decision making. Current decision making techniques (e.g., minimizing cost/benefit) were also evaluated, but it was determined that the relationship between energy consumption, cost and condition was not accounted by focusing on a single attribute.

A decision analysis technique was developed based on two commonly used decision analysis methodologies. This technique represents a way for solving problems with multiple objectives using the values of the stakeholder groups, while also evaluating the entire feasible solution space as opposed to only optimal decisions. A survey was developed to assess the values and risk preferences of transportation professionals, and it was demonstrated how the results of the survey could be used with the proposed decision analysis technique in order to communicate potential outcomes to a larger group of stakeholders.

1.4. Background

1.4.1. Life Cycle Assessment

Life cycle assessments (LCA's) are the tools that are generally used to measure impacts of pavements on the surrounding environment. LCA's are tools that study the inputs and outputs of a system, generally with the goal of understanding the systems' environmental impacts in terms of greenhouse gas (GHG) emissions, energy consumption or material use. The purpose of a pavement LCA is to quantify the total environmental impact of the pavement throughout the pavements life, which is generally divided into the following five phases (Santero et al. 2011b); (*1*) raw materials and production, (*2*) construction, (*3*) use, (*4*) maintanenance and (*5*) end of life. An important consideration for LCA is the boundaries chosen for the analysis. Ideally, an LCA is a cradle to grave analysis that accounts for the entire life of the materials, all the processes involved with the system, as well as other processes directly impacted by the system. However, lack of information and an inability to accurately predict certain parameters, such as material life and the impact of the system condition on the user, sometimes lead to a constraint on the system boundaries for a pavement. Thus, in the case of pavements, typical LCA boundaries are constricted to cover only the time period from material extraction through the end of the construction phase of the project.

The purpose of an LCA is to compile and quantify such impacts as CO_2 emissions and energy input into the system (Huang et al. 2009). The LCA of a pavement through the materials and construction phases has been extensively researched. An example of an LCA through the construction phase, Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) was developed and released in 2003 by researchers at the University of California-Berkeley. PaLATE has an integrated database of materials and construction equipment for the user to draw on while performing the LCA (Horvath, 2003).

LCA's are generally based on process-based models, economic input-output models or hybrid (a combination of process-based and input-output models). Process-based models compute the resource use and environmental impacts from the main processes of the system under evaluation (Suh et al. 2004). Generally, the process-based LCA's can be represented as flow diagrams or matrices describing each process interactions. Economic input-output models are top down hierarchical models which use total factor multipliers based on the national economy to determine embodied effects per unit of production (Lenzen, 2008). Different parameters within the process are weighted based on their contribution, and then broken into more detailed levels until the entire process is defined at an adequate level of detail. Input-output LCA models account for interdependencies between sectors and processes using monetary transactions between the sectors on a national or global economic scale. A more detailed discussion of the LCA types, along with a comparison of strengths and weaknesses can be found in Santero et al. (2011a).

Santero et al. (2011b) note an important distinction between life-cycle inventories (LCI's) as the part of an LCA in which the resource use and pollutant releases are quantified. In contrast, a full LCA includes several steps in addition to conducting a full LCI, it requires an impact analysis and interpretation of the results. Currently, the most common method for conducting an LCA is a process-based method that is defined by the International Organization for Standardization (ISO). The ISO outlines a four step approach in their standard ISO 14040 and ISO 14044, Standards for a Process-Based LCA Approach (International Organization for Standardization 2006). The steps are as follows:

1. **Goal and scope**. Define the reasons for carrying out the LCA, the intended audience, geographic and temporal considerations, system functions and boundaries, impact assessment, and interpretation methods;
2. **Inventory assessment**. Quantify life-cycle energy use, emissions, and land and water use for technology use in each life-cycle stage;
3. **Impact assessment**. Estimate the impacts of inventory results; and
4. **Interpretation**. Investigate the contribution of each life-cycle stage and technology use throughout the life cycle and include data quality, sensitivity, and uncertainty analyses.

Huang et al. (2009) describe the process given in ISO 14040 in more general terms as (1) defining the scope, (2) performing the LCI to gather all relevant environmental burdens (this is where the majority of the work resides), (3) perform a lifecycle impact assessment (LCIA) where the results are presented in such a manner that supports comparison, interpretation of the results or further analysis.

1.4.2. Applications of LCA to Pavements

Santero et al. (2011b) performed a critical assessment of the current state of pavement LCA's by extensively reviewing available literature on the topic. The researchers identified four attributes of the methodology of the LCA that are essential for comparing the studies, (1) Functional Unit Comparability, (2) System Boundary Comparability, (3) Data Quality and Uncertainty and (4) Environmental Metrics. Functional unit comparability becomes an issue when trying to compare results from studies that evaluate different pavements that facilitate different traffic types across different climates or environmental regions. Essentially, many of the results of LCA's found in literature cannot be directly compared due to the differing functional units (Santero et al. 2011b). The researchers note the omission of the use phase from the majority of pavement LCA's as possibly the most significant shortfall of modern studies. Furthermore, it was noted that a majority of the studies that included maintenance in the system boundaries simplified the maintenance practices to a series of repeated impacts, and did not include the impact of preservation practices such as diamond grinding or crack sealing on either pavement or environmental performance.

The impact of data accuracy on LCA results was noted to be significant, and is possibly a function of differing technological assumptions, differing system boundaries (for extraction and production) and differing regional processes. The example was given for the range of energy used for cement and bitumen as 4.6 – 7.3 MJ/kg of cement; for bitumen, the range is 0.70 – 6.0 MJ/kg respectively (Santero et al. 2011b). It was also noted that, although energy consumption was used throughout many of the studies, other metrics used varied between the studies. For example, some studies included specific gases released into the environment (e.g., NO_x and SO_x), and others included factors such as nitrogen released into water (Santero et al. 2011b). A holistic pavement LCA would include all impacts such as land use, water use, greenhouse gas emissions, leachate and runoff, along with many other factors. Another metric that varied among the many studies is the use of feedstock energy associated with bitumen. The debate whether to include the feedstock energy into the bitumen energy consumption has been extensively discussed, and a general understanding was reached at a workshop in 2010 that the energy should be reported separately for the decision makers to decide whether to include it for each study (UCPRC 2010).

In a follow up, Santero et al. (2011c) present the current state of knowledge regarding traffic delay during the construction and maintenance phases, the use phase and the end-of-life phase. The researchers discuss the development of several tools, such as the US Environmental Protection Agency (EPA) MOVES (EPA 2012), which can be used to include traffic delay and emissions into a pavement LCA. Additionally, it is discussed that judicious design and management of pavements, especially along high volume roads with significant truck traffic, can decrease the rolling resistance along the pavement (Santero et al., 2011c). The researchers also discuss that a pavement has three possible fates at its end of life, each of which require a different assessment technique for the LCA, (1) excavated and landfilled, (2) excavated and recycled and (3) left in place as structure for new pavement (Santero et al., 2011c).

The majority of pavement related LCA studies to this point have been developed for process contained only through the material extraction and construction phase, as well as the maintenance phase of the pavement. In general, the pavement related studies were conducted either to better understand the benefits of using alternative or recycled materials in the construction process, quantify the benefits of waste minimization during construction or compare project types and construction techniques. Many of the reports are briefly discussed in this section.

Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) was developed and released in 2003 by researchers at the University of California Berkeley. PaLATE is a spreadsheet-based tool that accounts for both economic and environmental factors related to the construction processes of a pavement. PaLATE has an integrated database of materials and construction equipment for the user to draw on while performing the LCA. For the economic analysis, PaLATE uses a LCCA based model with annualized costs (Horvath, 2003). For the environmental assessment, PaLATE assesses emissions associated with the production of materials, construction, material transport and maintenance and recycling (Horvath 2003).

Park et al. (2003) evaluated the environmental loads due to the processes throughout the lifecycle of a highway, defined in four stages as: (1) manufacturing of materials; (2) construction; (3) maintenance and (4) end of life (demolition/recycling). The researchers focused on energy consumption, then used appropriate factors to translate the energy consumption into equivalent emissions and estimate pollutant discharge into water. The research presented a thorough assessment of construction practices, but notably excluded the use phase from the definition of the pavement lifecycle.

In 2004, research was conducted by researchers from Oregon State University in order to assess the energy consumption for both asphalt and Portland cement concrete pavements. The assessment was performed based on an LCA, with boundaries from material extraction/production through construction (Zapata and Gambatese 2005). The Life Cycle Inventory was obtained through an exhaustive literature search and from information obtained from construction companies. Much like other studies, Zapata and Gambatese (2005) experienced some limitations due to the lack of availability of certain information relating to the LCA. The uniqueness of the study was that it set precedence for obtaining local contractor data for energy consumption and inventory information.

Huang et al. (2009) evaluated modern LCA data and methods pertaining to pavements, then applied the techniques to an asphalt paving project at an airport. The research identified major shortcomings with many modern LCA methods, such as their inapplicability to pavements, and proposed an updated LCA model based on the processes contained within asphalt pavement construction. The model was built in Microsoft Excel with parameters that were based on data and processes specific to the UK through the construction phase of asphalt pavements. The researchers identified the quality of the gathered data as an important parameter that should be continuously improved as new data arises. The results of an example LCA using the developed model proved insightful for decision makers and understanding the critical factors that contribute to adverse environmental impacts (Huang et al. 2009). Furthermore, the paper depicted a detailed set of unit processes involved in the construction of an asphalt pavement. A less detailed version is shown in Figure 1-2.

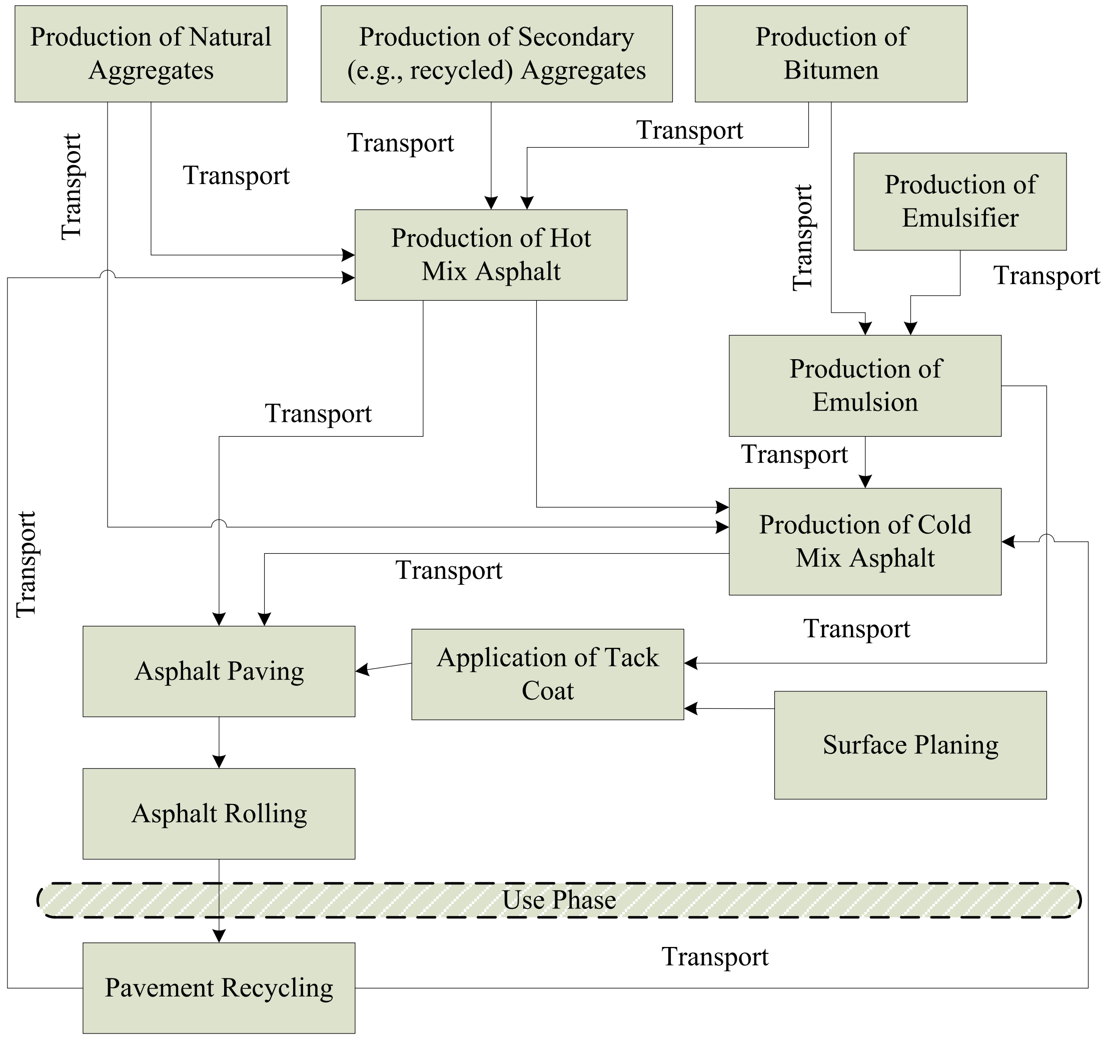

Figure 1-2 Processes in Asphalt Pavement Construction, ***After (Huang et al., 2009)***

In 2010, the New Zealand Transport Agency released a report that was developed in order to quantify the results from waste minimization in road construction (Patrick and Arampamoorthy 2010). The report analyzed the energy consumption in all of the processes and operations. This energy use was then converted to CO_2 emissions by assuming a certain amount of the energy came from certain sources (e.g., diesel or power grid). This was critical, because a significant portion of energy in New Zealand comes from hydroelectric generation. The energy values used in the New Zealand report were mainly compiled from an extensive literature review from transportation and manufacturing sources. The research concluded that potentially significant savings in energy consumption and emissions can be achieved through waste minimization. Furthermore, the method used showed the importance of using location specific energy and emissions information.

Weiland and Muench (2010) evaluated LCA's for three different options of replacing a Portland Cement Concrete (PCC) pavement, including two HMA options and one PCC option. The LCA's included the construction and maintenance phases, and the maintenance schedules were developed such that each of the options had a life of 50 years. The report presented the processes included in the LCA for each of the options in detail, the processes included in the reconstruction using PCC option are summarized in Figure 1-3. The study presented a thorough evaluation of each of the alternatives using many tools available, such as the US Environmental Protection Agency's (EPA) NONROAD model for construction equipment and the EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) during the impact assessment.

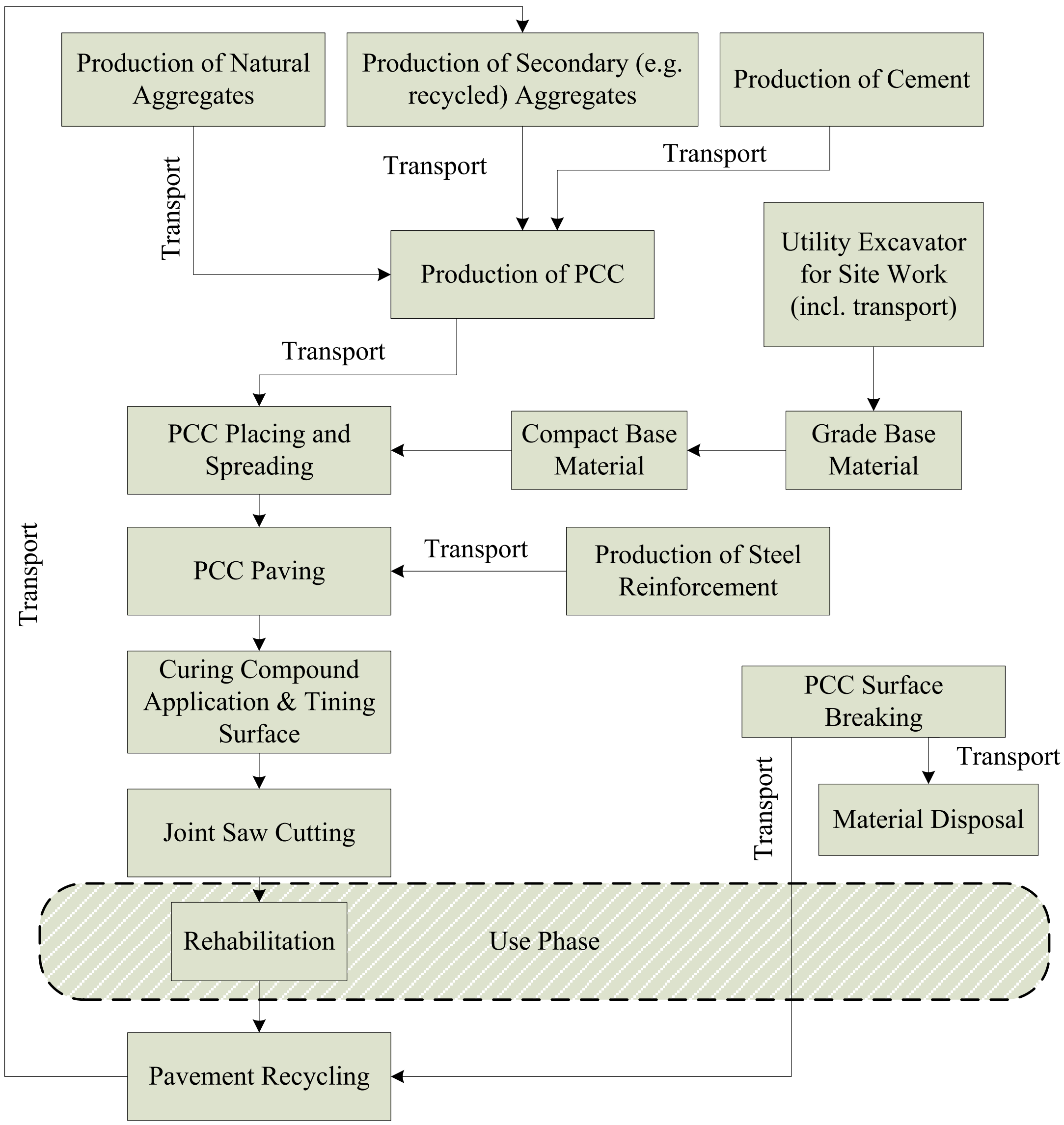

Figure 1-3. Processes Included in PCC Pavement Construction/Rehabilitation

Zhang et al. (2010) presented a comprehensive pavement LCA that included increased fuel consumption due to an increase in roughness over time during the use phase, although other factors contributing to an increase in rolling resistance were not included. The study was designed to compare three types of overlays over time, and included six modules or phases: (1) material production; (2) construction; (3) distribution (or transportation of the materials); (4) traffic congestion; (5) usage and (6) end of life. An interesting result was that the model was quite sensitive to future traffic growth projections. Furthermore, the projected traffic congestion caused by construction and maintenance activities was significant to the LCA model. One drawback of the study is that the model used to relate IRI to fuel consumption is a linear function developed using data from heavy truck testing.

Wang et al. (2012) presented an LCA model that included the material production phase, construction/maintenance/rehabilitation phase, use phase and end of life phase. The use phase included calculating additional fuel consumption due to the deterioration of the pavement in terms of IRI and mean profile depth, then using the HDM 4 model to estimate the additional rolling resistance. The US EPA program MOVES was used to calculate vehicle fuel consumption and emissions for specific traffic information. The results showed that considerable savings in fuel consumption and emissions can be realized over the life of a high volume road.

1.4.3. Pavement Use Phase

In contrast to the extensive literature about LCA's for the construction and maintenance phase of a pavement, publications documenting the impact of the use phase of the pavement are much less prevalent. However, the impact of the use phase of pavements on the environment is expected to be significant when compared to the construction and maintenance phases. Several factors can be influenced by the condition of the pavement. For example, Zaabar (2010) evaluated the effect of the pavement surface properties on rolling resistance, damaging goods in transport and mechanical wearing to the vehicle (e.g., tire wear, etc.). A more extensive evaluation would potentially reveal many more impacts that the pavement condition has on transportation, but the focus of this research is how to include the effect of pavement properties on vehicle fuel consumption and greenhouse gas emissions into pavement LCA's.

According to the Texas Transportation Institute (TTI), in 2011, congestion in the top US urban areas resulted in an average of 19 gallons of excess fuel consumption per auto commuter per year (Schrank et. al. 2012). There is no similar figure assessing the wasted fuel due to the trillions of vehicle miles travelled (VMT) over rough pavement sections. In a passenger car, rolling resistance can account for up to 33 percent of the vehicle's energy that reaches the driveline. The rolling resistance is affected by the tire characteristics, tire operating conditions, environmental conditions, and road surface characteristics. Tire characteristics include construction and tread while operating conditions include tire inflation, load, speed, slip angel, camber angle, driving/breaking force, wheel/axle and configuration. Environmental conditions include temperature, water and snow/ice. Road surface characteristics include micro-texture, macro-texture, mega-texture and unevenness (EPA/Eurobitum2 2004).

One of the earliest studies on the effects of road roughness on fuel consumption was performed in 1983 in Sweden by Sandberg at VTI (Swedish National Road and Transportation Research Institute) (Sandberg 1990). The study evaluated 20 different roadway characteristics representing the full range of Swedish roads at speeds of 50, 60 and 70 km/h. Vehicle fuel consumption was found to be correlated best with short wave unevenness ($r = 0.91$), mega-texture ($r = 0.83$) and macro-texture ($r = 0.60$). Mega-texture is generally defined as a pavement surface texture due to surface irregularities having a relative wavelength between 5 cm and 0.5 meters (Flintsch et al. 2003). Pavement macro-texture is generally defined as a pavement surface texture having a relative wavelength between 0.5 mm and 50 mm, and is a result of large aggregate particles in the mixture (Flintsch et al. 2003). The short wave unevenness range is close to the wavelength sensitivity range of the IRI which is between 1.2 to 30 m (Sayers and Karamihas 1998).

1.4.4. Rolling Resistance

Evans et al. (2009) defines rolling resistance as the mechanical energy loss by a tire moving a unit distance along the roadway, and is effected by both properties of the tire and of the pavement. This is similar to the definition used by Michelin (2003), as well as many other literature sources (e.g., Schuring and Futamura (1990), TRB (2006) and ISO (2009)). However, as discussed in Sandberg (2011), this leaves losses from the suspension system out of the definition of rolling resistance. From a pavement management perspective, the pavement properties induce losses due to the rolling resistance as it has been traditionally defined (i.e., as in Michelin (2003)), as well as losses in the vehicle suspension system. Therefore, this dissertation will adopt the definition of rolling resistance from Sandberg (2011) as including: tire rolling resistance (from the tradition rolling resistance definitions), bearing resistance (i.e., deflection of the pavement surface), suspension resistance and transmission resistance (i.e., the rotating parts of the tire).

The energy that is lost due to rolling resistance comes directly from the power that is used to propel the vehicle, and as a consequence, more fuel must be consumed to propel a vehicle over a pavement with higher rolling resistance. Evans et al. (2009) reported that as much as 1/3 of the total energy that is available to the wheels can be expended to overcome the rolling resistance. Other factors that consume the energy used to propel the vehicle (the energy that makes it through to the driveline) are aerodynamic resistance and braking (TRB 2006).

The following are factors that have been identified in past research as pertinent to consider during the use phase of the pavement (Santero et al. 2011b; Sandberg et al. 2011; Chatti 2010): tire – pavement interaction; traffic flow; maintenance treatments and practices; albedo; leachate and lighting. The tire-pavement interaction is the main factor in rolling resistance, and is impacted by several variables such as: macro-texture, pavement stiffness, roughness, rutting and the transversal slope of the pavement. Traffic flow along a pavement route, in terms of congestion, speed limit and the interaction with vehicles entering or leaving the route also impact the vehicle fuel consumption. Maintenance can impact the fuel consumption of vehicles by causing congestion along the route. Furthermore, the performance of the pavement maintenance treatment also has an impact on the vehicle fuel consumption by affecting the variables related to tire-pavement interaction.

1.4.4.1. Relationship between Rolling Resistance and Fuel Consumption

Vehicle fuel consumption is a function of many variables, one of which is rolling resistance. Only a relatively small portion of the fuel consumed is used to propel the vehicle, the rest is consumed by the engine, driveline and the peripherals connected with driving (e.g., air conditioning, etc.). The majority of losses associated with rolling resistance are expected to come from the visco-elastic behavior of the rubber tires (TRB 2006). Given that the majority of the losses come from the hysteresis effects of the rubber, as the load on the tire increases the energy lost in the deformation of the tire increases.

Evans et al. (2009) measured the rolling resistance of several different tire types and reported that a 10 percent reduction in rolling resistance can lead to a 1 to 2 percent reduction in fuel consumption, with an average reduction of 1.1 percent. Schuring and Futamura (1990) have shown that this relationship can be taken as linear. TIAX (2003) reported that during highway driving, the 2 percent reduction in fuel consumption per 10 percent reduction in rolling resistance is expected, and the figure is closer to a 1 percent reduction during urban driving. Some estimations have shown that a 10 percent reduction in rolling resistance could save between 1 and 2 billion gallons of fuel annually (of 130 billion gallons currently consumed) among the passenger car fleet, assuming the driving habits used in the 2006 study (TRB 2006).

Chatti and Zaabar (2012) reported the results of calibrating the HDM 4 models for vehicle operating costs in the National Cooperative Highway Research Program (NCHRP) report 720. This research calibrated fuel consumption models as a function of pavement roughness for several vehicles and several speeds. The impact of the vehicle speed and type as a function of roughness can be described by the terms of equation 1-1. The total power requirement variable in equation 1-1 is a function of the rolling resistance, and their relationship is detailed elsewhere (see: Chatti and Zaabar 2012).

$$FC = 1000\beta\left(\frac{P_{tot}}{v}\right) \tag{1-1}$$

Where FC is the vehicle fuel consumption, β is the fuel efficiency factor, P_{tot} is the total power requirement, and v is the vehicle velocity.

1.4.4.2. Relationship between Fuel Consumption and Vehicle Emissions

The relationship between emissions and fuel consumption depends on many factors, such as the vehicle type and the type of fuel being consumed, as well as the specific characteristics of the vehicle. In order to facilitate emissions calculations, the US EPA has developed software that tracks vehicle emissions along a transportation corridor, known as the Motor Vehicle Emission Simulator (MOVES). The software also estimates vehicle fuel consumption along the corridor. Wang et al. (2012) presented an application of MOVES to calculate vehicle fuel consumption and emissions for specific traffic information.

1.4.5. Tire – Pavement Interaction

The tire-pavement interaction is one of the main factors in rolling resistance, and can be impacted by both the properties of the tire (e.g., air pressure or material properties) and properties of the pavement surface. The impact of the tire on rolling resistance will not be discussed in this research. The pavement side of the interaction is impacted by several variables such as: macro-texture; pavement stiffness; roughness; rutting and the transversal slope of the pavement. It is important to note that many of the studies that investigated the tire-pavement interaction were conducted using different methodologies, which means it is important to understand all assumptions and simplifications made in the analysis before a direct comparison between the studies can be made. The results of the studies are discussed below as they were presented in the individual research projects.

1.4.5.1. Macro-Texture

Zaabar (2010) evaluated the effect of pavement macro-texture on fuel consumption, and determined that an increase in fuel consumption with increasing mean profile depth of the pavement was statistically significant at the 95 percent confidence level for lower speeds. Laganier and Lucas (1990) found that macro-texture could lead to overconsumption of up to 5 percent from a base consumption of 0.7 l/km. At high speeds, it is expected that aerodynamic resistances dominate the resistance forces, thus causing the effect of macro-texture to be overshadowed. Conversely, Sandberg (1990) found that the effect of macro-texture on fuel consumption was more defined at higher speed; though the author pointed to poorly selected driving conditions as a possible cause of low speed driving having a lower correlation.

The increase in fuel consumption as a function of the pavement macro-texture is dependent on the vehicle type, and is expected to be higher for heavy vehicles. According to Sandberg (1997), the lower limit for expected effect of macro-texture on rolling resistance is a 2.5 percent increase in rolling resistance per unit increase of mean profile depth (in mm). Zaabar (2010) reported that for trucks, an increase in mean profile depth from 0.5 mm (0.02 in) to 3 mm (0.12 in) is expected to result in an increase in fuel consumption between 1 and 1.6 percent.

Hammarström et al. (2008) used coast-down methods, or measurements of a vehicles velocity or acceleration while it is allowed to roll freely across a section of pavement, to measure the impact of pavement roughness, travel velocity and macro-texture on rolling resistance. The research proposed a set of equations to relate rolling resistance to macro-texture and roughness by comparing measurements taken during the research and theoretical models used to quantify the impact of each factor. The tests were conducted using a car, light truck and heavy truck. Some generalized results presented by Hammarström et al. (2008) are that an increase in rolling resistance of 17 percent per unit of mean profile depth is expected for a starting speed of 50 km/h for the car, and an increase of 30 percent per unit of mean profile depth is expected for a starting speed of 90 km/h for the car. The results showed that if the total driving resistance is considered, an increase in mean profile depth from 0 to 1 at 50 km/h is expected to lead to an increase of driving resistance of 10.5 percent for the car. The researchers noted that more measurements would be required to obtain results for the trucks.

1.4.5.2. Pavement Stiffness

Much of the research pertaining to the impact of pavement stiffness on rolling resistance has been derived from studies comparing asphalt concrete pavements to Portland cement concrete pavements. Taylor and Patten (2006) conducted field tests using both cars and heavy trucks driven over asphalt concrete pavements and Portland cement concrete pavements in order to evaluate differences in fuel consumption for each case. The research also tested over multiple seasons and the trucks were subjected to multiple loading conditions. In most cases, the results of the research showed anywhere from a 1 percent to a 5 percent savings in fuel consumption when driving on concrete pavements. However, during many of the tests in the summer, the research indicated a fuel saving for composite pavements when compared to concrete pavements (Taylor and Patten 2006). Although the test results indicated differences in fuel consumption with varying pavement stiffness, the developed models did not include surface wear and anomalies (e.g., potholes). Furthermore, other surface properties, such as tining of the concrete surface or texture of the pavement, were not accounted for in the study. Thus, the results of the study are not considered ideal for inclusion in an LCA of the use phase of the pavement.

Santero et al. (2011a) evaluated the impact that the pavement stiffness has on the fuel consumption of a vehicle travelling along the pavement by developing a mechanistic model. The researchers proposed a beam on elastic foundation as the model to describe the behavior of the pavement subjected to a wheel load, and calibrated their model using data from the Long Term Pavement Performance (LTPP) database. The model indicated less fuel consumption over more stiff pavements, especially in the case of truck traffic. However, it is important to note that the model was developed in order to better understand the mechanisms that contribute to increasing rolling resistance with increased deflections, and field studies were not used to calibrate the model.

A follow up to the study by Santero et al. (2011a) calibrated the model that was developed to describe pavement deflections, and developed scaling factors for each of the inputs (Akbarian and Ulm 2012). The calibration was conducted using additional sites from the LTPP database, and an example application of implementing the model into an LCA was conducted using data from the Athena Institute. The results of the study indicated that for high volume roads, the GHG emissions from the pavement-vehicle interaction can be greater than the GHG emissions from the materials and construction phases (Akbarian and Ulm 2012). However, the additional work was performed using a small number of pavement segments from the long term pavement performance database, thus the results may still be seen as theoretical or speculative.

Whereas much research has been conducted on the differences in pavement type on rolling resistance, Wang et al. (2012) pointed out that sufficiently validated models have yet to be developed to calculate the impact of pavement stiffness on fuel consumption and emissions. This is mainly a consequence of the experimental designs of the studies that compare asphalt pavements to concrete pavements. Although models were developed by Akbarian and Ulm (2012) as well as Santero et al. (2011a) to quantify the impact of stiffness on fuel consumption, these models are considered first order attempts at understanding the mechanism of the pavement vehicle interaction, and are not yet sufficiently corroborated with field measurements to be used in a pavement LCA.

However, even in the absence of calibrated models, there is strong evidence of the differences in fuel consumption between asphalt and concrete pavements over certain conditions. Zaabar (2010) showed that at 35 mph (56 km/hr) during summer conditions, there is a statistically significant difference between vehicle fuel consumption along apshalt and concrete pavements for trucks (with the conrete performing better). The development of more accurate models in the future will facilitate the inclusion of pavement type, or pavement stiffness, into a pavement use phase LCA.

1.4.5.3. Roughness

An early study on the impact of the pavement roughness on fuel consumption was conducted in 1983 in Sweden at VTI) (Sandberg 1990). The difference in fuel consumption between smooth and rough pavement was around 4.5 percent (EPA/EuroBitume 2004). Laganier and Lucas (1990) found that pavement unevenness could lead to overconsumption of fuel of up to 6 percent from a base consumption of 0.7 l/km. Laganier and Lucas (1990) also calculated the power lost in the shock absorbers as a function of roughness level and found most loss occurs at wavelength between 1 m and 3.3 m which corresponds to the unevenness range as well as the most sensitive IRI range. According to Sandberg (1997), the lower limit for expected effect of roughness on rolling resistance is a 0.8 percent increase in rolling resistance per unit increase of IRI (in m/km).

In the United States, WesTrack test results showed that rougher pavements result in increased fuel consumption of trucks (Epps et al. 1999). Zhang et al. (2010) used the WesTrack models in the LCA of an overlay system. One downfall of the WesTrack model was that it was developed for heavy trucks over a small variation of conditions. Zaabar (2010) evaluated the impact of pavement roughness (in terms of IRI) on the change in fuel consumption, and used the data to calibrate HDM 4 prediction models.

Chatti and Zaabar (2012) reported the results of calibrating the HDM 4 models for vehicle operating costs in the National Cooperative Highway Research Program (NCHRP) report 720. During this research, fuel consumption models as a function of pavement roughness for several vehicles and several speeds were calibrated. A vehicle operating cost modeling program was developed in the form of a spreadsheet tool by Chatti and Zaabar (2012) as a part of the NCHRP project. Part of the spreadsheet output is the estimation of the additional fuel consumption as a function of the following variables: pavement roughness; mean texture depth; roadway grade; super-elevation; pavement type (i.e., asphalt vs. concrete); vehicle speed and air temperature. To demonstrate the impact of roughness on fuel consumption, the results of the additional fuel consumption for four different types of vehicles, four different roughness values and three speeds are shown in Table 1-1. The mean texture depth was held at 1 mm (0.04 in), the grade and super-elevation were left at 0 percent, the pavement type was assumed to be asphalt, and the air temperature was assumed as 20° Celsius (68° Fahrenheit).

Table 1-1 Relative Fuel Consumption for 4 Vehicle Types as a Function of Speed and IRI; The Increases are Relative to an IRI of 63 in/mile

Speed (mph)	IRI (in/mile)	Car	Light Truck	Heavy Truck	Articulated Truck
35	**63**	0.00%	0.00%	0.00%	0.00%
35	**75**	0.49%	0.23%	0.40%	0.42%
35	**85**	0.86%	0.41%	0.70%	0.73%
35	**95**	1.22%	0.58%	1.00%	1.05%
55	**63**	0.00%	0.00%	0.00%	0.00%
55	**75**	0.48%	0.18%	0.28%	0.28%
55	**85**	0.83%	0.31%	0.49%	0.49%
55	**95**	1.19%	0.44%	0.69%	0.71%
68	**63**	0.00%	0.00%	0.00%	0.00%
68	**75**	0.43%	0.15%	0.22%	0.23%
68	**85**	0.75%	0.26%	0.39%	0.40%
68	**95**	1.07%	0.37%	0.56%	0.57%

1.4.5.4. Rutting

Rutting was one of the variables analyzed in a VTI report aimed at using coast down measurements to determine the effect of the road surface conditions on rolling resistance (Hammarström et al. 2008). However, rutting was not found to be significant on its own, and the researchers noted that the high correlation between rutting and the measured IRI may be good reason to leave rutting out of a generalized driving resistance model. The relationship between rutting and roughness has been demonstrated elsewhere (Mactutis et al. 2000), thus a separate factor relating rutting to rolling resistance is not necessary to develop, and would be required to be decoupled from the IRI effect if it was developed.

1.4.5.5. Transverse Slope

The transverse slope of the pavement, sometimes known as the crossfall or crossslope of the pavement, has an impact on the side forces of the vehicle, which in turn affects the rolling resistance along the pavement (Sandberg et al. 2011). Although this feature of the pavement is recognized to impact rolling resistance, no significant amount of research exists to quantify its effects. Therefore, until research is reported that demonstrates the impact of the transverse slope on the rolling resistance, this dissertation will not adress it any further.

1.4.6. Traffic Flow

Traffic flow along a pavement route impacts the fuel consumption and emissions from a vehicle by affecting the engine and vehicular speed (Zaabar 2010). Many factors that can mostly be controlled by judicious engineering can impact traffic flow, such as congestion (due to the roadway being over capacity), the posted speed limit and the interaction with vehicles entering or leaving the route. For example, Barth and Boriboonsomsin (2008) investigated the relationship between traffic congestion and CO_2 emissions and presented some techniques to minimize congestion, with the goal of minimizing CO_2 created by traffic. One tool that is used for determining the impact of traffic flow on emissions is EPA MOVES (EPA 2012).

1.4.7. Maintenance Treatments and Practices

The maintenance phase of the pavement is generally taken as separate from the use phase, although maintenance occurs within the use phase of the pavement. LCA's for the maintenance phase generally consists of components from all other phases of the pavement life, and have been demonstrated in literature (Chiu et al. 2007; Huang et al. 2011; Wang et al. 2012). Some research has shown that the additional fuel consumption and emissions from vehicles because of the work zone congestion along the route being maintained can be significantly higher than those of the materials and construction. Furthermore, the performance of the treatment also has an impact on the vehicle fuel consumption by affecting the variables related to the rolling resistance, and thus effecting the use phase.

1.4.8. Other Factors Impacting the Pavement LCA

Aside from rolling resistance, it is recognized that there are many other factors that should be implemented into a thorough pavement LCA. For example, the albedo of the pavement, a measure of the pavement surface reflection, has been shown to have a considerable impact on the urban heat island effect. It is important to recognize the regional effect of albedo. It can be demonstrated that increasing albedo in hot weather climates can greatly benefit energy costs by reducing the local temperature slightly, and thus reducing the need for cooling. However, the same may not be true for cities in colder climates, which have more cost associated with heating than with cooling a structure.

Leachate, pavement lighting, vehicle and tire wear, and damage to goods during the use phase are other variables that should be included for a more holistic LCA. Zaabar (2010) evaluated the latter two variables and calibrated the HDM 4 models to account for them. Furthermore, the amount of lighting required along a pavement may change based on the surface reflectance, thus impacting the energy consumption requirements due to the pavement. However, this dissertation will not address these factors in its current form, but subsequent research should address the impact of each of these factors on the results of the LCA.

1.4.9. Ecological Discounting

An aspect that must be addressed when comparing environmental impacts over different time horizons is ecological discounting, or the concept that future environmental impacts should be adjusted back to some present value through a discount rate. Notably, economic measures are discounted over time, meaning that as the time horizon increases, future economic values impact the present value economic results less and less. However, there is still no widely accepted method for discounting environmental performance measures over time. Discounting future environmental loads is a topic that is thoroughly explored in Sumaila and Walters (2005). The main argument is that discounting future environmental loads is not merely a scientific issue, but inevitably a policy issue. Given that the environment is not an asset traded on the financial market, discounting future loads makes assumptions about human proclivity in future generations. However, the critical result of not discounting future environmental loads is that as the time horizon increases, the environmental performance measures will seem to inflate relative to the economic performance measures, and potentially dominate the analysis for substantially long time periods.

It is important to realize that the views on discounting environmental impacts over a time horizon is still evolving and vary widely. For example, Hellweg et al. (2003) concludes that discounting environmental impacts over time breaks a fundamental rule of ethics in most cases, whereas Almansa and Martinez-Paz (2011) discuss the importance of weighting future environmental impacts to determine the economic viability of alternatives. Gollier (2010) describes the issue of discounting future environmental impacts in terms of the wealth effect as:

> "*(T)he main economic justification of discounting is based on a wealth effect. If one believes that future generations will be wealthier than us, one more unit of consumption is more valuable to us than to them, under decreasing marginal utility of consumption*."

However, if the economic argument made in Gollier (2010) is followed (i.e., the decreasing marginal utility of wealth is attributed to the assumption that future generations will continue to gain wealth), then an argument may be made for inflating the future environmental impacts. In other words, as future generations continue to be left with an accumulation of adverse environmental impacts, the value assigned to reducing a marginal amount of future environmental impacts will hold a greater value than reducing a marginal amount of modern environmental impacts. In this manner, it can be said that the effect of the accumulation of wealth for future generations is the inverse of the effect of the accumulation of environmental pollutants.

There exists major drawbacks for each of the cases of discounting future environmental impacts or not discounting them, as discussed in Philibert (1999) and Fearnside (2002). When a discount rate that reflects that of the financial system is used, preference in climate change mitigation strategies tends to be given to those strategies which reduce short term emissions (because the equivalent value of emissions in the long term approaches zero). However, not discounting future emissions to reflect a decreasing marginal utility of value for pollutants released in the long term will lead to the selection of strategies which, when compared to the long term costs, favor long term reduction in in emissions over strategies which promote short term reductions.

Although, if applied, ecological discounting will impact the future value of environmental impacts significantly, and influence the results of an environmental LCA, no general consensus has been widely accepted on whether ecological discounting should be performed during an LCA. Therefore, this dissertation will adopt the view presented in Hellweg et al. (2003) and Sumaila and Walters (2005). In other words, judgments about the values assigned to future environmental impacts should not attribute a diminishing marginal utility to future environmental impacts. The assumption made throughout this dissertation is that the value assigned to environmental impacts will not be discounted or inflated over time.

1.4.9.1. Time Adjusted Global Warming Impacts of Emissions

Whereas ecological discounting refers to a decreasing value placed on environmental impacts over a given time frame, Kendall (2012) discusses the importance of accounting for the timing of GHG emissions. For example, the impact of a given amount of emissions occurring during one point in time is not expected to be the same as an equivalent amount of emissions released over a time horizon (Kendall 2012). The main reason that the timing of the release of emissions is important is that the impact of the emissions on radiative forcing, a measure of radiant energy received by the earth versus energy reflected back into space, depends on the rate of decay of the gas that is emitted. Kendall (2012) developed a publicly available spreadsheet model to calculate the global warming potential of GHG emissions at different points in time that can be used in LCA's.

This concept will be implemented in the analysis presented in Chapter 4 of this dissertation to adjust the results of the LCA for the project specific evaluation with a significantly long time horizon. However, the majority of the work presented in this dissertation focuses on shorter term pavement management policies, which precludes the need to adjust for the timing of emissions. Therefore, the majority of the work in this dissertation will take the time-steady International Panel on Climate Change approach.

1.5. SUSTAINABILITY AS IT APPLIES TO PAVEMENT MANAGEMENT

Sustainable pavement management is the application of sustainability considerations to traditional pavement management practices. Thus, an understanding of pavement management principles is essential to understanding how to management pavement assets more sustainably. It is well known that maintaining pavements by merely rehabilitating those that are in the worst condition is not an optimal strategy. Instead, a balance must be made between rehabilitating pavements in poor condition and preserving pavements in good condition, often in the face of limited funding. Finding the optimal maintenance and rehabilitation (M&R) strategy given several pavement assets in varying conditions and several M&R options is the foundation of pavement management. More formally, pavement management is a systematic, objective and consistent procedure to assess the current condition and predict future condition of pavements given certain constraints (e.g., budgetary) and M&R options (Shahin 2005). This follows the terminology provided by Hudson et al. (1997), which defined management as "*the coordination and judicious use of means and tools, such as funding and economic analysis to optimize output or accomplish a goal of infrastructure operation.*"

Sustainable pavement management implies maintaining acceptable condition of pavements while also considering the tradeoff between cost, environmental impacts and social impacts of pavement investments. Generally the tradeoff between economic, environmental and social factors requires that the agency in charge of managing pavements maintains an accurate database that includes the pavement condition and models to predict the resulting impacts of pavement management decisions on each of the factors. In many cases, assumptions must be made about the environmental and social impacts, and therefore pavement management decisions must reflect the level of certainty that the agency has in the assumptions. Consequently, a high level of uncertainty in many cases tends to lead the agency to only consider economic considerations within pavement management, and environmental mitigation techniques are employed after the selection of the intervention or design of the pavement is complete.

1.5.1. Incorporating Sustainability in the Pavement Management Decision Making Process

Beyond defining pavement sustainability and sustainable performance measures is the critical step of implementing sustainability into the pavement management decision making process. This includes incorporating sustainability as a fundamental business practice within the agency where considerations about project selection, treatment type selection, lifecycle management, and the tradeoff between the triple bottom line (economic, environmental and social impacts) are addressed in the initial decision processes. Sustainability can be included at all three levels of the pavement management process, and each will be discussed in more detail in the following sections.

1.5.1.1. Project level

Decisions about pavement design, construction practices and scheduling, material acquisition and congestion management plans are just a few examples where sustainability can be implemented at the project level. For example, Diefenderfer et al. (2012) discuss an *in situ* pavement recycling process used on part of a Virginia interstate that attempted to minimize the use of virgin construction materials, minimize construction costs and minimize the impact on the travelling public through a use of innovative management practices. In the case discussed by Diefenderfer et al. (2012), the lowest lifecycle cost option that was considered also had the most environmental benefit, and the least adverse social impact (as measured by travel time interruption, depletion of virgin materials and reduction of construction waste).

Another aspect that should be considered at the project level is the impact of the maintenance on the rolling resistance and vehicle operating costs from a lifecycle perspective. For example, the minimal maintenance cost alternative for rehabilitating a pavement may be to apply light maintenance for a defined number of intervals. However, a more extensive rehabilitation may reduce the rate of deterioration of the pavement condition and the rate of increase in roughness for a road, which in turn leads to a reduction in the overall vehicle operating costs, fuel consumption and vehicle emissions for the pavement.

Pavement type selection and design are fundamental project level pavement management business process. Pavement type selection refers to choosing the most appropriate paving material (i.e., Portland cement concrete or asphalt concrete) to be used during construction. Typically, this choice comes down to the result of a lifecycle cost analysis, the availability of local construction materials and the familiarity of local contractors with constructing using the materials (Hallin et al. 2011). However, many more factors can be included, and their tradeoffs considered, in order to make the pavement type selection process more sustainable. For example, given the models that relate vehicle fuel consumption to pavement properties, a lifecycle assessment can be conducted for each paving material in consideration. It is clear that values for the surface texture and pavement roughness will change over time at different rates for different material types, thus resulting in different fuel consumption, emissions profiles and total vehicle operating costs for each pavement over a defined time frame (Chatti and Zaabar 2012). Secondly, maintenance practices and the availability of local materials (virgin or recycled) differ for each pavement type, which will impact the results of any assessment of sustainability during pavement type selection (Patrick and Arampamoorthy 2010). Finally, the impact of the pavement surface characteristics on effects such as carbonation, pavement lighting requirements and the urban heat island effect (considering pavement albedo) should also be considered during pavement type selection (Santero et al. 2011b).

1.5.1.2. Network Level

Sustainable pavement management practices at the network level includes designing maintenance strategies and selecting projects considering impacts related to the triple bottom line of sustainability. This may include modifying the objectives of a network level analysis to consider a multiple criteria beyond cost and condition. Generally, the resulting multi-objective decision problem arising from the network level pavement management process is converted to a single objective problem by treating some of the objectives as the constraints (Wu and Flintsch 2009). In this way, an agency seeks to maximize or minimize one particular objective (e.g., minimizing the cost divided by the performance of the pavement condition) subject to constraints that arise from the original objectives (e.g., budgetary constraints or constraints defining a minimum allowable pavement condition).

A shortcoming with the single criterion approach is that when objectives are reformulated as constraints, the resulting analysis becomes non-compensatory (Goodwin and Wright 1998). In other words, undesirable values in the newly formulated constraints are no longer compensated for by highly desirable values in the objective values. Consequently, there is no longer a guarantee that the selected value is non-dominated, and a more optimal value may exist depending on the extent to which the constraints are relaxed. Secondly, the non-compensatory analysis tends to bias the results to the parameter that is chosen as the objective function, thus rendering other objectives as lower level considerations.

Giustozzi et al. (2012) presented a multi-criteria approach for evaluating preventive maintenance activities that included costs, performance and environmental impact measures during the analysis. Several maintenance strategies were evaluated based on the measures, and a method for comparing all strategies by rescaling each measure was developed. The first step in the analysis was to define the strategies, as well as the associated lifecycle cost for each strategy. Then the performance was calculated as the area beneath the curve defining the condition as a function of time. Finally, the energy consumption and emissions related to each strategy were calculated for the materials and construction phase of the LCA. The measures were all scaled between zero and one, with one representing the worst case and zero representing the worst case value, and the rescaled values were weighted and summed to calculate a single index.

1.5.1.3. Strategic Level

The strategic level of pavement management is where goals and objectives are defined, and strategic planning occurs. The AASHTO Asset Management Implementation Guide (AASHTO 2011) discusses the importance of planning at the strategic level. Strategic planning is an organizations process of defining its strategy, or direction, and making decisions on allocating its resources to pursue this strategy. Strategic planning should clarify the goals, mission, vision, value and strategies of the organization, as well as the performance measures used to evaluate progress toward each of the goals.

1.6. DISSERTATION ORGANIZATION

The dissertation follows a manuscript format which includes a collection of papers. Each manuscript is included as an individual chapter of the dissertation. They represent the research work in which the author was involved at Virginia Tech during the duration of his doctoral studies.

Chapter 1 Introduction, Objective and Background. This chapter discusses several topics fundamental to pavement management and lifecycle assessment, as well as previous research that relates to the work presented in this dissertation. The general contents of the dissertation, the problem statement, the research objectives, background and the research approach are presented.

Chapter 2 Analysis of Rolling Resistance Models to Analyze Vehicle Fuel Consumption as a Function of Pavement Properties. This paper presents a discussion of the findings from the initial literature review, as well as an analysis of some models that were found in the literature review. This paper adds to the state of knowledge of two newly developed rolling resistance models by identifying variables to which the model is most sensitive, allowing agencies that manage pavement assets to better gauge what factors they should focus on to reduce the pavements overall energy consumption. This paper will be presented at the 2014 International Society for Asphalt Pavements Conference.

Chapter 3 Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements. This paper investigates how a transportation agency can evaluate the energy consumption of their pavement network at a network level using one of the rolling resistance models analyzed in Chapter 2. This paper proposes a probabilistic approach in order to consider uncertainty. This paper was presented at the 93rd annual meeting of the Transportation Research Board and has been accepted for publication in *Journal of the Transportation Research Board*.

Chapter 4 A Life Cycle Assessment of Recycling and Conventional Pavement Construction and Maintenance Practices. This paper presents a detailed project level account of a LCA for three pavement management alternatives for a specific pavement section in Virginia. The work demonstrates which processes in the pavement rehabilitation, reconstruction, maintenance, materials and use phases have the greatest detrimental impact on the natural environment. This paper represents the first detailed account of a specific project-level pavement LCA that includes the use phase and congestion phase. This paper has been submitted to the journal *Structure and Infrastructure Engineering*.

Chapter 5 A Multi Criteria Decision Analysis Technique for Sustainable Infrastructure Management Business Practices. This paper presents a decision analysis technique that was developed in order to compare the tradeoffs between the costs of maintaining a pavement network, the resulting condition of the network and the total energy consumption attributed to the pavement network. Furthermore, the methodology is used to compare the preferences and weights of several stakeholders, and demonstrate the potential for the decision makers to adaptively learn from evaluating the different stakeholder values. This paper has been submitted for publication in *Transport Research Part D*.

Chapter 6 Evaluating Values in Multi-Criteria Decision Making for Pavement Management. This paper presents a method for evaluating the values of pavement management personnel, as well as the value functions for the travelling public for use in decision analysis.

Chapter 7 Conclusions and Recommendations for Future Research. This chapter provides a summary of the research conducted throughout this dissertation, as well as results and key findings. Recommendations are also made for future research based on needs identified throughout this dissertation.

1.7. ATTRIBUTIONS

This dissertation is based on a number of projects conducted at the Center for Sustainable Transportation Infrastructure at the Virginia Tech Transportation Institute. This dissertation includes five self-contained chapters that were published in or submitted to peer-reviewed journals and conferences. This attribution page introduces the co-authors and clarifies their contributions in these chapters.

Chapter 2 Analysis of Rolling Resistance Models to Analyze Vehicle Fuel Consumption as a Function of Pavement Properties. James Bryce conducted the literature review, analyzed the models and prepared the paper. Joao Santos from the University of Coimbra (Portugal) reviewed the models and results, as well as suggested revisions to the paper. Gerardo Flintsch from Virginia Tech, Samer Katicha from the Virginia Tech Transportation Institute and Kevin McGhee from the Virginia Center for Transportation Innovation and Research reviewed the paper and provided suggestions for revisions.

Chapter 3 Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements. James Bryce conducted the literature review, developed the models and prepared the paper. Gerardo Flintsch from Virginia Tech, Samer Katicha from the Virginia Tech Transportation Institute, Nadarajah Sivaneswaran from the Federal Highway Administration and Joao Santos from the University of Coimbra reviewed the paper and provided suggestions for revisions.

Chapter 4 A Life Cycle Assessment of Recycling and Conventional Pavement Construction and Maintenance Practices. James Bryce worked jointly with Joao Santos from the University of Coimbra on this paper, and Joao Santos is listed as the main author on this paper. The main contributions by James Bryce to this work were: (1) develop the methodology to adjust the effective traffic level based on rolling resistance in order to link the rolling resistance models to environmental pollutants; (2) develop all of the lookup tables of environmental pollutants from USEPA's MOVES model, (3) develop the models to predict the future performance of the different strategies and (4) writing a significant portion of the paper. The main contributions by Joao Santos to this work were: (1) developing and programming of the LCA model; (2) linking the data provided by James Bryce to the LCA model databases; (3) conducting the lifecycle impact assessment; (4) define the maintenance schedules based on values from the Virginia Department of Transportation and the models developed by James Bryce and (5) writing a significant portion of the paper. Gerardo Flintsch from Virginia Tech, Adelino Ferreira from the University of Coimbra and Brian Diefenderfer from the Virginia Center for Transportation Innovation and Research reviewed the paper and provided suggestions for revisions.

Chapter 5 A Multi Criteria Decision Analysis Technique for Sustainable Infrastructure Management Business Practices. James Bryce developed the decision analysis technique, analyzed the example network and prepared the paper. Gerardo Flintsch and Ralph Hall from Virginia Tech reviewed the paper and provided recommendations for revisions.

Chapter 6 Evaluating Values in Multi-Criteria Decision Making for Pavement Management. James Bryce developed the survey and prepared the paper. Gerardo Flintsch and Christian Wernz from Virginia Tech reviewed the paper and provided recommendations for revisions.

1.8. CHAPTER 1 REFERENCES

AASHTO. (2011). *Transportation Asset Management Guide, A Focus on Implementation.* Washington, DC: American Society of State Highway and Transportatoin Officials.

ACPA (American Concrete Pavement Association). (2002). *Albedo: A Measure of PAvement Surface Reflectance.* Skokie, IL: American Concrete Pavement Association.

Akbarian, M., and Ulm, F.-J. (2012). *Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements.* Cambridge, MA: Massachusetts Institute of Technology - Concrete Sustainability Hub.

Almansa, Carmen, and José M. Martínez-Paz. What weight should be assigned to future environmental impacts? A probabilistic cost benefit analysis using recent advances on discounting. *Science of the Total Environment No. 409*, 2011: 1305-1314.

Barth, M., and Boriboonsomsin, K. (2008). Real-World Carbon Dioxide Impacts of Traffic Congestion. *Transportation Research Record: Journal of the Transportation Research Board of the National AcademieS, No. 2058*, 163-171.

Bryce, J., Katicha, S., Flintsch, G., Sivaneswaran, N., and Santos, J. (2014). Probablistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements . *93rd Annual Meeting of the Transportation Research Board of the National Academies.* Washington, D.C.

Chamorro, A., and Tighe, S. L. (2009). Development of a Management Framework for Rural Roads in Developing Countries. *Transportation Research Record: Journal of the Transportation Research Board of the National AcademieS, No. 2093*, 99-107.

Chatti, K., and Zaabar, I. (2012). *Estimating the Effects of Pavement Condition on Vehicle Operating Costs.* Washington, DC: Transportation Research Board of the National Academies.

Chiu, Chui-Te, Tseng-Hsing Hsu, and Wan-Fa Yang. (2008) Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resources, Conservation and Recycling* No. 52, pp. 545–556.

Davis, S., Caldeira, K., and Matthews, D. (2010). Future CO^2 Emissions and Climate Change from Existing Energy Infrastructure. *Science No. 329*, 1330-1333.

Diefenderfer, B., Apeagyei, A., Gallo, A., Dougald, L., and Weaver, C. (2012). In-Place Pavement Recycling on I-81 in Virginia. *Transportation Research Record: Journal of the Transportation Research Board, 2306*, 21–27.

EAPA/EuroBitume. (2004). *Environmental Impacts and Fuel Efficiency of Road Pavements - Industry Report.* Brussels, Belgium: Joint EAPA/EuroBitume Task Group on Fuel Efficiency.

EPA. (2012, October 12). *MOVES (Motor Vehicle Emission Simulator)*. Retrieved November 27, 2012, from http://www.epa.gov/otaq/models/moves/index.htm

Epps, J. A., Leahy, R. B., Mitchell, T., Ashmore, C., Seeds, S., Alavi, S., et al. (1999). WESTrack - The Road to Performance Related Specifications. *Paper prepared for International Conference on Accelerated Pavement Testing;*. Reno, NV: University of Nevada, Reno.

Evans, L. R., Jr., J. D., Harris, J. R., Yates, K., Dudek, W., Holmes, J., et al. (2009). *NHTSA Tire Fuel Efficiency Consumer Information Program Development: Phase 2 – Effects of Tire Rolling Resistance Levels on Traction, Treadwear, and Vehicle Fuel Economy.* East Liberty, OH: National Highway Traffic Safety Administration.

Fearnside, Philip M. (2002). Time preference in global warming calculations: a proposal for a unified index. *Ecological Economics No. 41*, 21-31.

Flintsch, G. W., León, E. d., McGhee, K. K., and Al-Qadi, I. L. (2003). Pavement Surface Macrotexture Measurement and Applications. *Transportation Research Record 1860*, 168-177.

Giustozzi, F., Crisino, M., and Flintsch, G. (2012). Multi-attribute Life Cycle Assessment of Preventive Maintenance Treatments on Road Pavements for Achieving Environmental Sustainability. *International Journal of Lifecycle Assessment, 17*, 409-419.

Gollier, C. (2010). Ecological discounting. *Journal of Economic Theory*, 812-829.

Goodwin, P., and Wright, G. (1998). *Decision Analysis for Management Judgment, 2nd ed.* West Sussex: John Wiley & Sons,.

Hallin, J., Sadasivan, S., Mallela, J., Hein, D., Darter, M., and Von Quintus, H. (2011). *Guide for Pavement Type Selection: NCHRP Report 720.* Washington, DC.: Transportation Research Board of the National Academies .

Hammarström, U., Eriksson, J., Karlsson, R., and Yahya, M. (2011). *Rolling Resistance Model, Fuel Consumption Model and the Traffic Energy Saving Potential fom Changed Road Surface Considtions.* Linköping: Swedish National Road and Transport Research Institute.

Hellweg, Stefanie, Thomas B. Hofstetter, and Konrad Hungerbuhler. "Discounting and the Environment: Should Current Impacts be Weighted Differently than Impacts Harming Future Generations." *The International Journal of Life Cycle Assessment (8) 1*, 2003: 8-18.

Horvath, A. (2003). *Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements.* Berkeley: University of California Transportation Center.

Huang, Y., Bird, R., and Heidrich, O. (2009). Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production, 17*, 283-296.

Hudson, R., Haas, R., and Uddin, W. (1997). *Infrastructure management: integrating design, construction, maintenance, rehabilitation, and renovation.* New York: McGraw Hill.

ISO. (2006). *Environmental Management - Life Cycle.* International Organization of Standardization (ISO) Standard Series 14040. Geneva, Switzerland.

ISO. (2009). *Passenger car, truck and bus tires – Methods of measuring rolling resistance – Single point test and correlation of measurement results*. International Organization of Standardization (ISO) Standard 28580, Geneva, Switzerland.

Izevbekhai, B. (2012). Concrete Paving and Texturing for Sustainability. Minneapolis, MN: Presented at Center For Transportation Studies Research Conference.

Kendall, A. (2012). Time-Adjusted Global Warming Potentials for LCA and Carbon Footprints. *International Journal of Life Cycle Assessment*, 1042-1049.

Laganier, R. and Lucas, J. (1990). *The Influence of Pavement Eveness and Macrotexture on Fuel Consumption*. Surface Characteristics of Roadways: International Research and Technologies. ASTM STP 1031, ASTM International, Philadelphia. pp. 454-459.

Mactutis, J., Alavi, S., and Ott, W. (2000). Investigation of relationship between roughness and pavement surface distress based on WesTrack project. *Transportation Research Record: Journal of the Transportation Research Board, No. 1699*, 107-113.

Michelin (2003). *The tyre - Rolling resistance and fuel savings*. Société de Technologie Michelin. Clermont-Ferrand, France.

Morosiuk, G., Riley, M., and Toole, T. (2006). *Highway Development and Management (HDM 4) Volume Two Applications Guide.* Paris: The World Road Association (PIARC).

Park, K., Hwang, Y., Seo, S., and Seo, H. (2003). Quantitative Assessment of Environmental Impacts on Life Cycle of Highways. *ASCE Journal of Construction Engineering and Management*, 25-31.

Patrick, J., and Arampamoorthy, H. (2010). *Quantifying the Benefits of Waste Minimisation.* New Zealand: Opus International Consultants.

Philibert, Cedric. (1999). The economics of climate change and the theory of discounting. *Energy Policy Volume 27, Issue 15*, 913-927.

Sandberg, U. (1997). Influence of Road Surface Texture on Traffic Characteristics Related To Environment, Economy and Safety. *VTI notat 53A-1997*. Statens väg- och transportforskningsinstitut. Linköping, Sweden.

Sandberg, U. (1990). Road Macro and Mega Texture Influence on Fuel Consumption. In W. E. Meyer, and J. Reichert, *Surface Characteristics of Roadways* (pp. 460-479). Baltimore, MD: American Society for Testing and Materials.

Sandberg, U. (2011). *Rolling Resistance – Basic Information and State of the Art on Measurement Methods.* Linköping, Sweden: Swedish Road and Transport Research Institute.

Santero, N., Loijos, A., Akbarian, M., and Ochsendorf, J. (2011a). *Methods, Impacts and Opportunities in the Concrete Pavement Life Cycle.* Cambridge MA: Massachusetts Institute of Technology.

Santero, N., Masanet, E., and Horvath, A. (2011b). Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling*, 801-809.

Santero, N., Masanet, E., and Horvath, A. (2011c). Life-cycle assessment of pavements Part II: Filling the research gaps. *Resources, Conservation and Recycling*, 810-818.

Sayers, M., and Karamihas, S. (1998). *The Little Book of Profiling*. Ann Arbor, MI: The University of Michigan.

Schrank, D., Eisele, B., and Lomax, T. (2012). *TTI's 2012 Urban Mobility Report.* College Station, TX: Texas A&M Transportation Institute.

Schuring, D. J. and S. Futamura. (1990). Rolling Loss of Pneumatic Highway Tires in the Eighties. *Rubber Chemistry and Technology*: July 1990, Vol. 63, No. 3, pp. 315-367.

Shahin, M. (2005). *Pavement Management for Airports, Roads, and Parking lots.* New York: Springer.

Suh, S., Lenzen, M., Treloar, G., Hondo, H., Horvath, A., Huppes, G., Norris, G. (2004). System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science and Technology*, 657-664.

Sumaila, U. R., and Walters, C. (2005). Intergenerational discounting: a new intuitive approach. *Ecological Economics*, 135-142.

Taylor, G., and Patten, J. (2006). *Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III.* Ottawa, Ontario: Centre for Surface Transportation Technology - National Research Council of Canada.

TIAX, LLC. (2003). *California State Fuel-Efficient Tire Report: Volume 2.* Cupertino, CA: California Energy Commission.

TRB (2006). Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance. *TRB Special Report 286*. Washington, D.C.: Transportation Research Board: Committee for the National Tire Efficiency Study.

UCPRC. (2010, September 8). *Pavement Life Cycle Assessment Workshop*. Retrieved November 27, 2012, from http://www.ucprc.ucdavis.edu/P-LCA/

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B., and Kim, C. (2012). Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production*, 86-96.

Weiland, C., and Muench, S. (2010). *Lifecycle Assesment of Portland Cement Concrete Interstate Highway Rehabilitation and Replacement.* Seattle, WA: Washington State Transportation Center, University of Washington.

Wu, Z., and Flintsch, G. (2009). Pavement Preservation Optimization Considering Multiple Objectives and Budget Variability. *ASCE Journal of Transportation Engineering, 135*(5), 305-315.

Zaabar, I. (2010). *Effect of Pavement Conditions on Vehicle Operating Costs Including Fuel Consumption, Vehicle Durability and Damage to Transported Goods.* East Lansing, MI: Michigan State University.

Zapata, P., and Gambatese, J. (2005). Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Construction. *ASCE Journal of Infrastructure Systems*, 9-20.

Zhang, H., Lepech, M., Keoleian, G., Q. S., and Li, V. (2010). Dynamic Life-Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration. *ASCE Journal of Infrastructure Systems*, 299-309.

Chapter 2.
Analysis of Rolling Resistance Models to Analyse Vehicle Fuel Consumption as a Function of Pavement Properties[1]

James Bryce[1], Joao Santos[2], Gerardo Flintsch[3], Samer Katicha[4], Kevin McGhee[5]

[1] Graduate Research Assistant, Virginia Tech Transportation Institute, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: jmbp54@vt.edu

[2] Graduate Student, Universidade de Coimbra and Virginia Tech, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: jmos@student.dec.uc.pt

[3] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: flintsch@vt.edu

[4] Senior Research Associate, Virginia Tech Transportation Institute, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: skaticha@vt.edu

[5] Virginia Center for Transportation Innovation and Research, 530 Edgemont Road, Charlottesville, VA 22903, Email: Kevin.McGhee@vdot.virginia.gov

2.1. ABSTRACT

This paper presents an analysis of two recently developed models that relate pavement properties to vehicle rolling resistance and fuel consumption, as well as the sensitivity of each model to roughness, texture and future traffic predictions. The two models are the Vehicle Operating Cost model developed as part of the National Cooperative Highway Research Program (NCHRP) project 1-45 outlined in NCHRP report 720, and the model developed as part of an international collaboration, Models for rolling resistance In Road Infrastructure Asset Management systems (MIRIAM). Furthermore, several pavement related factors that contribute to vehicle rolling are discussed. It was found that the fuel consumption was highly sensitive to future traffic growth projections. Also, the pavement macrotexture can have a significant impact on excess fuel consumption of vehicles, particularly in the case that the MIRIAM model is used to calculate fuel consumption.

2.2. INTRODUCTION

According to the Texas Transportation Institute (TTI), in 2011, congestion in the top US urban areas resulted in an average of 19 gallons of excess fuel consumption per auto commuter per year (Schrank et al. 2012). Although it is expected to be significant, there is no similar figure assessing the wasted fuel due to the trillions of vehicle miles travelled (VMT) over rough pavement sections that contribute to relatively high rolling resistance values. Rolling resistance is the mechanical energy loss by a tire moving

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a unit distance along the roadway, and is effected by both properties of the tire and of the pavement (Evans et al. 2009). The energy that is lost comes directly from the power that is used to propel the vehicle, and as a consequence, more fuel must be consumed to propel a vehicle over a pavement with higher rolling resistance. Evans et al. (2009) reported that as much as 1/3 of the total energy that is available to the wheels can be expended to overcome the rolling resistance. Other factors that consume the energy used to propel the vehicle (the energy that makes it to the driveline) are aerodynamic resistance and braking (TRB 2006).

Evans et al. (2009) measured the rolling resistance of several different tire types and reported that a 10 percent reduction in rolling resistance can lead to a 1 to 2 percent reduction in fuel consumption, with an average reduction of 1.1 percent. Schuring and Futamura (1990) have shown that this relationship can be taken as linear. TIAX (2003) reported that during highway driving, the 2 percent reduction in fuel consumption per 10 percent reduction in rolling resistance is expected, and the figure is closer to a 1 percent reduction during urban driving. Some estimations have shown that a 10 percent reduction in rolling resistance could save between 1 and 2 billion gallons of fuel annually (of 130 billion gallons currently consumed) among the passenger car fleet, assuming the driving habits used in the 2006 study (TRB 2006). Thus, it can be conclusively said that if the rolling resistance of a pavement were reduced, the vehicle fuel consumption along that pavement would also be reduced.

2.3. OBJECTIVE

The objective of this paper is to discuss the impact of pavement properties on vehicle rolling resistance, as well as present an analysis and comparison of current rolling resistance models. Two commonly used models to assess the additional vehicle fuel consumption due to rolling resistance will be compared, one model from the United States and one from Europe.

2.4. BACKGROUND

Many factors contribute to the fuel consumption of a vehicle, not the least of which is the interaction of the vehicle tire with the pavement surface. One of the earliest studies on the effects of road roughness on fuel consumption was performed in 1983 in Sweden by Sandberg at VTI (Swedish National Road and Transportation Research Institute) (Sandberg 1990). The study evaluated 20 different roadway characteristics representing the full range of Swedish roads at speeds of 50, 60 and 70 km/h (30, 37 and 45 miles/h). Vehicle fuel consumption was found to be correlated best with short wave unevenness ($r = 0.91$), mega-texture ($r = 0.83$) and macro-texture ($r = 0.60$).

Mega-texture is generally defined as a pavement surface texture due to surface irregularities having a relative wavelength between 5 cm and 0.5 meters (2 in and 20 in) (Flintsch et al. 2003). Pavement macro-texture is generally defined as a pavement surface texture having a relative wavelength between 0.5 mm and 50 mm (20 mils to 2 inches), and is a result of large aggregate particles in the mixture (Flintsch et al. 2003). It is important to note that macro-texture plays an important role in pavement friction. The short wave unevenness range is close to the wavelength sensitivity range of the IRI which is between 1.2 to 30 m (4 to 100 ft) (Sayers and Karamihas 1998). The following are pavement related factors that have been identified in past research as pertinent to consider during an analysis of the rolling resistance of the pavement: macro-texture, pavement stiffness, roughness, rutting and the transversal slope of the pavement (Santero et al. 2011; Sandberg et al. 2011; Chatti and Zaabar 2012).

2.4.1. Macro-Texture

Chatti and Zaabar (2012) evaluated the effect of pavement macro-texture on fuel consumption, and determined that an increase in fuel consumption with increasing mean profile depth of the pavement was statistically significant at the 95 percent confidence level for lower speeds. Laganier and Lucas (1990) found that macro-texture could lead to overconsumption of up to 5 percent from a base consumption of 0.7 l/km. At high speeds, it is expected that aerodynamic resistances dominate the resistance forces, thus causing the effect of macro-texture to be overshadowed. Conversely, Sandberg (1990) found that the effect of macro-texture on fuel consumption was more defined at higher speed; though the author pointed to a possible cause of low speed driving having a lower correlation as poorly selected driving conditions.

The increase in fuel consumption as a function of the pavement macro-texture is dependent on the vehicle type, and is expected to be higher for heavy vehicles. According to Sandberg (1990), the lower limit for expected effect of macro-texture on rolling resistance is a 2.5 percent increase in rolling resistance per unit increase of mean profile depth (in mm). Zaabar (2010) reported that for trucks, an increase in mean profile depth from 0.5 mm (0.02 in) to 3 mm (0.12 in) is expected to result in an increase in fuel consumption between 1 and 1.6 percent. Hammarström et al. (2008) used coast-down methods, or measurements of a vehicles velocity or acceleration while it is allowed to roll freely across a section of pavement, to measure the impact of pavement roughness, travel velocity and macro-texture on rolling resistance. The research proposed a set of equations to relate rolling resistance to macro-texture and roughness by comparing measurements taken during the research and theoretical models used to quantify the impact of each factor. The tests were conducted using a car, light truck and heavy truck. Some generalized results presented by Hammarström et al. (2008) are that an increase in rolling resistance of 17 percent per unit of mean profile depth is expected for a starting speed of 50 km/h for the car, and an increase of 30 percent per unit of mean profile depth is expected for a starting speed of 90 km/h for the car. The results showed that if the total driving resistance is considered, an increase in mean profile depth from 0 to 1 at 50 km/h is expected to lead to an increase of driving resistance of 10.5 percent for the car. The researchers noted that more measurements would be required to obtain results for the trucks.

2.4.2. Pavement Stiffness

Much of the research pertaining to the impact of pavement stiffness on rolling resistance has been derived from studies comparing asphalt concrete pavements to Portland cement concrete pavements. Taylor and Patten (2006) conducted field tests using both cars and heavy trucks driven over asphalt concrete pavements and Portland cement concrete pavements in order to evaluate differences in fuel consumption for each case. The research also tested over multiple seasons and the trucks were subjected to multiple loading conditions. In most cases, the results of the research showed anywhere from a 1 percent to a 5 percent savings in fuel consumption when driving on concrete pavements. However, during many of the tests during summer days, the research indicated a fuel saving for composite pavements when compared to concrete pavements (Taylor and Patten 2006). Although the test results indicated differences in fuel consumption with varying pavement stiffness, the developed models did not include surface wear and anomalies (e.g., potholes). Furthermore, other surface properties, such as tining of the concrete surface or texture of the pavement, were not accounted for in the study. Thus, the results of the study are not considered ideal for inclusion in an LCA of the use phase of the pavement.

Santero et al. (2011) evaluated the impact that the pavement stiffness has on the fuel consumption of a vehicle travelling along the pavement by developing a mechanistic model. The researchers proposed a beam on elastic foundation as the model to describe the behavior of the pavement subjected to a wheel load, and calibrated their model using data from the Long Term Pavement Performance (LTPP) database. The model indicated less fuel consumption over more stiff pavements, especially in the case of truck traffic. However, it is important to note that the model was developed in order to better understand the mechanisms that contribute to increasing rolling resistance with increased deflections, and field studies were not conducted to calibrate the model.

A follow up to the study by Santero et al. (2011) was conducted that calibrated the model that was developed to describe pavement deflections, and scaling factors were developed for each of the inputs (Akbarian et al. 2012). The calibration was conducted using additional sites from the LTPP database, and an example application of implementing the model into an LCA was conducted using data from the Athena Institute. The results of the study indicated that for high volume roads, the greenhouse gas (GHG) emissions from the pavement-vehicle interaction can be greater than the GHG emissions from the materials and construction phases (Akbarian et al. 2012).

Whereas much research has been conducted on the differences in pavement type on rolling resistance, Wang et al. (2012) pointed out that sufficiently validated models have yet to be developed to calculate the impact of pavement stiffness on fuel consumption and emissions. This is mainly a consequence of the experimental designs of the studies that compare asphalt pavements to concrete pavements. Although models were developed by Akbarian and Ulm (2012) as well as Santero et al. (2011) to quantify the impact of stiffness on fuel consumption, these models are generally considered first order attempts at understanding the mechanism of the pavement vehicle interaction, and are not yet sufficiently corroborated with field measurements to be used in a pavement LCA.

However, even in the absence of calibrated models, there is research demonstrating the differences in fuel consumption between asphalt and concrete pavements over certain conditions. Zaabar (2010) showed that at 35 mph (56 km/hr) during summer conditions, there is a statistically significant difference between vehicle fuel consumption along apshalt and concrete pavements for trucks. The development of more accurate models in the future will facilitate the inclusion of pavement type, or pavement stiffness, into a pavement use phase LCA.

2.4.3. Pavement Roughness

An early study on the impact of the pavement roughness on fuel consumption was conducted in 1983 in Sweden at VTI) (Sandberg 1990). The difference in fuel consumption between smooth and rough pavement was around 4.5 percent (EAPA/EuroBitume 2004). Laganier and Lucas (1990) found that pavement unevenness could lead to overconsumption of fuel of up to 6 percent from a base consumption of 0.7 l/km. Laganier and Lucas (1990) also calculated the power lost in the shock absorbers as a function of roughness level and found most loss occurs at wavelength between 1 m and 3.3 m which corresponds to the unevenness range as well as the most sensitive IRI range. According to Sandberg (1997), the lower limit for expected effect of roughness on rolling resistance is a 0.8 percent increase in rolling resistance per unit increase of IRI (in m/km).

In the United States, WesTrack test results showed that rougher pavements result in increased fuel consumption of trucks (Epps et al. 1999). Zhang et al. (2010) used the WesTrack models in the LCA of an overlay system. One downfall of the WesTrack model was that it was developed for heavy trucks over a small variation of conditions. Zaabar (2010) evaluated the impact of pavement roughness (in terms of IRI) on the change in fuel consumption, and used the data to calibrate HDM 4 prediction models.

Hammarström et al. (2008) also measured the impact of pavement roughness on rolling resistance using coast-down measurements. The research found that for the car, an increase in rolling resistance of 1.8 percent per unit of IRI is expected for a starting speed of 50 km/h, and an increase of 6 percent per unit of IRI is expected for a starting speed of 90 km/h. The results for the car showed that if the total driving resistance is considered, an increase in mean profile depth from 0 to 1 at 50 km/h is expected to lead to an increase of driving resistance of 1.2 percent. The researchers noted that more measurements are required to obtain results for trucks.

Chatti and Zaabar (2012) reported the results of calibrating the HDM 4 models for vehicle operating costs in the National Cooperative Highway Research Program (NCHRP) report 720. During this research, fuel consumption models as a function of pavement roughness for several vehicles and several speeds were calibrated. A vehicle operating cost modeling program was developed in the form of a spreadsheet tool by Chatti and Zaabar (2012) as a part of the NCHRP project. Part of the spreadsheet output is the estimation of the additional fuel consumption as a function of the following variables; pavement roughness, mean texture depth, roadway grade, super-elevation, pavement type (i.e., asphalt vs. concrete), vehicle speed and air temperature.

2.4.4. Rutting

Rutting was one of the variables analyzed in a VTI report aimed at using coast-down measurements to determine the effect of the road surface conditions on rolling resistance (Hammarström et al. 2008). However, rutting was not found to be significant on its own, and the researchers noted that the high correlation between rutting and the measured IRI may be good reason to leave rutting out of a generalized driving resistance model. The relationship between rutting and roughness has been demonstrated elsewhere (Mactutis et al. 2000), thus a separate factor relating rutting to rolling resistance would require rutting to be decoupled from the IRI effect if it was developed.

2.4.5. Transverse Slope

The transverse slope of the pavement, sometimes known as the crossfall or crossslope of the pavement, has an impact on the side forces of the vehicle, which in turn affects the rolling resistance along the pavement (Sandberg 2011). Although this feature of the pavement is recognized to impact rolling resistance, similar to superelevation, no significant amount of research exists to quantify its effects. However, Chatti and Zaabar (2011) included superelevation as a variable in the spreadsheet resulting from the NCHRP report 720, and it can be expected that the mechanism relating crossfall to rolling resistance behaves similar to the mechanism relating superelevation to rolling resistance.

2.5. ROLLING RESISTANCE MODELS

Two commonly used models relating pavement properties to rolling resistance and fuel consumption have been developed in recent years. One model was developed by Chatti and Zaabar (2012) by calibrating the HDM 4 models for vehicle operating costs. The fuel consumption model was calibrated over several pavements in the state of Michigan using six different vehicles: a medium car; sport utility vehicle; van; light truck and an articulated truck. The details of the model can be found in the NCHRP report 720 (Chatti and Zaabar 2012), along with a Microsoft Excel® tool developed as part of the NCHRP project that can be used to estimate vehicle operating costs (as well as vehicle fuel consumption) given several conditions.

The second model was developed as part of an international collaboration, Models for rolling resistance In Road Infrastructure Asset Management systems (MIRIAM), and is described in detail in Hammarstom et al. (2011). The model was developed based on empirical results from coast down measurements in Sweden, and includes impacts of: pavement roughness; macrotexture; temperature; speed; horizontal curvature and the road grade. The model was developed for three vehicle types: a car; a heavy truck and a heavy truck with a trailer.

2.5.1. Impact of Pavement Roughness on Vehicle Speed

An important variable that must be considered when evaluating fuel consumption as a function of pavement properties is the impact of the pavement roughness on the average vehicle speed. Hammarstom et al. (2011) investigated the impact of roughness on speed ffor European conditions. It is noted in Hammarstom et al. (2011) that reducing roughness may have the effect of increasing vehicle fuel consumption due to a corresponding increase in average vehicle travel speed. Yu and Lu (2013) investigated the relationship between roughness and speed and found that the average speed of a vehicle decreases 0.84 km/h for every increase in roughness of 1 m/km (0.0083 mph per every 1 in/mile). The data used in developing the relationship were taken from vehicles travelling along several pavement sections in California (both rigid and flexible pavements), and was limited to vehicles travelling between 80 and 145 km/hr (50 to 80 mph) to exclude times of congestion and vehicles that are potentially exceeding the speed limit by a significant amount.

2.6. ANALYSIS

In order to analyze and compare the two rolling resistance models, a baseline case of traffic was evaluated with the parameters shown in Table 2-1. The change in fuel consumption based on four variables will be evaluated: (1) the change in fuel consumption based on varying the roughness as a function of time; (2) the impact of the relationship between the reduction in average speed as a function of pavement roughness; (3) sensitivity to traffic growth; and (4) sensitivity to macrotexture. The relationship between roughness and average speed given by Yu and Lu (2013) was included in the baseline calculations.

Table 2-1 Baseline Case for Evaluating the Models

Variable	Baseline Value	Variable	Baseline Value
Initial Roughness	0.87 m/km (55 in/mile)	Traffic (AADT)	30,000
Temperature	20° C (68° F)	Traffic Growth Rate (Compounding Interest)	3%
Horizontal Curvature	0	Medium Trucks	10%
Grade	0%	Articulated Trucks	15%
Crossfall	0%	Speed	105 km/h (65 mph)
Macrotexture	0.5 mm (0.02 inches)	Pavement Type	Flexible

A second order polynomial was assumed for the roughness growth model which (with IRI given in units of in/mile) as $a*(x)^2+b*(x)+c=IRI(x)$, where *IRI(x)* is the value of the IRI in year *x*, *c* was set at 55 in/mile, *b* was set as 1.23 in/mile/yr and *a* was changed to the following values [0, 0.15, 0.3, 0.45, 0.6], with a value of *a*=0 chosen as the baseline case for roughness. This value is taken from McGhee and Gillespie (2006) which reported a near constant growth in IRI of 1.23 in/mi-yr for a seven year time period for asphalt pavements in Virginia. The roughness growth over a ten year time frame can be seen in Figure 2-1 for each value of *a*. A ten year analysis period was evaluated, and the additional fuel consumption (i.e., the fuel consumption above the baseline case) was calculated per 1 km (0.62 miles) of pavement using the MIRIAM model (Hammarstom et al. 2011) as well as the software that accompanied the NCHRP report 720 (Chatti and Zaabar 2012). The results are shown in Figure 2-2 .

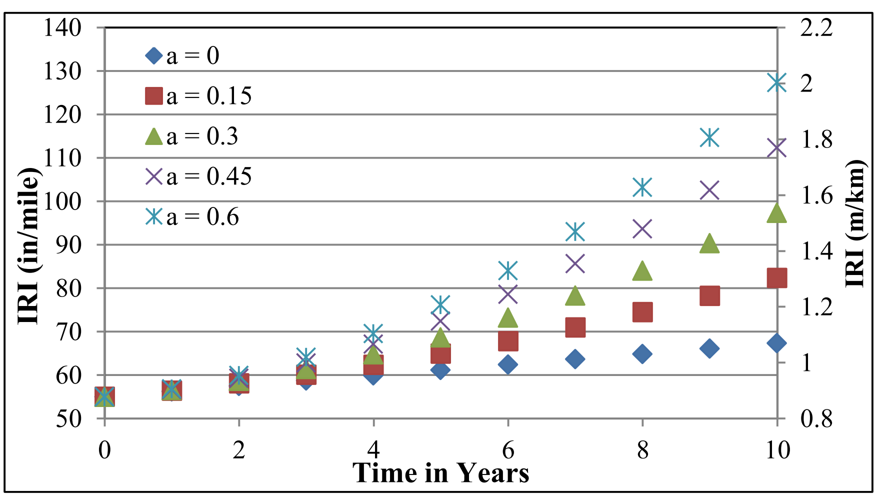

Figure 2-1 Roughness Growth Models

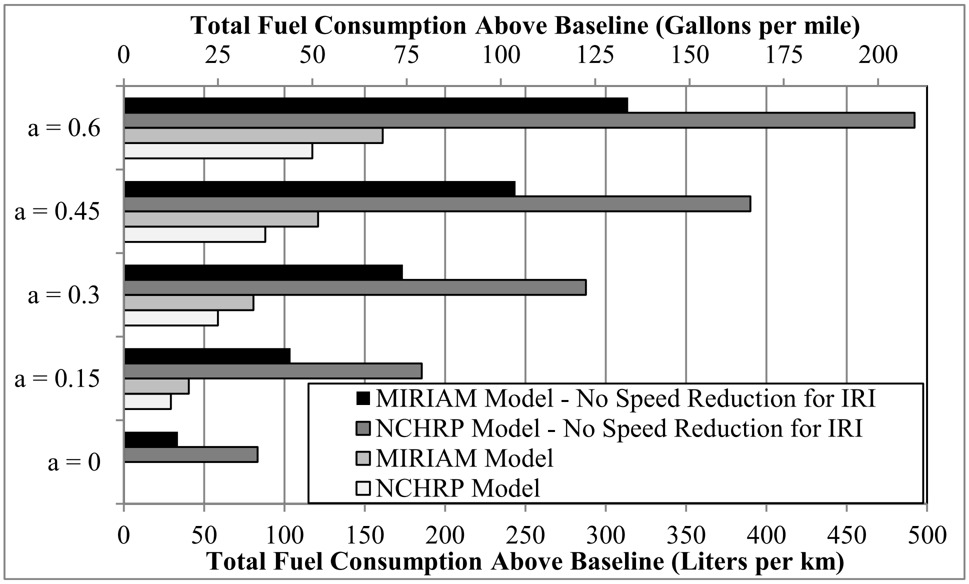

Figure 2-2 Fuel Consumption above Baseline Case as a Function of Roughness

It can be seen in Figure 2-2 that the NCHRP model is much more sensitive to the speed reduction due to an increase in IRI than the MIRIAM model. Although the models produce similar results, the highest amount of fuel consumption occurs when no speed reduction is taken into account and the NCHRP model is used. Conversely, the lowest amount of fuel consumption occurs with the NCHRP model when the speed reduction is taken into account. Next, the influence of macrotexture on the excess fuel consumption was calculated, assuming the baseline case of 0.5 mm (0.02 in), and a constant growth in roughness of 0.02 m/km/yr (1.23 in/mile/yr) per McGhee and Gillespie (2006). The results can be seen in Figure 2-3.

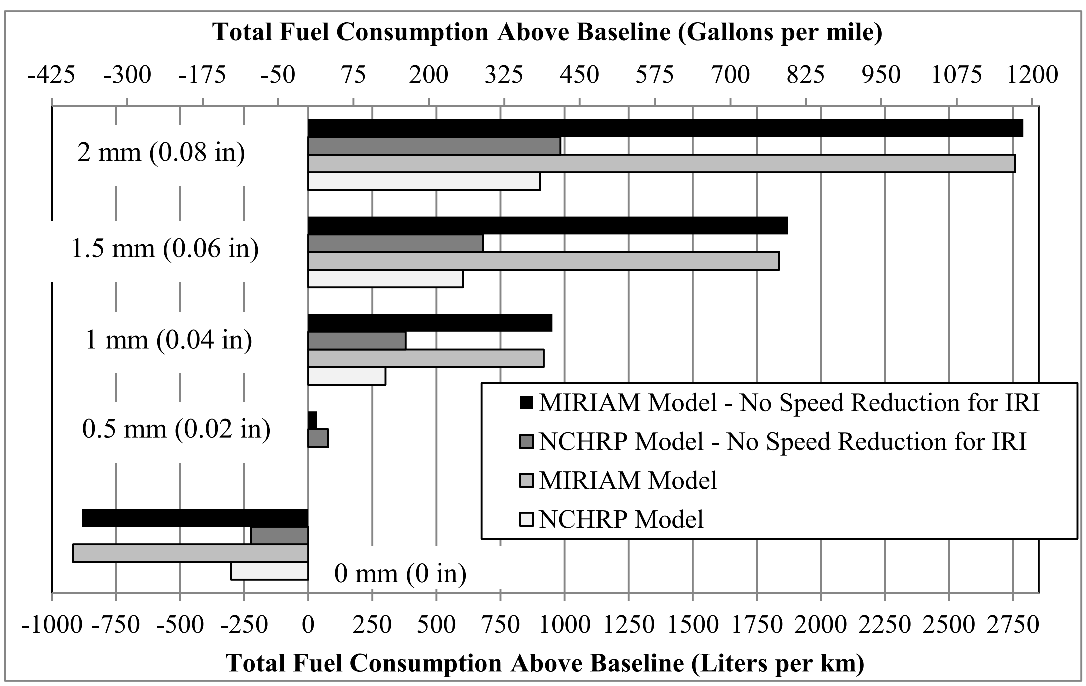

Figure 2-3 Fuel Consumption above Baseline Case as a Function of Macrotexture

It can be seen in Figure 2-3 that the MIRIAM model is much more sensitive to changes in macrotexture than the NCHRP model. Also, the difference between the case where the speed reduces as a function of IRI and the case where no speed reduction is considered is nearly insignificant when compared to changes in the values for macrotexture. Finally, the influence of the traffic growth rate (compound growth) on the excess fuel consumption above the baseline case was evaluated, and the results can be seen in Figure 2-4.

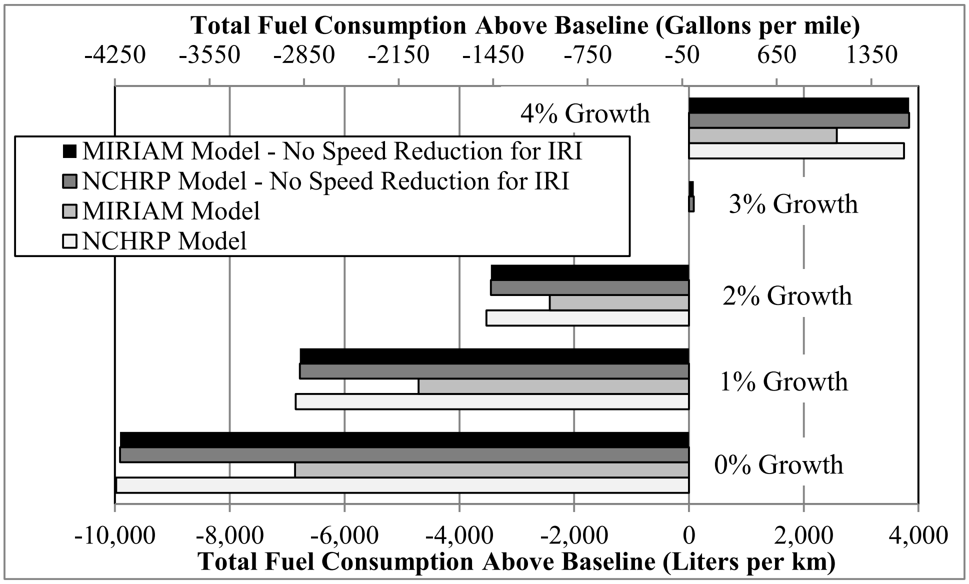

Figure 2-4 Fuel Consumption above Baseline Case as a Function of Traffic Growth (Using Compound Growth)

Of the four variable analysed (IRI growth, macrotexture, speed reduction as a function of IRI and traffic growth rate), it can be seen that the traffic growth rate most significantly impacts the excess fuel consumption. This seems to indicate that if a transportation agency has the goal of reducing fuel consumption within a pavement network, the most influential factor of those that were analyzed is to reduce the number of vehicles travelling in the network in future years. Second to the traffic growth rate is the macrotexture of the pavement. However, it is important to note that macro-texture plays an important role in pavement friction (Flintsch et al. 2003), as well as an important role in controlling pavement noise.

In order to better represent the sensitivity of the fuel consumption on the macrotexture, roughness and speed for each model, the three variables were plotted on the same figure for values that yield the same fuel consumption (Figure 2-5 and Figure 2-6). The value for fuel consumption chosen as the iso-plane was taken as the baseline case (defined in Table 2-1). One notable result is that the NCHRP model is more sensitive to changes in the average vehicle speed than the MIRIAM model (as seen by the smaller variation in speed in Figure 2-5). Secondly, both models produce flat planar surfaces, as opposed to having curvature.

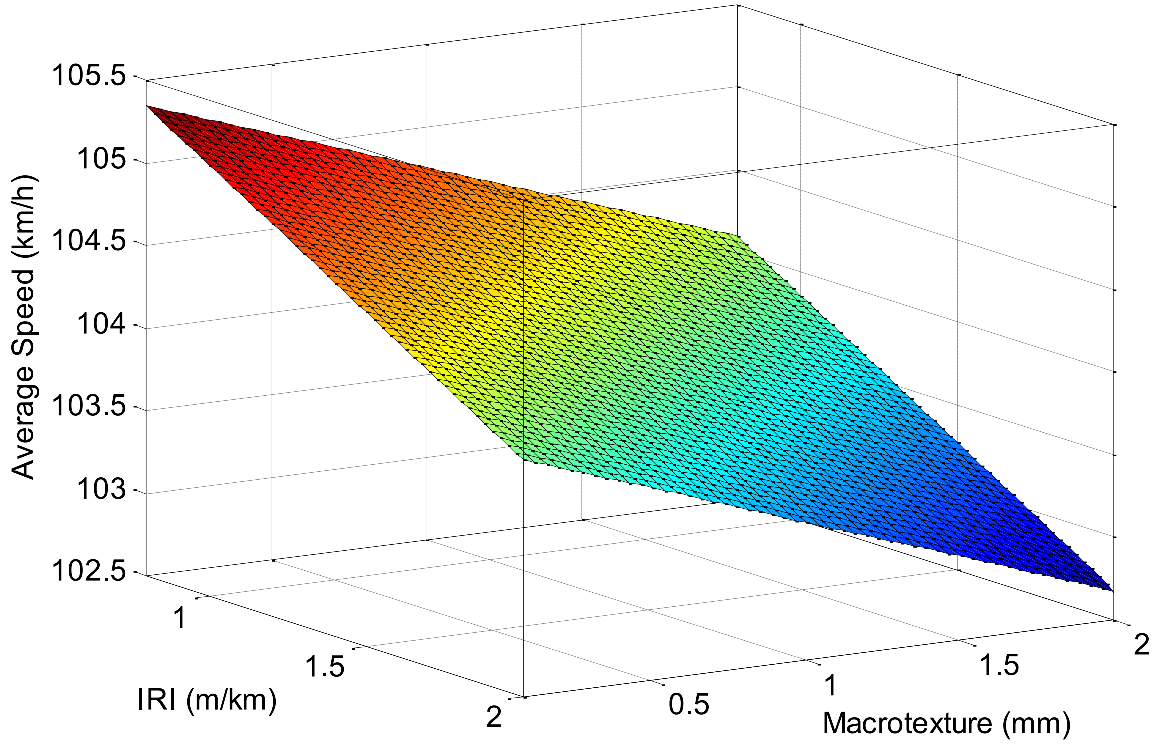

Figure 2-5 Surface for Constant Fuel Consumption Using the NCHRP Model

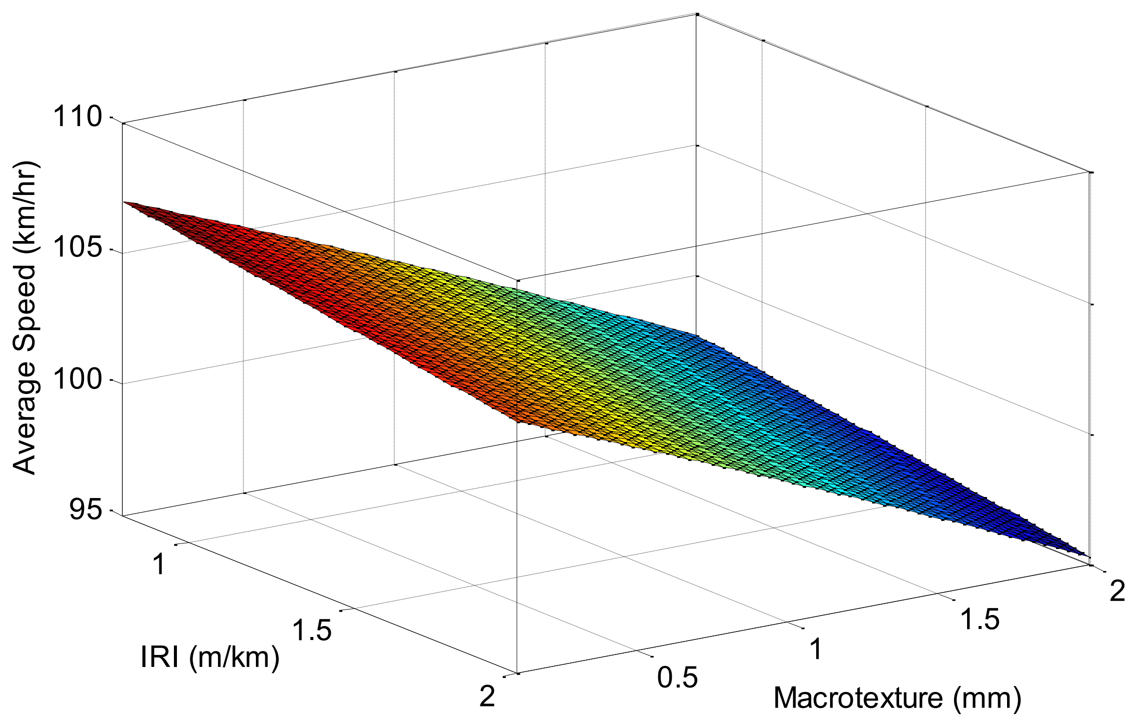

Figure 2-6 Surface for Constant Fuel Consumption Using the MIRIAM Model

2.7. DISCUSSION AND CONCLUSIONS

Models that relate vehicle rolling resistance to pavement properties can prove to be a valuable resource for transportation agencies, particular when they are concerned with analyzing such factors as the impact of excessive roughness on fuel consumption or the potential value of smoothness to road users. This paper presented two recently developed models, as well as an evaluation of their sensitivity to variables pavement roughness, pavement macrotexture and average vehicle speed. It is clearly shown that small variations in average speed can have a much more significant impact on the vehicle fuel consumption than the typical range of pavement roughness or macrotexture. Also, it was found that the total excess fuel consumption was highly sensitive to future traffic growth projections. Furthermore, the pavement macrotexture has a significantly higher impact on excess fuel consumption of vehicles than pavement roughness for both models analyzed.

2.8. ACKNOWLEDGEMENTS

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2.9. CHAPTER 2 REFERENCES

Akbarian, M., and Ulm, F.-J. (2012). *Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements.* Cambridge, MA: Massachusetts Institute of Technology - Concrete Sustainability Hub.

Chatti, K., and Zaabar, I. (2012). *Estimating the Effects of Pavement Condition on Vehicle Operating Costs.* Washington, DC: Transportation Research Board of the National Academies.

EAPA/EuroBitume. (2004). *Environmental Impacts and Fuel Efficiency of Road Pavements - Industry Report.* Brussels, Belgium: Joint EAPA/EuroBitume Task Group on Fuel Efficiency.

Epps, J. A., Leahy, R. B., Mitchell, T., Ashmore, C., Seeds, S., Alavi, S., et al. (1999). WESTrack - The Road to Performance Related Specifications. *Paper prepared for International Conference on Accelerated Pavement Testing;*. Reno, NV: University of Nevada, Reno.

Evans, L. R., Jr., J. D., Harris, J. R., Yates, K., Dudek, W., Holmes, J., . . . Salaani, M. K. (2009). *NHTSA Tire Fuel Efficiency Consumer Information Program Development: Phase 2 – Effects of Tire Rolling Resistance Levels on Traction, Treadwear, and Vehicle Fuel Economy.* East Liberty, OH: National Highway Traffic Safety Administration.

Flintsch, G. W., León, E. d., McGhee, K. K., and Al-Qadi, I. L. (2003). Pavement Surface Macrotexture Measurement and Applications. *Transportation Research Record 1860*, 168-177.

Hammarström, U., Eriksson, J., Karlsson, R., and Yahya, M. (2011). *Rolling Resistance Model, Fuel Consumption Model and the Traffic Energy Saving Potential fom Changed Road Surface Considtions.* Linköping: Swedish National Road and Transport Research Institute.

Hammarström, U., Karlsson, R., and Sörensen, H. (2008). *Road surface effects on rolling resistance – coastdown measurements with uncertainty analysis in focus*. Linköping: Swedish National Road and Transport Research Institute .

Laganier, R. and Lucas, J. (1990). *The Influence of Pavement Eveness and Macrotexture on Fuel Consumption*. Surface Characteristics of Roadways: International Research and Technologies. ASTM STP 1031, ASTM International, Philadelphia. pp. 454-459.

Mactutis, J., Alavi, S., and Ott, W. (2000). Investigation of relationship between roughness and pavement surface distress based on WesTrack project. *Transportation Research Record: Journal of the Transportation Research Board, No. 1699*, 107-113.

McGhee, K. K., and Gillespie, J. S. (2006). *Impact of a Smoothness Incentive/Disincentive on Hot-Mix Asphalt Maintenance Resurfacing Costs.* Charlottesville, VA: Virginia Transportation Research Council.

Sandberg, U. (1990). Road Macro and Mega Texture Influence on Fuel Consumption. In W. E. Meyer, & J. Reichert, *Surface Characteristics of Roadways* (pp. 460-479). Baltimore, MD: American Society for Testing and Materials.

Sandberg, U. (1997). Influence of Road Surface Texture on Traffic Characteristics Related To Environment, Economy and Safety. *VTI notat 53A-1997*. Statens väg- och transportforskningsinstitut. Linköping, Sweden.

Sandberg, U., Haider, M., Conter, M., Goubert, L., Bergiers, A., Glaeser, K.-P., … Harvey, J.T. (2011). *Rolling resistance - basic information and state-of-the-art on measurement methods* (Report MIRIAM SP1 01). Retrieved from MIRIAM project website: http://www.miriam-co2.net/Publications/Publications.htm

Santero, N., Loijos, A., Akbarian, M., and Ochsendorf, J. (2011). *Methods, Impacts and Opportunities in the Concrete Pavement Life Cycle.* Cambridge MA: Massachusetts Institute of Technology.

Sayers, M., and Karamihas, S. (1998). *The Little Book of Profiling*. Ann Arbor, MI: The University of Michigan.

Schrank, D., Eisele, B., and Lomax, T. (2012). *TTI's 2012 Urban Mobility Report.* College Station, TX: Texas A&M Transportation Institute.

Schuring, D. J. and S. Futamura. (1990). Rolling Loss of Pneumatic Highway Tires in the Eighties. *Rubber Chemistry and Technology*: July 1990, Vol. 63, No. 3, pp. 315-367.

Taylor, G., and Patten, J. (2006). *Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III.* Ottawa, Ontario: Centre for Surface Transportation Technology - National Research Council of Canada.

TIAX, LLC. (2003). *California State Fuel-Efficient Tire Report: Volume 2.* Cupertino, CA: California Energy Commission.

TRB (2006). Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance. *TRB Special Report 286*. Washington, D.C.: Transportation Research Board: Committee for the National Tire Efficiency Study.

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B., and Kim, C. (2012). Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production*, 86-96.

Yu, Bin and Lu, Qing. (2013). Empirical model of roughness effect on vehicle speed. *International Journal of Pavement Engineering*, DOI:10.1080/10298436.2013.792931.

Zaabar, I. (2010). *Effect of Pavement Conditions on Vehicle Operating Costs Including Fuel Consumption, Vehicle Durability and Damage to Transported Goods.* East Lansing, MI: Michigan State University.

Zhang, H., Lepech, M., Keoleian, G., Q. S., and Li, V. (2010). Dynamic Life-Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration. *ASCE Journal of Infrastructure Systems*, 299-309.

Chapter 3.
Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements[2,3]

James Bryce[1], Samer Katicha[4], Gerardo Flintsch[3], Nadarajah Sivaneswaran[5], Joao Santos[2]

[1] Graduate Research Assistant, Virginia Tech Transportation Institute, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: jmbp54@vt.edu

[2] Senior Research Associate, Virginia Tech Transportation Institute, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: skaticha@vt.edu

[3] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: flintsch@vt.edu

[4] Senior Research Civil Engineer, FHWA Turner-Fairbank Highway Research Center, 6300 Georgetown Pike, HRDI-20, McLean, VA 22101-2296, Phone: 202-493-3147, Email: n.sivaneswaran@dot.gov

[5] Graduate Student, Universidade de Coimbra and Virginia Tech, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: jmos@student.dec.uc.pt

3.1. Abstract

Agencies that manage pavement networks have a role in mitigating the factors that affect global climate change by managing their networks in such a way that these factors are minimized. Whereas much research is still required in order to quantify the climate change impact of many variables relating to pavements, the impact of pavement condition on vehicle fuel consumption has been clearly demonstrated in several recent research projects. In light of extensive research that has shown that pavement characteristics have a significant impact on vehicle fuel consumption, it can be shown that maintaining a network of pavements to minimize roughness can potentially limit the energy consumption of vehicles travelling on the pavement network. The objective of this paper is to demonstrate a method by which transportation agencies can measure the impact of their management decisions towards reducing the energy consumption of their network. The use of an LCA to probabilistically quantify energy consumption for a given set of expected maintenance actions defined at the network-level will be demonstrated. Furthermore, it will be shown how the results of the LCA can be used to evaluate the energy consumption attributed to the pavement network over a defined time frame.

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[2] The MATLAB® code used to obtain the data in this chapter can be found in Appendix A of this dissertation.

[3] This paper was presented at the 93rd Annual Meeting of the Transportation Research Board, January 2014, Washington, D.C., and accepted for publication in the 2014 series of the *Transportation Research Record: Journal of the Transportation Research Board* (forthcoming). The material from your paper is reproduced with permission of the Transportation Research Board. Permission for reproduction of the work is documented in Appendix E

3.2. INTRODUCTION

Agencies that manage pavement networks have a role in mitigating the factors that affect global climate change by managing their networks in such a way that these factors are minimized. To this end, the United States Federal Highway Administration (FHWA) has committed itself to mitigating climate change factors, such as the reduction of energy consumption attributed to the pavement network (FHWA 2013). It has been established that the majority of the energy consumed during the lifecycle of a pavement occurs during the use phase of the road (i.e., after the road has been opened to traffic), and only 2 to 5 percent of the energy is consumed during construction, maintenance and operation (i.e., lighting and traffic controls) EAPA/EuroBitume (2004). Variables that most impact the energy consumed during the use phase include fuel consumption as a function of pavement condition, heat island effect of the pavement, effect of pavement albedo and others. Whereas much research is still required in order to quantify the climate change impact of many of the variables, the impact of pavement condition on vehicle fuel consumption has been clearly demonstrated in several recent research studies. In light of extensive research that has shown that pavement characteristics have a significant impact on vehicle fuel consumption, it can be shown that maintaining a network of pavements to minimize roughness (as measured by the International Roughness Index (IRI)) can potentially limit the energy consumption of vehicle travelling along the pavement network.

In order to quantify such factors as energy consumption of a system or greenhouse gas emissions, a lifecycle assessment (LCA) is generally employed. LCA's are methods that are used to systematically and clearly evaluate the inputs and resulting outputs of a system. In the context of pavements, LCA's have generally been deterministic in nature and left for project-level evaluation (Zapata and Gambatese 2005; Huang et al. 2009; Patrick and Arampamoorthy 2010; Weiland and Muench 2010). The use of an LCA to probablistically quantify energy consumption for a given set of expected maintenance actions defined at the network-level will be demonstrated in this paper.

The application of probablistic approaches to assess the impact of pavement management alternatives has been demonstrated in several applications (Harvey et al. 2012; Chen and Flintsch 2012; Tighe 2012). Among the cited benefits of a probablistic approach to life cycle cost analysis is the ability for the decision makers to evaluate the risks associated with the alternatives given uncertainty in model parameters and measured variables. Defining the expected energy consumption probablistically is important given the large uncertainties that exist in many of the varibles, such as traffic growth and the change of the pavement IRI over time. Furthermore, it will be shown how probablistic results of an LCA can be used to evaluate the energy consumption attributed to the pavement network over a defined time frame.

3.3. OBJECTIVE

The objective of this paper is to demonstrate a probabilistic approach by which transportation agencies can measure the impact of the uncertainties associated with management decisions while working towards reducing the energy consumption of their pavement networks. The methods presented in this paper are for a network-level evaluation of the impact of project selection on the energy consumption attributed to the pavement network. However, the excess energy consumption due to congestion during maintenance will not be included in the process presented in this paper. This paper will focus on flexible pavements, but it is expected that a similar method can be employed to evaluate Portland cement concrete (PCC) and composite pavements. A process based LCA approach is used to assess the energy consumption. The process based approach is defined in the International Standards Organization (ISO) standard ISO 14040 and ISO 14044, Standards for a Process-Based LCA Approach.

3.4. BACKGROUND

The purpose of a pavement LCA is to quantify the total environmental impact of the pavement throughout its life, which is generally divided into the following five phases (after Santero et. al. 2011): (1) raw materials and production; (1) construction; (3) use; (4) maintanenance and (5) end of life. An important consideration for LCA is the boundaries chosen for the analysis. Ideally, an LCA is a cradle to grave analysis that accounts for the entire life of the pavement, all the processes involved with the system, as well as other processes impacted by the system. However, lack of information and an inability to accurately predict certain parameters, such as material life and the impact of the system condition on the user, sometimes lead to a constraint on the system boundaries for a pavement. Thus, in the case of pavements, typical LCA boundaries are constricted to cover only the time period from material extraction through the end of the construction phase of the project.

The first two phases of a pavement LCA, material production and construction, have been the focus of extensive research. For example, Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is a spreadsheet based tool that was developed to account for both economic and environmental factors related to the construction processes of a pavement (Horvath 2003). For the environmental assessment, PaLATE assesses emissions associated with the production of materials, construction, material transport, maintenance and a database of recycled materials built in. As another example, Park et al. (2003) evaluated the environmental loads due to the processes throughout the lifecycle of a highway, defined in four stages as: (1) manufacturing of materials, (2) construction, (3) maintenance and (4) end of life (demolition/recycling), but notably the use phase is excluded from this definition of the pavement lifecycle. The researchers focused on energy consumption, then used appropriate factors to translate the energy consumption into equivalent emissions and estimate pollutant discharge into water. A few other notable LCA studies relating to the first two phases of the lifecycle are Zapata and Gambatese (2005), Huang et al. (2009) and Patrick and Arampamoorthy (2010).

Much of the research pertaining to the use phase of the pavement (the third phase of an LCA) has been to quantify the effect of rolling resistance on emissions and energy consumption from vehicles travelling on the pavement. Several research projects with the objective of quantifying the impact of pavement properties on rolling resistance have been undertaken, and some research has shown that in all driving conditions, an overall average of 25 percent of fuel consumption is expended on rolling resistance leaving 75 percent to overcome air drag and inertia (Izevbekhai 2012). Thus, if the rolling resistance of a pavement were reduced, the vehicle fuel consumption along that pavement would be reduced. Furthermore, a 10 percent reduction in rolling resistance can lead to between a 1 and 2 percent reduction in fuel consumption, which also leads to a reduction of greenhouse gas emissions (Transportation Research Board 2006; Evans et al. 2009). The tire-pavement interaction is the main factor in rolling resistance, and is impacted by several variables such as macro-texture, pavement stiffness, roughness, rutting and the transversal slope of the pavement. Relatively good relationships have been developed to determine the impact of IRI and macro-texture, as measured by the mean profile depth (MPD), on a vehicles rolling resistance (Chatti and Zaabar 2012; Karlsson et al. 2012).

Chatti and Zaabar (2012) reported the results of calibrating the HDM 4 models for vehicle operating costs in the National Cooperative Highway Research Program (NCHRP) report 720, and their research clearly demonstrates the relationship between fuel consumption and pavement factors such as its IRI and mean pavement depth (MPD), which is a measure of surface texture. Within the scope of this paper, the influence of the pavement IRI on fuel consumption will be the only factor considered for the use phase. It is important to note that the MPD of the pavement is known to play a role in pavement safety (Flintsch et al. 2003). Thus, reducing the MPD of the pavement in order to reduce fuel consumption may come at the tradeoff of safety to the travelling public. This aspect is not addressed in this paper.

3.4.1. Uncertainties in Pavement Management

Uncertainties are an inevitable part in every analysis conducted by a transportation agency, and are typically a result of predicting current and future values in the face of limited information and using models of assumed future behaviors. Economic uncertainties in the form of agency costs typically exist in many forms; namely, uncertainties associated with project construction costs, discount rate, costs of future treatments, life of the treatments (in determining next treatment timing) and salvage or remaining value. User cost uncertainties (defined by user delay) generally arises from uncertainties in the current and projected traffic volumes and composition, road user behavior (carpool, no-show, detour, etc.), value of time by vehicles type, as well as uncertainties in the estimation of congestion delay time and construction duration. In light of these uncertainties, one of two approaches is used to perform a lifecycle cost analysis: (1) a deterministic analysis where expected values are used and solutions are presented as fixed; or (2) a probabilistic assessment that utilizes some form of simulation (e.g., Monte Carlo Simulation as described by Herbold (2000)) and solutions are represented by distributions of possible values.

Uncertainties relating to environmental measures include; uncertainties about the environmental impacts for a given project, uncertainties in the prediction models relating the environmental impacts during the use phase (e.g., the relationships between IRI and fuel consumption), uncertainties in the prediction of future pavement properties and uncertainties about current and future traffic characteristics. Similar to the economic uncertainties, it is expected that the environmental performance measures can be addressed either through a deterministic assessment or through probabilistic simulation. This paper will address the probabilistic assessment of the environmental factors.

Many of the uncertainties can be described by distributions of possible values in a probabilistic assessment. For example, Perrone et al. (1998) describes the use of a triangular distribution in lifecycle cost analysis to simulate treatment life, given that minimum, expected and maximum values are generally known for a treatment life. Similar parameters are known for future prediction models of pavement parameters (e.g., IRI and traffic characteristics), and thus a similar probabilistic assessment may be employed where distributions are assigned based on mean values and the nature of the known or expected variance in the variables.

3.5. Defining the Energy Consumption Attributed to Maintenance Actions

An important consideration is that the level of detail of information used at the network-level is lower than that at the project-level. Whereas project-level analysis is done using greater detail about a specific location, at the network-level work types and costs are generalized estimates for a large network of pavements until further investigation is done at the project-level for a specific project. For example, the Virginia Department of Transportation (VDOT) uses a set of matrices and filters based on pavement condition to choose work types at the network-level, and generalizes the work types into: Do Nothing; Preventative Maintenance; Corrective Maintenance; Restorative Maintenance and Rehabilitation/Reconstruction (VDOT 2008). Each of the work types have an accompanying expected cost and expected life used in network-level analysis. This principle will hold true for environmental considerations, where expected environmental loads of the different maintenance actions can be estimated probabilistically given expected values and deviations from the expected values. For example, if Corrective Maintenance is generally characterized by a mill and overlay, an expected environmental load can be estimated per unit area treated.

3.5.1. Maintenance Actions

The maintenance actions used by VDOT for network-level pavement management are used to quantify the energy consumption in this paper. The maintenance actions defined in Table 3-1 are used for network-level planning purposes, and the various category levels are triggered based on the pavement condition, distress types present and the structural condition of the pavement (VDOT 2008).

Table 3-1 VDOT Maintenance Actions for Network-Level Decision Making (adapted from (VDOT 2008))

Category	Activities
Do Nothing (DN)	N/A
Preventive Maintenance (PM)	1. Minor Patching (<5% of Pavement Area: Depth 2”)
	2. Crack Sealing
	3. Surface Treatment (e.g., Chip Seal, Microsurface, etc.)
Corrective Maintenance (CM)	1. Moderate Patching (<10% of pavement area: Depth 6”)
	2. Partial Depth Patching (<10% of Pavement Area: Depth 4”-6”) and Surface Treatment
	3. Partial Depth Patching (<10% of Pavement Area: Depth 4”-6”) and Thin (≤ 2”) AC Overlay
	4. ≤ 2” Milling and ≤ 2” AC Overlay
Restorative Maintenance (RM)	1. Heavy Patching (<20% of Pavement Area: Depth 12”)
	2. ≤4” Milling and Replace with ≤4” AC Overlay
	3. Full Depth Patching (<20% of Pavement Area: Depth 9”-12”) and 4” AC Overlay
Rehabilitation /Reconstruction (RC)	1. Mill, Break and Seat and 9”-12” AC Overlay
	2. Reconstruction

For the purposes of this paper, PM will be represented by Microsurfacing, CM will be represented by a distribution approximating a two inch mill and overlay, RM will be represented by a distribution approximating a four inch mill and overlay and RC will be represented by a distribution approximating a ten inch mill and overlay with re-compaction of the subgrade. Each of the maintenance actions will also be represented with uncertainty to signify that assumptions are made about the extent of work done.

3.5.2. Energy Consumption

A literature review was conducted in order to define the energy consumption related to the various processes within the construction phase of a pavement. Using the processes for the construction phase, a subset of processes was defined for the maintenance activities (following (Wang et al. 2012)). The expected energy consumption for each process in the maintenance actions is shown in Table 3-2.

Table 3-2 Energy Values for Materials and Processes

Phase	Process	Energy[a] (Energy has been converted to common units from cited reference)	Energy
Removal	Mill Asphalt	11.12 MJ/Ton (Patrick and Arampamoorthy 2005)	4,550 MJ/lane-mile/inch
	Loading Material	3.2 MJ/Ton (Horvath 2003)	1,310 MJ/lane-mile/inch
Aggregate Production	Aggregate Production	38 MJ/Ton (Crushed) (Cerea 2012)	14,770 MJ/lane-mile/inch[b]
Bitumen Production	Bitumen Production	5,450 MJ/Ton (Zapata and Gambatese 2005)	111,500 MJ/lane-mile/inch[b]
HMA Production	Production Process	318 MJ/Ton (Zapata and Gambatese 2005)	130,125 MJ/lane-mile/inch
HMA Paving	SubGrade Compaction	0.58 MJ/yd2 (Patrick and Arampamoorthy 2005)	7,040 MJ/lane-mile
	Application of Tack Coat (Including Material Energy)	3260 MJ/lane-mile[c]	3,260 MJ/lane-mile
	Paving	2.23 MJ/Ton (Patrick and Arampamoorthy 2005)	913 MJ/lane-mile/inch
	Rolling	1.4 MJ/Ton (Horvath 2003)	573 MJ/lane-mile/inch
Slurry Equipment (PM)	Placement of Microsurfacing	2470 MJ/lane-mile (Giustozzi et al. 2012)	2470 MJ/lane-mile
PM Materials - Assumed Microsurfacing	Combined Energy of Mix Design[d]	34.07 MJ/m2 (Cerea 2012)	200,548 MJ/lane-mile
Hauling Materials	Transport	13.34 MJ/veh-km for 35.3 Ton Load (Patrick and Arampamoorthy 2005)	21.5 MJ/veh-mile per 35.3 Tons

a. Mean value used when multiple values are reported.

b. Asphalt mix was assumed to be composed of 5% binder by weight and 95% aggregate by weight. No reclaimed asphalt was factored into the calculation. 130 lb/ft3 Assumed Unit Weight for Aggregate, 155 lb/ft3 Assumed Unit Weight for Asphalt.

c. 1 tack truck=26.5 L/h Fuel *(3)*; Expected 0.13 liters per yd^2 Application (50% asphalt mixture) (http://pavementinteractive.org/index.php?title=Tack_Coats), 1mile/hr.

d. 11% Modified Emulsion Binder, 82% Aggregate, 1% Filler, 6% Water *(24)*.

3.5.3. Assessment of Energy Consumption per Maintenance Action

Several uncertainties exist during the network-level analysis, and these uncertainties should be accounted for during the assessment of the expected energy consumption of the maintenance action. Some examples of uncertainties include uncertainty about the extent of maintenance (e.g., the predicted thickness of the overlay at the network-level may not be the same as when determined at the project-level) and uncertainties about the hauling distances for the materials. In general, these uncertainties can be accounted for by introducing the variables as distributions as opposed to deterministic values. For example, if CM is defined as in Table 3-1 as less than or equal to a two inch mill and overlay, then a potential representation of the variable may be as a normal distribution with a mean of 1.7 inches and a standard deviation of 0.4 inches. In this case, 77 percent of the time the actual overlay will be less than two inches, 2 percent of the overlays will be greater than 2.5 inches and 96 percent of the overlays will be over one inch thick. Thus, the uncertainty in predicting CM at the network-level is addressed by assuming that the majority of the time the overlay will fall between one and 2.5 inches thick, with some outliers as expected.

Another uncertainty that must be addressed is whether the amount of milled asphalt is equivalent to the depth of the overlay. In many cases, particularly where clearance is not an issue, an agency might not wish to expend the resources to mill to the same depth as the overlay. This assumption impacts both the energy consumption assumed for the milling and the transportation amount for disposal, which may add up to a significant portion of the expected energy consumption for the maintenance treatment. In order to address this, the amount milled was made a function of the thickness of the overlay by defining it as a single peaked triangular distribution with a minimum of half the thickness and a maximum value and expected value equal to the thickness of the overlay.

There are also a number of uncertainties associated with the energy consumption of the equipment and material manufacturing. The uncertainties within the quantities were addressed by assuming the energy per unit as a normal distributed variable with an assigned standard deviation. In general 10 percent of the mean was assigned as the standard deviation, thus approximately 95 percent of the data fell between 0.8 and 1.2 times the mean value. The distributions of the variables used in the analysis are given in Table 3-3.

Given that the inputs to the system are uncertain, the calculated energy consumption will also be represented by a distribution. In order to calculate the distributions of the energy consumption for the different maintenance actions, the Monte Carlo simulation method was used. Readers are referred elsewhere for a detailed discussion of the Monte Carlo method (e.g., (Metropolis and Ulam 1949). However, the basic steps of the Monte Carlo method can be generalized as follows: (1) Assume the distribution of input variables is known; (2) sample each distribution of input variable independantly; (3) calculate an output and (4) repeat over a large number of iterations. The Monte Carlo method has been used in pavement management in terms of analyzing proabalistic life cycle costs (FHWA 2004), and allows many types of distrubtions to be combined within a single analysis. In order to determine the distribution of energy consumption for each of the maintenance actions, a set of MATLAB™ codes were developed and will be made available to the reader for download upon request. The result of the Monte Carlo method is a distrubtion or histogram of potential outcomes based on the distributions defined for the input values. The histograms of the energy consumption per lane-mile for the the various maintenance actions is shown in Figure 3-1.

Table 3-3 Distributions Used in Analysis of Maintenance Actions

	PM	CM	RM	RC
Overlay Thickness (OL)	N/A	Normal[1.8,0.4] inches	Normal[3.6,0.5] inches	Normal[9,1.5] inches
Mill Thickness (mill)	N/A	Triangular Distribution [0.5*OL,OL,OL] [b]	Triangular Distribution [0.5*OL,OL,OL] [b]	Triangular Distribution [0.5*OL,OL,OL] [b]
Mill Energy	N/A	Normal[4550*mill ,450*mill] MJ/lane-mile [c]	Normal[4550*mill ,450*mill] MJ/lane-mile [c]	Normal[4550*mill ,450*mill] MJ/lane-mile [c]
Loading Material Energy	N/A	Normal[1310*mill ,130*mill] MJ/lane-mile [c]	Normal[1310*mill ,130*mill] MJ/lane-mile [c]	Normal[1310*mill ,130*mill] MJ/lane-mile [c]
Aggregate Production	N/A	Normal[14770*OL,1477*OL] MJ/lane-mile	Normal[14770*OL,1477*OL] MJ/lane-mile	Normal[14770*OL,1477*OL] MJ/lane-mile
Bitumen Production	N/A	Normal[111500*OL,11150*OL] MJ/lane-mile	Normal[111500*OL,11150*OL] MJ/lane-mile	Normal[111500*OL,11150*OL] MJ/lane-mile
Production Process	N/A	Normal[130125*OL,13012*OL] MJ/lane-mile	Normal[130125*OL,13012*OL] MJ/lane-mile	Normal[130125*OL,13012*OL] MJ/lane-mile
SubGrade Compaction	N/A	N/A	N/A	Normal[7040,704] MJ/lane-mile
Application of Tack Coat (Including Material Energy)	N/A	Normal[3260,326] MJ/lane-mile	Normal[3260,326] MJ/lane-mile	Normal[3260,326] MJ/lane-mile
Paving	N/A	Normal[913*OL,91*OL] MJ/lane-mile	Normal[913*OL,91*OL] MJ/lane-mile	Normal[913*OL,91*OL] MJ/lane-mile
Rolling	N/A	Normal[573*OL,57*OL] MJ/lane-mile	Normal[573*OL,57*OL] MJ/lane-mile	Normal[573*OL,57*OL] MJ/lane-mile
Placement of Preventive Maintenance (Equipment)	Normal[2470, 247] MJ/lane-mile	N/A	N/A	N/A
Combined Energy of Mix Design for Preventive Maintenance	Normal[200548, 20055] MJ/lane-mile	N/A	N/A	N/A
Transport Distance	Uniform [1 mile, 50 mile]	Uniform [1 mile, 50 mile]	Uniform [1 mile, 50 mile]	Uniform [1 mile, 50 mile]
Transport Amount - Disposal	N/A	Normal[409*mill,41*mill] MJ/lane-mile [d]	Normal[409*mill,41*mill] MJ/lane-mile [d]	Normal[409*mill,41*mill] MJ/lane-mile [d]
Transport Amount - Aggregate to Plant	Normal[200,10] Tons/lane-mile [a]	Normal[343*OL,34*OL] MJ/lane-mile [e]	Normal[343*OL,34*OL] MJ/lane-mile [e]	Normal[343*OL,34*OL] MJ/lane-mile [e]
Transport Amount - Plant to Site	Normal[200,10] Tons/lane-mile [a]	Normal[409*OL,41*OL] MJ/lane-mile [d]	Normal[409*OL,41*OL] MJ/lane-mile [d]	Normal[409*OL,41*OL] MJ/lane-mile [d]

[a] 0.0283 tons/yd^2 per (Cerea 2010); [b] OL refers to the thickness of overlay (inches); [c] Mill refers to the thickness milled (inches); [d] Density of asphalt was assumed as 155 pounds per cubic foot; [e] Aggregate density was assumed as 130 pounds per cubic foot

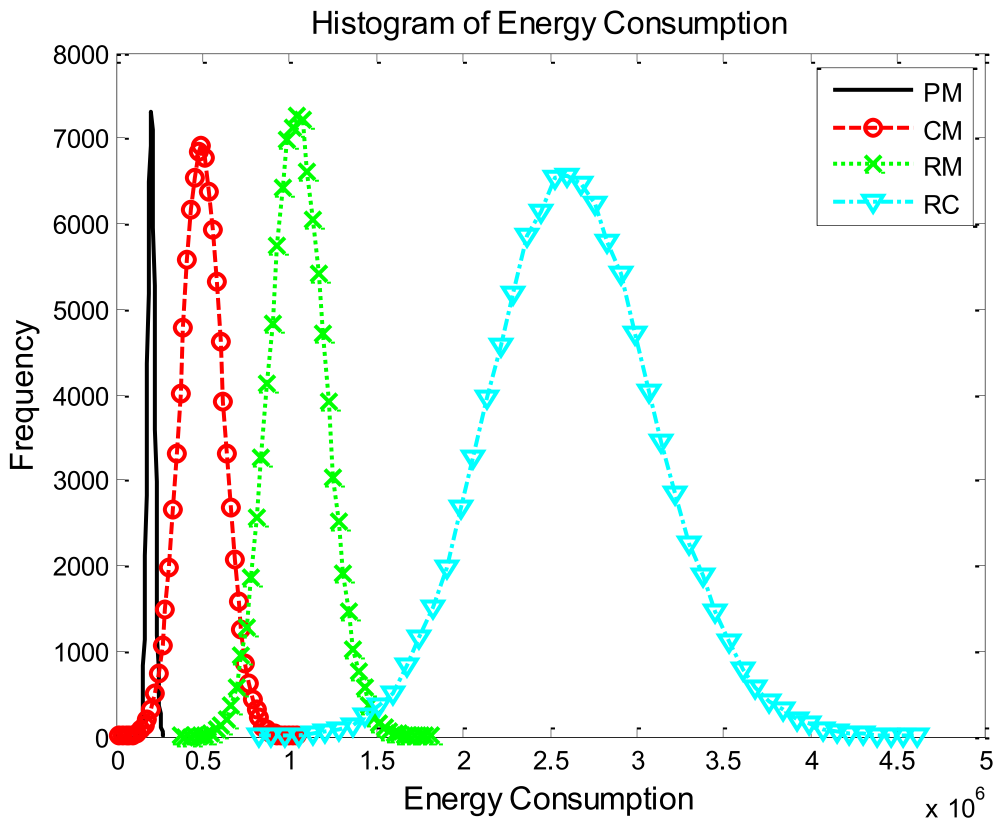

Figure 3-1 Energy Consumption for Maintenance Actions in Mega Joules (MJ)

3.6. ENERGY CONSUMPTION DURING THE USE PHASE

The energy consumption during the use phase of the pavement comes in the form of fuel consumed by vehicles travelling over the pavement. Furthermore, the condition of the pavement impacts the fuel consumption of the vehicles by increasing the rolling resistance of the vehicles travelling along the pavement. This effect has been quantified in the NCHRP report 720 and accompanying software by Chatti and Zabaar (2012). The impact of the IRI of the pavement on excess fuel consumption will be the variable assessed for the use phase in this paper.

In order to quantify the impact of the roughness on fuel consumption, a baseline roughness must be set. It is important to note that the roughness of a pavement after construction is not zero. McGhee and Gillespie (2006) reported that pavements subject to a smoothness specification had an initial roughness of 67.4 in/mile with a standard deviation of 10.2. Those pavements not subject to the specification had an initial roughness of 76.2 in/mile with a standard deviation of 11.5. Furthermore, the reported average increase in IRI over a 7 year period was 1.23 in/mile/year. An initial IRI of 70 in/mile with a standard deviation of 10 will be used in this paper, and a triangular distribution with a range of ± 1.5 times the standard deviation from the mean will represent the IRI after the maintenance action. Thus, a minimum value of 55 in/mile will be considered for the fuel consumption calculations. Furthermore, the growth rate of IRI as a function of time will be assumed as a nomally distributed variable with a mean of 1.25 in/mi-yr and a standard deviation of 0.13.

In order to run the model developed by Chatti and Zabaar (2012) to determine the additional fuel consumption as a function of IRI, the mean texture depth was held at 0.05 inches, the grade and super-elevation were left at 0 percent, the pavement type was asphalt, the speed was assumed at 55 mph and the air temperature was assumed as 68 degree Fahrenheit. These variables were input into the software that accompanies the National Cooperative Highway Research Program (NCHRP) report 720 (Chatti and Zabaar 2012), and the impact of roughness on the fuel consumption was assessed over a range of roughness values between 55 in/mile to 120 in/mile. The values used for the combustion energies of gasoline and diesel were 132 MJ/Gallon and 146 MJ/Gallon respectively.

3.6.1. Network-Level Evaluation

In order to demonstrate the evaluation of energy consumption at the network-level during the use phase, an example network of roads was developed (Table 3-4). In this case, the energy consumption is a function of the road length, AADT, the percentage of trucks, the roughness and construction type. The length of the roads and the initial roughness of the roads were taken as deterministic values because it can be assumed that the roughness values in this case were measured just prior to the analysis. The traffic values were treated as normally distributed variables with a standard deviation of 1,000, and the percentages of trucks were set within the range typically found on highly travelled interstate routes (e.g., Interstate 81 in Virginia). The condition values are indices representing the overall functional condition of the pavement (i.e., a combination of cracking, rutting, etc.), where a value of 100 represents a pavement with no distresses and a value of 0 represents the worst case condition. The results from analyzing the energy consumption due to the rolling resistance from a 5 year analysis for the road network are shown in Figure 3-2. A normally distributed traffic growth rate with a 3 percent mean and a 0.3 percent standard deviation was used in the analysis, and a growth rate of the IRI as nomally distributed with a mean of 1.25 in/mi-yr and a standard deviation of 0.13. Traffic growth was calculated using compounding growth methods.

Table 3-4 Example Road Network Characteristics

Road	Length (miles)	Traffic (AADT)	Percent Trucks	Initial Roughness[a] (in/mile)	Condition	Construction
1	1.8	20,000	23%	130	65	Asphalt
2	2.2	37,000	25%	80	83	Asphalt
3	1.1	25,000	21%	77	92	Asphalt
4	2.4	12,000	27%	115	55	Asphalt
5	2.1	32,000	25%	97	73	Asphalt
6	1.6	41,000	19%	110	68	Asphalt
7	1.3	15,000	22%	65	93	Asphalt
8	1.9	30,000	24%	91	75	Asphalt

a. Roughness at the start of the analysis period

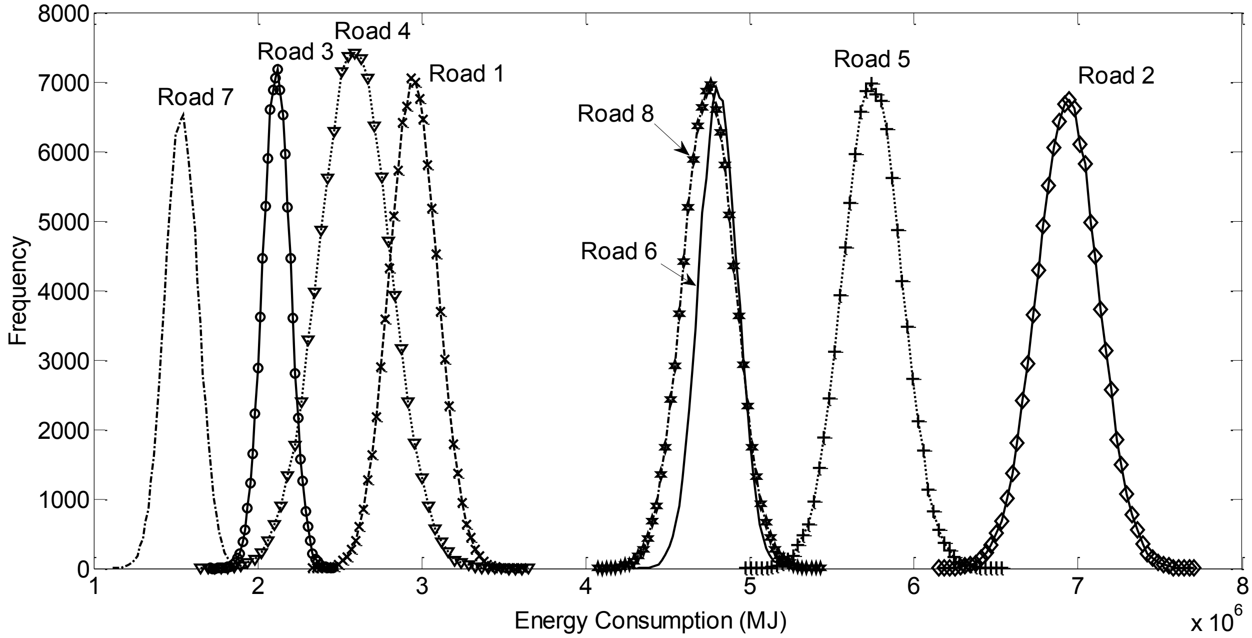

Figure 3-2 Energy Consumption for the Roads in the Network: 5 Year Analysis

3.7. MULTICRITERIA OPTIMIZATION

So far, this paper has demonstrated methods to probabilistically assess an LCA of the use and maintenance phases of the pavement at a level of detail sufficient for network-level analysis. This information has direct implications to decision making by providing both expected values for the energy consumption and distributions of probable values for the decision maker to be aware of. In an effort to contribute to climate change mitigation, the FHWA has focused resources on assuring that more sustainable decision making is promoted htrough a balanced tradeoff between environmental, economic and social factors (FHWA 2013). Thus, a sustainable decision framework should incorporate these three factors as primary considerations. One key consideration in the decision making or decision analysis process is the certainty about the outcomes, which makes a probabilistic assessment of the variables a key contributor to the decision process.

Generally, multi-objective programs using optimization techniques are employed. Multi-objective programs using an optimization technique refers to the selection of a best element from some set of available alternatives (INFORMS 2012). No single solution may be considered optimal in the case of multiple objectives, but instead a set of solutions can be found that represent a non-dominated set (referred to as a Pareto set) given different values for each objective. Any solution that falls along the Pareto set can be considered optimal, and thus the '*best*' solution depends on the amount of tradeoff between the criteria that the agency is willing to make. Three objectives will be considered in this analysis as;

$$\left[\textbf{Min}\left(\text{Cost}\right), \textbf{Max}\left(\text{Condition}\right), \textbf{Min}\left(\text{Energy}\right)\right] \tag{3-1}$$

In order to demonstrate multi-objective optimization on the pavement network shown in Figure 3-4, a three year analysis was performed considering average condition of the network (over the three year time frame), total maintenance cost and energy consumption (from maintenance and rolling resistance).

The three year time frame was chosen in order to show the variations in outcomes while maintaining the constraint that each road is selected no more than once throughout the analysis period. The deterioration curve for the condition of the pavements was set as:

$$Condition(age) = a(age)^2 + b(age) + c \tag{3-2}$$

Where age is the pavement age in years, c was set at 100, a and b were set as uniformly distributed variables (in order to simulate uncertainty in the deterioration modeling) that had values between [-0.216, -0.324] and [-1.536, -2.304], respectively. The energy consumption due to maintenance and cost were set as a function of the condition of the pavement where the following thresholds were set: condition above 90 was do nothing; condition between 80 and 90 set as PM and assigned a cost of \$1,400 per mile; condition between 65 and 80 was set as CM and assigned a cost of \$14,100 per mile; condition between 50 and 65 was set as RM and assigned a cost of \$35,600 per mile; and condition less than 50 was set as RC and assigned a cost of \$100,000 per mile. The costs used in the analysis were taken from (VDOT 2008) and scaled such that the maximum cost was \$100,000. Approximately 1.7 million variations of maintenance plans were evaluated (i.e., choosing to maintain road i in year j), and then the surface containing the Pareto set was found by minimizing the vector length defined by the following set of points representing the normalized values of each variable (Figure 3-3):

$$\left[\frac{Energy - Energy_{Min}}{Energy_{Max} - Energy_{Min}}, \frac{Condition_{Max} - Condition}{Condition_{Max} - Condition_{Min}}, \frac{Cost - Cost_{Min}}{Cost_{Max} - Cost_{Min}}\right] \tag{3-3}$$

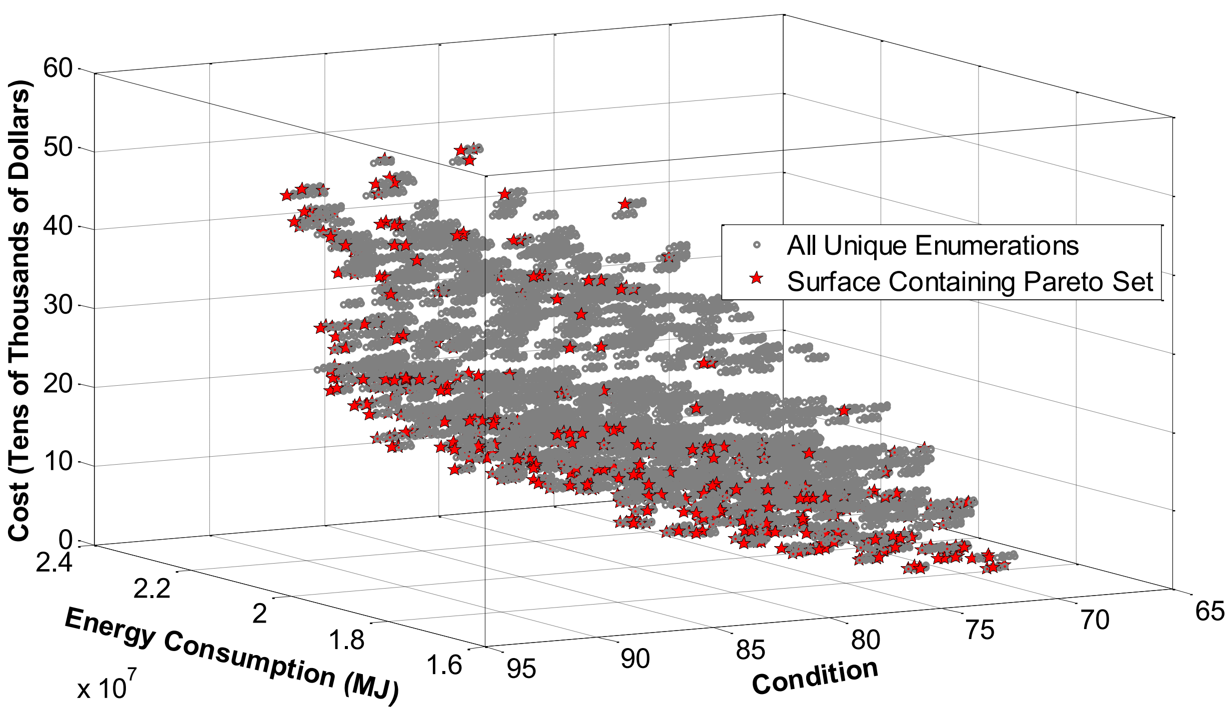

Figure 3-3 Surface Containing Pareto Set for the Alternatives for Maintenance of the Network

The data shown in Figure 3-3 are for the mean condition (i.e., the average of all of the stochastic variables). In order to demonstrate the change in the Pareto sets when the maintenance plans that form the set are evaluated probabilistically, a subset was evaluated using a 5 percentile (i.e., a 5 percent probability that the actual values will be as good as or better than the reported number) and 95 percentile level of certainty. The results are shown in Figure 3-4.

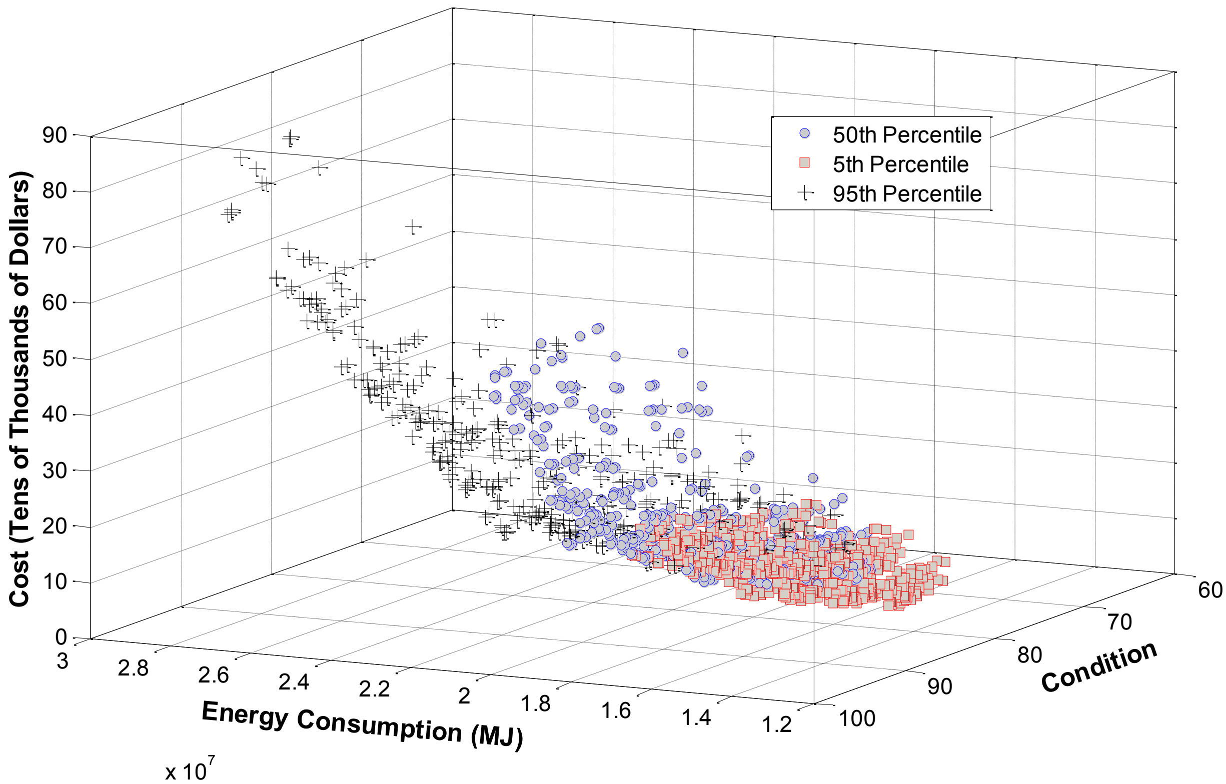

Figure 3-4 Probabilistic Consideration of Pareto Set

In order to evaluate the potential range of values when two maintenance plans are analyzed probabilistically over a three year period, one that yielded values that were contained in the Pareto set, as well as a plan that is not considered optimal, two maintenance plans were chosen and analyzed over a range of probabilities. The plan that was considered as optimal (i.e., contained in the Pareto set) consisted of maintaining Roads 2, 4 and 6 in the first year, Road 8 in the second year, and no roads in the third year. The plan that was not contained in the Pareto set (i.e., the Non-optimal case) consisted of maintaining Road 1 in the first year, Road 6 in the second year and Road 4 in the third year. The non-optimal case was chosen so that both condition and energy consumption could be made better for similar costs. The results of the cost, condition and energies as a function of their level of certainty (i.e., the cumulative probability such that $P(x \leq X)$) are shown in Figure 3-5a through Figure 3-5d.

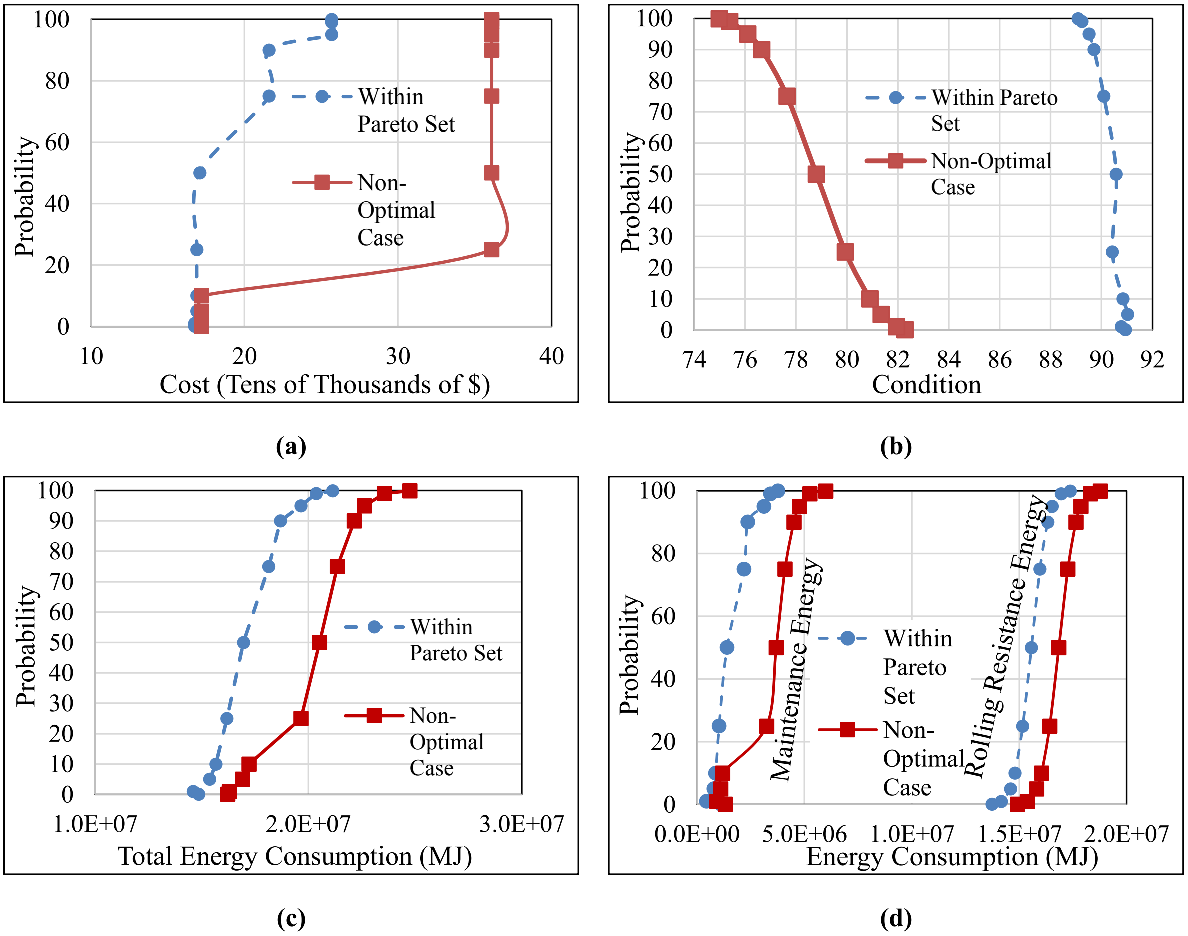

Figure 3-5 Probabilistic Outcome for Maintaining Roads 2, 4 and 6 in Year 1, Roads 3, 5, 7 and 8 in Year 2, and No Roads in Year 3 (Within Pareto Set) and Road 1 in Year 1, Road 6 in Year 2,and Road 4 in Year 3 (Non-Optimal Case)

It can be seen in Figure 3-5 that the range of potential values of the maintenance plan that is contained within the Pareto set is consistently less than the range of values of the non-optimal plan. The large increase in costs for probabilities above 25 percent in the non-optimal case are due to the uncertainties in the condition values when road 4 and road 5 are maintained (i.e., as probability increases, the condition in year two and year three decrease such that a higher level of maintenance is triggered). This jump in values also corresponds to a jump in values for maintenance energy (Figure 3-5d).

3.8. Conclusions

This paper presented a method by which an agency can evaluate the energy consumption of their road network, as well as the energy attributed to potential maintenance actions probabilistically. The main benefit of a probabilistic assessment over a deterministic assessment is the ability to incorporate uncertainties in the analysis to determine how the level of detail of the information may potentially impact the outcomes of the decision process. Furthermore, it was clearly demonstrated in this paper that a probabilistic assessment should be used when the uncertainties in the models may be significant. Another benefit of the probabilistic assessment is to determine which set of variables require more detailed information prior to decision making, and assess the impact of small changes in variable uncertainties in the overall outcome.

Incorporating environmental considerations into transportation decision making is an integral part of sustainable decision making, and is being promoted as a way to help mitigated global climate change factors. To this end, an agency should evaluate whether the currently used optimization and decision making techniques will facilitate environmental and societal considerations as objectives instead of soft constraints or secondary considerations. The process demonstrated in this paper represents one of many methods that an agency can use to evaluate sources of energy consumption and the impact of management actions on the energy consumption of their road network.

3.9. ACKNOWLEDGMENTS

This paper was produced under the sponsorship of the Transportation Pooled Fund TPF-5(268) National Sustainable Pavement Consortium. The authors would like to thank the Mississippi, Pennsylvania, Virginia and Wisconsin DOT, as well as the Federal Highway Administration for their support and guidance. The contributions of Edgar de Leon of VTTI and Kevin McGhee throughout the development of the project are also acknowledged.

3.10. CHAPTER 3 REFERENCES

Chatti, K., and Zaabar, I. (2012). *Estimating the Effects of Pavement Condition on Vehicle Operating Costs.* Washington, DC: Transportation Research Board of the National Academies.

Chen, C., and Flintsch, G. (2012). Fuzzy Logic Pavement Maintenance and Rehabilitation Triggering Approach for Probabilistic Life Cycle Cost Analysis. *Transportation Research Record: Journal of the Transportation Research Board of the National AcademieS, No. 1990*, 80–91.

EAPA/EuroBitume. (2004). *Environmental Impacts and Fuel Efficiency of Road Pavements - Industry Report.* Brussels, Belgium: Joint EAPA/EuroBitume Task Group on Fuel Efficiency.

Evans, L. R., Jr., J. D., Harris, J. R., Yates, K., Dudek, W., Holmes, J., et al. (2009). *NHTSA Tire Fuel Efficiency Consumer Information Program Development: Phase 2 – Effects of Tire Rolling Resistance Levels on Traction, Treadwear, and Vehicle Fuel Economy.* East Liberty, OH: National Highway Traffic Safety Administration.

Federal Highway Administration. FHWA Role in Climate Change. Retrieved from Federal Highway Administration, US Department of Transportation website: http://www.fhwa.dot.gov/environment/climate_change/index.cfm. January 4, 2013.

Flintsch, G. W., León, E. d., McGhee, K. K., and Al-Qadi, I. L. (2003). Pavement Surface Macrotexture Measurement and Applications. *Transportation Research Record 1860*, 168-177.

Harvey, J.T, Rezaei,A., and Charles Lee. (2012). Probabilistic Approach to Life Cycle Cost Analysis of Preventive Maintenance Strategies on Flexible Pavements. *Transportation Research Record: Journal of the Transportation Research Board, No. 2292*, 61-72.

Herbold, K.. (2000). Using Monte Carlo Simulation for Pavement Cost Analysis. *Public Roads*, November/December 2000, pp. 2-6.

Horvath, A. (2003). *Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements.* Berkeley: University of California Transportation Center.

Huang, Y., Bird, R., and Heidrich, O. (2009). Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production, 17*, 283-296.

Izevbekhai, B. (2012). Concrete Paving and Texturing for Sustainability. Minneapolis, MN: Presented at Center For Transportation Studies Research Conference.

Karlsson, R., Carlson, A. and Dolk, E. (2012). *Energy use generated by traffic and pavement maintenance. Decision support for optimization of low rolling resistance maintenance* (VTI Report 36A–2012).

Park, K., Hwang, Y., Seo, S., and Seo, H. (2003). Quantitative Assessment of Environmental Impacts on Life Cycle of Highways. ASCE Journal of Construction Engineering and Management, 25-31.

Patrick, J., and Arampamoorthy, H. (2010). *Quantifying the benefits of waste minimisation - NZTA Report 406.* Wellington, NZ: NZ Transport Agency.

Perrone, E., Clark, D., Ness, Q., Chen, X., and Hudson, S. (1998). *Risk Based Life Cycle Cost Analysis for Project Level Pavement Management.* Presented at the 4th International Conference on Managing Pavements, TRB Committee AFD10. Seattle, WA.

Santero, N., Masanet, E., and Horvath, A. (2011). Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling*, 801-809.

Susan Tighe. (2012). Guidelines for Probabilistic Pavement Life Cycle Cost Analysis. In *Transportation*

Research Record: Journal of the Transportation Research Board, No. 1769, 28-38.

TRB. (2006). *Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance TRB Special Report 286.* Washington, DC: Transportation Research Board: Committee for the National Tire Efficiency Study.

VDOT. (2008). *Supporting Document for the Development and Enhancement of the Pavement Maintenance Decision Matrices Used in the Needs Based Analysis*. Richmond, VA. Virginia Department of Transportation Maintenance Division.

Weiland, C., and Muench, S. (2010). Life-Cycle Assessment of Reconstruction Options for Interstate Highway Pavement in Seattle, Washington. *Transportation Research Record*, 18–27.

Zapata, P., and Gambatese, J. (2005). Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Construction. *ASCE Journal of Infrastructure Systems*, 9-20.

Chapter 4.
A Life Cycle Assessment of Recycling and Conventional Pavement Construction and Maintenance Practices[4]

Joao Santos[1], James Bryce[2], Gerardo Flintsch[3], Adelino Ferreira [4], Brian Diefenderfer [5]

[1] Graduate Student, Universidade de Coimbra and Virginia Tech, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: jmos@student.dec.uc.pt

[2] Graduate Research Assistant, Virginia Tech Transportation Institute, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: jmbp54@vt.edu

[3] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Email: flintsch@vt.edu

[4] Director, Road Pavements Laboratory, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal

[5] Senior Research Scientist, Virginia Center for Transportation Innovation and Research, Virginia Department of Transportation, 530 Edgemont Road, Charlottesville, VA 22903, Email: brian.diefenderfer@vdot.virginia.gov

4.1. Abstract

The application of in-place recycling techniques has emerged as a practical and effective way to enhance the sustainability of agency pavement management decisions for asphalt-surfaced pavements. However, the potential environmental benefits resulting from applying in-place recycling techniques have not been fully documented in the literature. This paper presents a comprehensive pavement life cycle assessment (LCA) model that extends the typical pavement LCA's system boundaries to include the environmental impacts resulting from the usage phase and the production of the energy sources. The results of the application of the pavement LCA model to a specific highway rehabilitation project in the state of Virginia showed that in-place recycling practices and an effective control of the pavement roughness can improve significantly the life cycle environmental performance of a pavement system.

4.2. Introduction

The United States' National Highway System (NHS) includes over 264000 km of highways (Federal Highway Administration [FHWA], 2011). With the majority of highway construction complete since the 1980's, a large part of the national highway system is reaching the end of its design life. Recently, the American Society of Civil Engineers report card (American Society of Civil Engineering [ASCE], 2013)

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[4] This paper has been submitted to the journal Structure and Infrastructure Engineering. Permission for Reproduction can be found in Appendix F.

evaluated the United States' roads, and assigned it a grade of D, partly as a result of the fact that 32% of the major roads are in poor or mediocre conditions. The report card estimates that traveling on deficient pavements cost US motorists approximately $67 billion a year, or $324 per motorist.

In an effort to address poor pavements condition, agencies have adopted different maintenance and rehabilitation (M&R) approaches. However, M&R of such an extensive road network consumes a significant amount of natural resources, mainly aggregates and bitumen. For example, the United States Geological Survey (USGS) reported that 460 million tonnes of crushed aggregate were used in 2011, mostly in the construction, maintenance and rehabilitation of the US pavement network (United States Geologic Services [USGS], 2013). Furthermore, approximately 23.4 million tonnes of paving bitumen was produced in 2008, according to Freedonia Group (2009). This pattern of consumption of natural resources does not appear to be sustainable and there has been growing societal concern about the environmental effects of constructing, operating and maintaining the highway infrastructure network. In an attempt to mitigate the adverse environmental impacts, transportation authorities are seeking more sustainable pavement technologies and strategies.

Some common practices highlighted by the literature to increase the environmental performance of the road projects include the usage of asphalt mixes requiring lower manufacturing temperatures (Rubio et al., 2013), and the incorporation of recycled materials and byproducts (Jullien et al., 2006; Chiu et al., 2008; Huang et al., 2007; Huang et al., 2009; Sayagha et al., 2010). In particular, in-place pavement recycling reduces the need for virgin materials and reuses materials that would be otherwise hauled away and stockpiled or landfilled. While the true environmental benefit resulting from applying some of the aforementioned measures appears to be dependent on the system boundaries considered in the analysis (Tatari et al., 2012; Vidal et al., 2013), some recycling practices have been proven to enhance the life cycle environmental performance of pavements. One example is the application of in-place pavement recycling techniques to rehabilitate distressed pavements (Thenoux et al., 2007).

A life cycle assessment (LCA) is the tool that is generally used to account for a systems environmental performance. The results of an LCA can provide beneficial information to an agency that is in charge of managing infrastructure; for example, it can help determine which processes and maintenance techniques produce the highest and lowest environmental burdens. An important consideration for LCA is the boundaries chosen for the analysis. Ideally, an LCA is a cradle to grave analysis that accounts for the entire life cycle of the materials, including all the processes involved with the system, as well as other processes impacted by the system. However, a lack of information and an inability to accurately predict certain parameters, such as material life and the impact of the system condition on the user, sometimes lead to a constraint on the system boundaries for a pavement LCA. Thus, in the case of pavements, most LCA have excluded the use phase of the project (Park et al., 2003; Zapata and Gambatese, 2005; Huang et al., 2009).

Recently, research has produced more reliable models to quantify the impact of the pavement condition on vehicle fuel consumption and emissions (Karlsson et al., 2012; Chatti and Zaabar, 2012), which facilitates the inclusion of the use phase into a pavement LCA. By including the usage phase in the pavement LCA, the environmental footprint associated with the application of in-place pavement recycling techniques can be analyzed more thoroughly than in the previous LCA studies analyzing the environmental performance of this pavement M&R alternative (Thenoux et al., 2007; Miliutenko et al., 2013).

4.3. OBJECTIVE

This paper presents the results of a pavement LCA conducted for an in-place pavement recycling rehabilitation project in the state of Virginia. It also illustrates the development of a comprehensive pavement LCA model that includes the usage phase into the system boundaries and accounts for the upstream impacts in the production and transportation of the energy sources. The project under consideration incorporated several in-place pavement recycling techniques and a unique traffic management approach. The results for the recycling-based project are compared to two other pavement management alternatives: (1) a traditional pavement reconstruction, and (2) a corrective maintenance approach. The three alternatives are summarized in Table 4-1. The reason for including more future actions in the corrective maintenance strategy will be discussed more thoroughly in a later section of this paper.

Table 4-1 - Summary of the M&R Strategies

M&R Strategy	Initial M&R Activity	Future M&R Activities
Recycling-Based	Left Lane: Cold in place recycling method to mill, refine and replace the top 18 cm (7 inches) of pavement. Right Lane: A combination of full depth reclamation and cold central plant recycling to treat 55 cm (22 inches) in depth. Both lanes received a HMA riding surface.	Maintenance actions performed in years 12, 22, 32 and 44 (Detailed in Table 4-2)
Traditional Reconstruction	Left Lane: Mill and replace the top 18 cm (7 inches) of pavement. Right Lane: Mill and replace full depth of existing pavement and apply a cement treatment to the base/subgrade. Apply an HMA riding surface to both lanes.	Maintenance actions performed in years 12, 22, 32 and 44 (Detailed in Table 4-3)
Corrective Maintenance	Both Lanes: 5 percent full depth patching followed by a 10 cm (4 inch) mill and overlay.	Maintenance actions performed in years 4, 10, 14, 18, 24, 28, 34, 38, 44 and 48 (Detailed in Table 4-4)

Note: Throughout this document the pavement M&R strategies are named “M&R Strategies”, whereas the individual activities that integrate each M&R strategy are named “M&R Activities”

4.4. METHODOLOGY

A comprehensive pavement LCA model was developed to calculate and compare the life-cycle environmental impacts and energy consumption of multiple maintenance and rehabilitation (M&R) activities applied in a road pavement section. The LCA was performed taking into account the guidelines provided by International Standard Organization (ISO, 2006a, 2006b) and the University of California Pavement Research Center (UCPRC) Pavement LCA Guideline (Harvey et al., 2010). Field data for the case study were provided by the Virginia Department of Transportation (VDOT) (Diefenderfer et al., 2012).

In the cases where no field data were available from VDOT, data were gathered from LCA inventories and relevant literature.

In order to automatically compute the environmental burdens assigned to the case study, the framework of the LCA model was implemented in a software written in Visual Basic .NET (VB.NET) and SQL programming languages (Santos et al., 2014a; 2014b), the latter being used for managing the data introduced and held in the system.

4.4.1. GOAL and Scope Definition

The paper presents the results from an extensive LCA conducted for three M&R strategies applied on a pavement segment. The first step consisted of developing a comprehensive pavement LCA model to estimate the environmental burdens related to the entire life cycle of the pavement section. The application of the pavement LCA model to the case study presented in this paper allowed for the following actions:

(1) Estimation of the potential environmental advantages resulting from applying in-place pavement recycling techniques against two traditional M&R methods;
(2) Demonstration of a methodology that facilitates the inclusion of environmental loads assigned to the processes and pavement LCA phases typically excluded from the system boundaries of a pavement LCA; and
(3) Identification of the most important processes, and consequently pavement life cycle phases, in driving the environmental load of a road pavement section throughout its life cycle.

These results will provide state and local agencies with quantitative evidence to support the adoption of more environmentally sound pavement management processes.

4.4.2. Functional unit

The specific project chosen for achieving the aforementioned objectives is a 5.95 km long, 2 lane asphalt section of Interstate 81 near Staunton Virginia. The project analysis period (PAP) is 50 years, beginning in 2011 with the in-place pavement recycling project that rehabilitated the existing pavement structure. The annual average daily traffic (AADT) for the first year was obtained from the VDOT traffic website[5] and consisted of approximately 25,000 directional vehicles with 28% trucks (85% of the truck traffic consisted of five- and six-axle tractor trailer combination vehicles). The traffic growth rate was assumed as 3%, and was calculated as compounding growth.

4.4.2.1. Pre-M&R conditions

Prior to the initial rehabilitation, the distresses along the pavement included cracking that extended through the full pavement depth in the right lane, and extensive rutting and patching throughout both lanes. The left lane was determined to be in better condition than the right lane, such that it was decided to design separate treatments for each lane. The overall structure of the pavement was evaluated, and deflection testing was used to determine that the structure of the pavement was in poor condition to the depth of the subgrade in the right lane. Thus, it was determined that a full reconstruction was needed for the right lane, and a heavy rehabilitation for the left lane. The project included two different construction methods, and further details about the project can be found in Diefenderfer et al. (2012). The left lane used a cold in place recycling

[5] Source: http://www.virginiadot.org/info/ct-trafficcounts.asp, Accessed on 1 August, 2013

(CIR) method to mill, refine, and replace the top layers of the pavement. The CIR was performed using one machine on the site. The reconstruction of the right lane consisted of a combination of cold central plant recycling (CCPR) and full depth reclamation (FDR) to extend to the subgrade.

4.4.2.2. M&R scenarios

This study compared the three maintenance alternatives presented in Table 4-1. Details on the actions performed in each M&R strategy, as well as the respective schedule for future M&R actions are presented in Tables 4-2, 4-3 and 4-4. For the recycling-based and traditional reconstruction M&R strategies, the expected M&R activities and respective M&R actions outlined by VDOT were followed (VDOT 2011). For the corrective M&R scenario, past performance and construction history indicates that a 5 cm mill and inlay would be required every four to six years, along with partial depth patching. This was verified by using deflection data obtained prior to the rehabilitation of the road to calculate the Modified Structural Index (MSI) of the pavement, and using it as a predictor of future performance as outlined in Bryce et al. (2013). The MSI of the pavement section was 0.78, which indicates a considerably weak structural condition and that the deterioration of the condition should occur much more rapidly than a pavement with adequate structure (i.e., a pavement with an MSI of 1) (Bryce et al., 2013). The predicted deterioration curve along with past condition data (in terms of the Critical Condition Index (CCI)), is shown in Figure 4-1a.

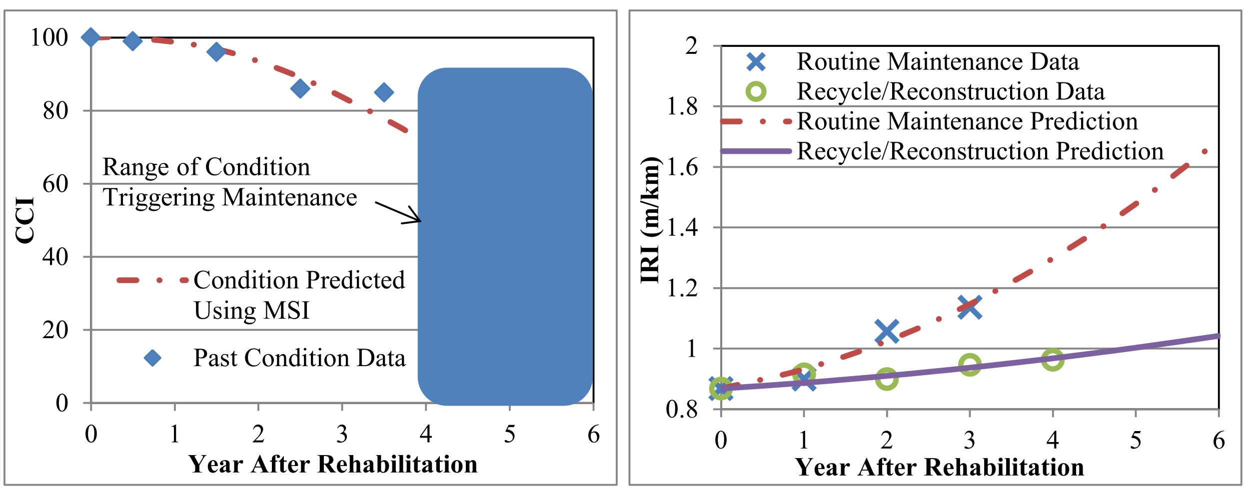

Figure 4-1 - (a) Predicted deterioration for the rehabilitation M&R strategy, and (b) predicted roughness for each M&R strategy

In order to determine the roughness of the pavement as a function of time for the corrective M&R strategy, past International Roughness Index (IRI) data for the pavement section was plotted and a function in the form of equation (4-1) was fitted to the data.

$$IRI(t) = at^2 + bt + c \quad (4\text{-}1)$$

Where *IRI(t)* is the IRI value in year *t, c* is the IRI value after M&R is performed and *a* and *b* are parameters that were found by minimizing the sum of square errors between the fitted function and the measured data.

The values of the aforementioned parameters are presented in Table 4-5. A similar procedure was conducted for the cases of the recycling-based and traditional reconstruction M&R strategies; however, in those M&R strategies data from an adjacent pavement section that was rehabilitated in 2005 was used. The reason for using data from the adjacent pavement section was the lack of long term IRI measurements for the pavement section under investigation. Furthermore, the adjacent pavement section had an MSI value of 1.3 (structurally adequate) and was expected to be subjected to similar environmental and traffic loading as the pavement section under investigation. The values of the parameters are presented in Table 4-5. The functions and measured data are shown in Figure 4-1b.

Table 4-2 - Features of the M&R actions included in the recycling-based M&R strategy

M&R activity	M&R actions	Thickness (cm)	Schedule (year)
Recycling-based reconstruction	Right lane: mill asphalt layers	25	0
	Right lane: FDR using calciment as the stabilizing agent	30	
	Right lane: CCPR using hydraulic cement and foamed asphalt as the stabilizing agents	15	
	Right lane: tack coat application	-	
	Right lane: overlay AC	10	
	Right lane: tack coat application	-	
	Right lane: overlay SMA	5	
	Left lane: mill	5	
	Left lane: CIR using hydraulic cement and foamed asphalt as the stabilizing agents	13	
	Left lane: tack coat application	-	
	Left lane: overlay AC	5	
	Left lane: tack coat application	-	
	Left lane: overlay SMA	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	12
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	22
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	41	32
	Right and left lanes: mill SM and IM layers	10	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	41	44
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	

Table 4-3 - Features of the M&R actions included in the traditional reconstruction M&R strategy

M&R activity	M&R actions	Thickness (cm)	Schedule (year)
Reconstruction	Right lane and outside shoulder: Mill	32	0
	Right lane and outside shoulder: undercut the existing base/subgrade	46	
	Right lane and outside shoulder: lay geotextile fabric	-	
	Right lane and outside shoulder: lay Open Graded Base (OGB)	30	
	Right lane and outside shoulder: lay 21B aggregate material	15	
	Right lane and outside shoulder: lay BM - 25.0D	25	
	Left lane and inside shoulder: mill	18	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lanes, and shoulders: lay IM-19.0D	5	
	Right and left lanes, and inside shoulder: tack coat application	-	
	Right and left lanes, and inside shoulder: resurface SMA- 12.5	5	
	Outside shoulder: tack coat application	-	
	Outside shoulder: overlay with SM-12.5A	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	12
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	22
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	41	32
	Right and left lanes: mill SM and IM layers	10	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	41	44
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	

Table 4-4 - Features of the M&R actions included in the corrective M&R strategy

M&R activity	M&R actions	Thickness (cm)	Schedule (year)
Major rehabilitation	Right and left lines: pre-overlay full-depth patching 5%	51	0
	Right and left lines: mill SM and IM layers	10	
	Right and left lines: replace AC IM	5	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lines, and shoulders - overlay AC wearing course	5	
Functional mill and replace	Right and left lines: pre-overlay full-depth patching 1%	36[a]	4, 18, 34, 38, 48
	Right and left lines: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lines: replace AC wearing course	5	
Functional mill and replace	Right and left lines: pre-overlay full-depth patching 1%	36	10, 24
	Right and left lines: mill	10	
	Right and left lanes: tack coat application	-	
	Right and left lines: replace AC IM course	5	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lines, and shoulders - overlay AC wearing course	5	
Major rehabilitation	Right and left lines: pre-overlay full-depth patching 5%	41[b]	14, 28, 44
	Right and left lines: mill SM and IM layers	10	
	Right and left lanes: tack coat application	-	
	Right and left lines: replace AC IM	5	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lines, and shoulders - overlay AC wearing course	5	

[a] Whenever the "pre-overlay full-depth patching 1%" M&R action is applied, its thickness increases 5 cm relatively to the previous application. An exception to this rule occurs in the case of the first type of "Functional mill and replace" M&R activity. The "Right and left lines: pre-overlay full-depth patching 1%" M&R action scheduled at years 34 and 38 have the same thickness (46 cm).

[b] Whenever the "pre-overlay full-depth patching 5%" M&R action is applied, its thickness increases 5 cm relatively to the previous application

Table 4-5 - Parameter Values of Equation 4-1

M&R strategy	Parameters		
	a	b	c
Recycling-based	0.002	0.017	0.868
Traditional Reconstruction	0.002	0.017	0.868
Corrective Maintenance	0.015	0.05	0.868

4.4.3. System boundaries, system processes and life cycle inventory data

The life cycle of a road pavement is generally divided into five phases (Harvey et al., 2010): materials extraction and production; construction; M&R; usage and end-of-life (EOL). However, in the proposed model, the environmental impacts associated with the on-road vehicles when subject to a work-zone (WZ) traffic management plan (implemented during the reconstruction and M&R activities) are treated as an individual phase and designated as WZ traffic management phase. The WZ traffic management phase was separated out in order to highlight the influence of the WZ on the environmental performance when compared to normal traffic flow. Transportation of materials and asphalt mixtures between facilities and work site, and vice-versa, was also analyzed separately. Therefore, the proposed pavement LCA model entails six pavement life cycle phases: (1) materials extraction and production; (2) construction and M&R; (3) transportation of materials; (4) WZ traffic management; (5) usage and (6) EOL. The various models evoked while modeling each pavement LCA phase, as well as the data required to run those models, are introduced and discussed in the following sections.

4.4.3.1. Materials extraction and production phase

Pavement-related environmental burdens assigned to this phase are due to material acquisition and processing. This includes all materials manufacturing processes, from extraction of raw materials to their transformation into a pavement input material (material extraction sub-phase), and ending up with the mixture production at a mixing plant (materials production sub-phase). The manufacturing of the facilities, such as the construction of the mixture production plants, is excluded from the system boundaries. All environmental burdens stemming from transportation between facilities (e.g., transporting aggregates from the quarry to the mixture production plant) are assigned to the materials extraction and production phase. The life cycle inventory (LCI) of the materials and mixtures used in this case study was collected from several published LCI and LCA reports.

Inventory data for both fine and coarse natural aggregate was taken from Stripple (2001). The LCI's for the bitumen, which in this case study was used either as binder in asphalt mixtures or as stabilizing agent, were obtained from Eurobitumen (2011). The LCI for the hydraulic cement used as an active filler was obtained by adapting Marceau et al.'s (2006) LCI corresponding to the hydraulic cement production through the precalciner process. The LCI of calciment (the stabilizing agent used during the FDR portion), a combination of hydraulic cement (70%) and lime kiln dust (30%), was determined by multiplying by a factor of 0.7 the hydraulic cements LCI. No environmental load was assigned to the lime kiln dust given that it is an existing by-product of another manufacturing process.

To estimate the LCI associated with the asphalt mixtures production at a mixing plant, data on the average fuel consumption per tonne of asphalt mixture produced and the emissions factors published by the AP-42 study of HMA plants (United States Environmental Protection Agency [US EPA], 2004) for a drum mixing plant powered by natural gas were adopted. The environmental burdens from CCPR process are accounted by the construction and M&R phase, since they are produced by a mobile plant which is classified as construction equipment.

4.4.3.2. Transportation phase

The environmental impacts resulting from the materials and mixture transportation are due to the combustion process emissions released by the transportation vehicles. All materials and mixtures were assumed to be hauled by heavy-duty vehicles (HDVs), and the US EPA Motor Vehicle Emissions Simulator (MOVES) (US EPA 2010a) was used to determine the average fuel consumption and airborne emissions factors for operating diesel powered, single unit short-haul trucks and long haul combination trucks. These factors were computed for the typical climate conditions during the month of April for Augusta County in Virginia. The payload capacity of both HDV types was assumed to be equal to 20 tonnes. The transportation distances considered for each material and mixture used in this case study are shown in Table 4-6. Outside of the system boundaries of this model are the air emissions associated with the production and maintenance of the hauling HDVs, as well as the transportation of the construction equipment from the construction company's facilities to the work-site.

Table 4-6 - Features of the movements of transportation of materials

Material/ mixture	One-way trip distance (km)
Milled asphalt material (prior to FDR)	1.9
Milled asphalt material (prior to CIR)	25
Removed granular material (Subgrade)	25
CCRP material	1.9
Hydraulic Cement and Calciment	346
Tap Water	20
Crushed and Fine Aggregates	0.6
Binder and Bitumen Emulsion	125
OGB 25.0 Asphalt Pavement Mix	25
21B aggregate material	25
Asphalt Mixes (to site)	25

4.4.3.3. Construction and M&R phase

The construction and M&R related environmental burdens were obtained by applying the methodology adopted by the US EPA's NONROAD 2008 model (US EPA, 2010b). Pollutants covered by this methodology include hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM), carbon dioxide (CO2) and sulfur dioxide (SO2). Fuel consumption is accounted for on the basis of the brake specific fuel consumption (BSFC) indicator. The calculation of N_2O and CH_4 emissions used the US EPA's guide on calculating GHG emissions from mobile sources (US EPA, 2008). Information regarding the type and features (brand, model, engine horsepower, etc.) of each equipment used to perform the several M&R activities, as well as their respective production rates were taken from Diefenderfer et al. (2012) and complemented with technical specifications from the equipment's manufacturers. Future M&R activities are assumed to take place during the month of April, as was the reconstruction and rehabilitation performed in the beginning of the PAP of each M&R scenario. The same production rates of construction equipment were assumed for the remaining M&R activities.

4.4.3.4. WZ traffic management phase

The WZ traffic management includes aspects for two routes: the single lane of I-81 to remain open during the work, and the detour road. As discussed in Diefenderfer et al. (2012), this project included an innovative traffic management technique that consisted of detouring cars from the road onto a parallel route, while trucks were allowed to remain on I-81 during construction. In this pavement LCA model, the fuel consumption and airborne emissions assigned to on-road vehicles during the WZ traffic management plan have been determined by adopting a two-step method. First, the US EPA's MOVES model was run multiple times to compute a set of fuel consumption and emissions factors representing the national scale vehicle fleet characteristics per type of vehicle, and Augusta county's average climatic conditions during the month of April in three distinct years of the PAP (2011, 2035 and 2050). For years between 2011 and 2050, the emissions factors were interpolated according to a Lagrangian interpolation function. The emission factors for the year 2050 were applied to analysis years beyond 2050. Each model run generated an output file displaying the emissions factors on an hourly basis as a function of sixteen speed ranges, called speed bins, and two types of road categorized as rural restricted access and rural unrestricted access. The former category is assumed to represent the operating conditions existing in I-81, whereas the latter fits the features of the detour road (Virginia Route 11).

Secondly, changes in driving patterns were modelled using the capacity and delay models proposed by the Highway Capacity Manual 2000 (Transportation Research Board [TRB], 2000) to determine several outputs, such as the number of vehicles that traversed the WZ, the average queue length, the average queue speed in each hour, etc. Each section where there is a change in driving pattern was considered to be a new road "link." The characteristics of each link (length, number of vehicles and average speed) was combined with the MOVES fuel consumption and emissions factors previously computed and stored in look up tables to derive the environmental load of a WZ day. Finally, the marginal fuel consumption and airborne emissions due to the WZ traffic management plan were calculated by subtracting fuel consumption and airborne emissions released during a WZ period from the results of an equivalent non-WZ period.

4.4.3.5. Usage phase

The usage phase addresses the pavement's environmental burden resulting from the interaction of the pavement with the vehicles and environment throughout its PAP. The following are factors that have been identified in past research as pertinent to consider during the use phase of the pavement (Santero et al., 2011; Sandberg et al., 2011; Chatti and Zaabar, 2012); Tire – Pavement Interaction, Traffic Flow, Albedo, Leachate and Runoff, Carbonation and Lighting. However, many of these factors (e.g., Albedo, Carbonation and Lighting) do not directly apply to the project currently under evaluation. Thus, the main contribution that was considered from the usage phase in this analysis is the tire-pavement interaction. Tire-pavement interaction influences vehicle rolling resistance, and is impacted by several variables such as macro-texture, pavement stiffness, roughness and the transversal slope of the pavement. Given that this study compared several maintenance plans using the same surface materials, the only factor that was considered in the usage phase is the impact of the pavement roughness on the pavements overall environmental burden.

In order to determine the impact of the pavement roughness on vehicle fuel consumption and emissions, the Vehicle Operating Cost (VOC) developed by Chatti and Zaabar (2012) was combined with data from the EPA's MOVES model. The approach proposed in this paper differs from other proposed approaches (e.g., Wang et al., 2012) in that the impact of increasing rolling resistance can be combined with the MOVES emissions rates models without the need to modify the vehicle specific power model within the MOVES program (which calculates emissions rates from vehicles travelling along a smooth surface). The first step in the proposed approach is to use the model given in Chatti and Zaabar (2012) to calculate the additional fuel consumption due to the vehicles travelling over the rough pavement surface when compared to the fuel consumption of the vehicles travelling over a smooth surface. Then, instead of using the actual AADT in the MOVES emissions rate model, an effective AADT was used to relate the increase in roughness to the increase in fuel consumption and emissions. The effective AADT ($AADT_E$) for a given roughness at time t, in terms of the International Roughness Index (IRI), was calculated using equation 4-2.

$$AADT_E(t) = AADT(t) * \frac{FC_{IRI(t)}}{FC_{Smooth}} \tag{4-2}$$

Where $FC_{IRI(t)}$ is the fuel consumption for the vehicle fleet travelling on a pavement with a specified IRI at time t, and FC_{Smooth} is the fuel consumption of the same vehicle fleet travelling along a typical smooth pavement.

4.4.3.6. End-of-life phase

When a road pavement reaches its service life, it can be given two main fates: (1) remain in place serving as support for a new pavement structure; and (2) be removed. Removed pavements materials are: (1) disposed in a landfill (generally a very small percentage in the US); or (2) recycled and re-used either as a replacement for virgin aggregate base or as a replacement for virgin asphalt and aggregate in new HMA. It is expected that the most likely EOL scenario for the pavements in this analysis is that they remain in place after reaching the end of the PAP, serving as foundation for the new pavement structure. Thus, no environmental impacts were assigned to the EOL phase of all M&R scenarios in comparison.

4.4.4. Energy source production

Energy source production refers to the impact of producing the energy that is used to power the various equipment and processes that are required for the project (e.g., the production of the fuel to power the transportation of the materials). Although it is not considered a pavement life cycle phase, as those previously introduced, the energy sources production and transportation is an unavoidable process that is common to all pavement life cycle phases. For this reason their life cycle impacts should be considered and displayed separately from the impacts due to the process energy consumption. Presenting the impacts from the energy sources production facilitates the understanding of where in the pavement life cycle the use of less environmentally burdensome energy sources may help reduce the environmental load of a road pavement. Therefore, before inclusion in the database, the LCI of each material and mixture was disaggregated to the processes level in order to distinguish the LCI due to the pre-combustion energy, from that due to the process energy combustion in the final destination. In this case study, the GREET model (Argonne National Laboratory, 2013) was used as the source of the LCI for the production and transportation of energy sources. For all energy sources except electricity, the GREET model default data was used. In the case of the electricity, a default electricity mix was modified to reflect the electricity production in the state of Virginia (United States Energy Information Administration [US EIA], 2012).

4.5. LIFE CYCLE INVENTORY

The LCI corresponding to the case study was performed for each life cycle phase of each pavement M&R strategy using the models and data sources presented in the previous sections. The inventory analysis was used to determine, both qualitatively and quantitatively, the materials, the energy flows and the atmospheric emissions associated with each individual process within the system under analysis. The outputs from those unit processes were posteriorly combined in order to derive the total environmental burden of the system. Table 4-7 provides the overall LCI per pavement life cycle phase of each pavement M&R strategy, expressed in terms of atmospheric emissions.

Table 4-7 - LCI per pavement life cycle phase of each M&R strategy

M&R Strategy	Life cycle phase	Sub component	CO_2 (Kg)	CH_4 (Kg)	N_2O (Kg)	SO_2 (Kg)	NO_x (Kg)	NH_3 (Kg)	CO (Kg)	VOC (Kg)	NMVOC (Kg)	$PM_{2.5}$ (Kg)	Pb (Kg)
Recycling-based	Materials	P.E:	1.33E+06	4.09E+02	4.35E+00	5.92E+02	2.13E+03	2.94E-01	1.23E+04	5.50E+02	6.16E+01	3.41E+02	2.70E-02
		P.C.E.	5.92E+05	1.18E+04	7.80E+02	1.53E+03	1.28E+03	0.00E+00	3.04E+02	1.48E+02	0.00E+00	2.01E+02	0.00E+00
	Construction and M&R	P.E:	1.38E+05	7.80E+00	3.47E+00	1.05E+02	8.16E+02	0.00E+00	5.55E+02	0.00E+00	0.00E+00	4.87E+01	0.00E+00
		P.C.E.	2.87E+04	2.50E+02	3.87E-01	4.48E+01	8.11E+01	0.00E+00	2.07E+01	1.43E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation	P.E:	1.81E+05	6.36E+00	3.27E-01	1.23E+00	4.92E+02	3.41E+00	1.52E+02	3.19E+01	2.69E+01	1.83E+01	0.00E+00
		P.C.E.	3.82E+04	3.33E+02	5.16E-01	5.98E+01	1.08E+02	0.00E+00	2.77E+01	1.90E+01	0.00E+00	0.00E+00	0.00E+00
	WZ Traffic Management	P.E:	3.48E+06	2.29E+02	3.60E+01	4.69E+01	3.15E+03	2.11E+02	1.51E+04	7.69E+02	5.40E+02	1.82E+02	0.00E+00
		P.C.E.	7.45E+05	6.50E+03	1.01E+01	1.17E+03	2.12E+03	0.00E+00	5.38E+02	9.81E+02	0.00E+00	1.27E+02	0.00E+00
	Usage	P.E:	1.12E+08	2.33E+03	2.46E+02	1.54E+03	1.39E+05	2.91E+04	1.09E+05	0.00E+00	6.39E+03	7.12E+05	0.00E+00
		P.C.E.	3.00E+07	2.61E+05	4.04E+02	4.71E+04	8.50E+04	0.00E+00	2.17E+04	3.11E+04	0.00E+00	3.36E+03	0.00E+00
	Total		**1.48E+08**	**2.83E+05**	**1.48E+03**	**5.22E+04**	**2.34E+05**	**2.93E+04**	**1.60E+05**	**3.36E+04**	**7.02E+03**	**7.16E+05**	**2.70E-02**
Traditional Reconstruction	Materials	P.E:	2.14E+06	7.91E+02	1.55E+01	1.47E+03	5.31E+03	4.03E-01	6.24E+03	1.89E+03	4.85E+01	2.68E+02	2.76E-02
		P.C.E.	1.12E+06	1.97E+04	1.40E+03	2.86E+03	2.34E+03	0.00E+00	5.50E+02	2.67E+02	0.00E+00	2.91E+02	0.00E+00
	Construction and M&R	P.E:	2.23E+05	1.26E+01	5.60E+00	2.76E+02	1.29E+03	0.00E+00	9.00E+02	0.00E+00	0.00E+00	4.91E+01	0.00E+00
		P.C.E.	4.62E+04	4.03E+02	6.24E-01	7.23E+01	1.31E+02	0.00E+00	3.35E+01	2.30E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation	P.E:	5.57E+05	1.79E+01	1.07E+00	3.78E+00	2.11E+03	1.11E+01	6.91E+02	1.75E+02	1.60E+02	8.13E+01	0.00E+00
		P.C.E.	1.17E+05	1.02E+03	1.58E+00	1.84E+02	3.32E+02	0.00E+00	8.49E+01	5.84E+01	0.00E+00	0.00E+00	0.00E+00
	WZ Traffic Management	P.E:	3.76E+06	2.41E+02	4.08E+01	5.31E+01	3.43E+03	2.45E+02	1.85E+04	9.84E+02	7.43E+02	2.21E+02	0.00E+00
		P.C.E.	8.04E+05	7.02E+03	1.09E+01	1.27E+03	2.28E+03	0.00E+00	5.81E+02	1.10E+03	0.00E+00	1.44E+02	0.00E+00
	Usage	P.E:	1.12E+08	2.33E+03	2.46E+02	1.54E+03	1.39E+05	2.91E+04	1.09E+05	0.00E+00	6.39E+03	7.12E+05	0.00E+00
		P.C.E.	3.00E+07	2.61E+05	4.04E+02	4.71E+04	8.50E+04	0.00E+00	2.17E+04	3.11E+04	0.00E+00	3.36E+03	0.00E+00
	Total		**1.51E+08**	**2.93E+05**	**2.12E+03**	**5.48E+04**	**2.42E+05**	**2.94E+04**	**1.58E+05**	**3.56E+04**	**7.34E+03**	**7.16E+05**	**2.76E-02**
Corrective Maintenance	Materials	P.E:	2.00E+06	9.06E+02	5.81E+00	7.51E+02	3.41E+03	4.99E-01	7.08E+03	2.17E+03	4.79E+01	3.10E+02	3.21E-02
		P.C.E.	1.03E+06	2.13E+04	1.37E+03	2.69E+03	2.21E+03	0.00E+00	5.29E+02	2.64E+02	0.00E+00	2.79E+02	0.00E+00
	Construction and M&R	P.E:	2.06E+05	1.16E+01	5.16E+00	5.65E+01	1.23E+03	0.00E+00	9.08E+02	0.00E+00	0.00E+00	1.01E+02	0.00E+00
		P.C.E.	4.27E+04	3.72E+02	5.76E-01	6.68E+01	1.21E+02	0.00E+00	3.09E+01	2.12E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation	P.E:	4.46E+05	1.78E+01	8.54E-01	3.02E+00	8.76E+02	8.84E+00	2.93E+02	6.26E+01	4.78E+01	2.86E+01	0.00E+00
		P.C.E.	9.39E+04	8.19E+02	1.27E+00	1.47E+02	2.66E+02	0.00E+00	6.80E+01	4.67E+01	0.00E+00	0.00E+00	0.00E+00
	WZ Traffic Management	P.E:	7.26E+06	4.83E+02	7.18E+01	9.10E+01	7.48E+03	3.91E+02	2.59E+04	1.36E+03	8.74E+02	3.67E+02	0.00E+00
		P.C.E.	1.55E+06	1.35E+04	2.09E+01	2.44E+03	4.40E+03	0.00E+00	1.12E+03	1.93E+03	0.00E+00	2.41E+02	0.00E+00
	Usage	P.E:	1.54E+08	3.29E+03	3.42E+02	2.16E+03	1.89E+05	4.04E+04	1.47E+05	0.00E+00	9.01E+03	1.00E+06	0.00E+00
		P.C.E.	4.22E+07	3.68E+05	5.69E+02	6.63E+04	1.20E+05	0.00E+00	3.05E+04	4.40E+04	0.00E+00	4.77E+03	0.00E+00
	Total		**2.09E+08**	**4.09E+05**	**2.38E+03**	**7.47E+04**	**3.28E+05**	**4.08E+04**	**2.13E+05**	**4.98E+04**	**9.98E+03**	**1.01E+06**	**3.21E-02**

Acronyms: P.E. - Process Energy; P.C.E. - Pre-Combustion Energy.

4.6. LIFE CYCLE IMPACT ASSESSMENT

The purpose of the life cycle impact assessment (LCIA) is to assign the LCI results to different impact categories based on the potential effects that the several pollutants have on the environment. According to the type of pollutants inventoried and the impact categories commonly recognized as the most representative of the three protection areas (human health, natural environment and natural resources), the following categories were selected: climate change (CC); acidification (AC); eutrophication (EU); human health criteria air pollutants (HH); photochemical smog (PS) and abiotic resource depletion (ARD). The US-based impact assessment tool, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.0 (TRACI 2.0), was chosen as the main methodology to conduct the impact assessment step of the LCA. The reader is referred to Bare (2011) for a more detailed discussion of TRACI 2.0. The characterization models and associated characterization factors from TRACI 2.0 were applied to quantify the contribution of each LCI element to the acidification, eutrophication, human health criteria air pollutants and photochemical smog impact category. The time-adjusted characterization model for the CC impact category that was proposed by Kendall (2012) was used in this approach as opposed to the traditional time-steady International Panel on Climate Change (IPCC) model. The April 2013 updated version of the CML-IA's characterisation factors (Guinée, 2002) was used to determine the impact assessment for ARD of mineral resources and fossil fuels. Furthermore, an energy analysis was carried out based on the cumulative energy demand (CED) indicators, expressed as fossil (CED F), nuclear (CED Nuc.) and renewable resources (CED R). This indicator was computed according to Hischier et al. (2010) but adopting the upper heating values (UHVs) defined in the GREET model.

Lastly, according to ISO 14044, normalization, grouping, and weighting steps in LCA are optional. While they might be useful in translating the impact scores of different impact categories into a more understandable and somehow digestible form (Dahlbo et al., 2013), they also entail a risk of oversimplifying the results. Therefore, in the pavement LCA model application reported in this paper the normalization, grouping and weighting steps were not included.

4.7. LIFE CYCLE IMPACT ASSESSMENT RESULTS AND DISCUSSION

The potential life cycle impacts for each pavement M&R strategy are shown in Table 4-8. Figure 4-2 shows the relative contribution of each life cycle phase for each impact category. As can be seen from Figure 4-2, the usage phase is by far the phase of the life cycle with the greatest impact in almost all the impact categories. Its contribution ranges between 90% (CC in corrective M&R strategy) and 96% (EU in recycling-based M&R strategy) depending on the impact category and the M&R strategy under analysis. Those results agree well with the literature that have accounted for the effects of this phase on the environmental performance of a pavement structure (Wang et al., 2012; Yu and Lu, 2012; Loijos et al., 2013). However, it should be noted that the impact from the usage phase could potentially be greater if the traffic carried by the section of interstate throughout the PAP was not constrained by the road capacity, since the possibility of increasing the road capacity by adding new lanes to existing ones was not considered. The exception to the dominance of the usage phase when evaluating the ARD MR, because this indicator is dominated by the use of raw materials. This outcome can be explained by the fact the mineral resources consumed during the pre-combustion energy-related processes are not tracked by the GREET model. Consequently, all the mineral resources accounted for the ARD MR are exclusively those existing in the aggregates and cement-based materials consumed during the M&R activities.

Table 4-8 - Total life cycle environmental impacts per pavement life cycle phase of each M&R strategy

M&R Strategy	Life cycle phase	CC (tonnes CO_2-eq.)	AC (H^+ moles eq.)	EU (Kg N eq.)	HH (Kg $PM_{2.5}$ eq.)	PS (g NO_x eq.)	ARD MR (Kg Sb- eq.)	ARD FF (MJ- eq.)
Recycling-based	Materials	(-52%) 1 436	(-55%) 144 914	(-53%) 99	(-46%) 604	(-53%) 3 336	(-40%) 0. 0022727	(-49%) 31 631 566
	Construction and M&R	(61%) 729	(71%) 196 680	(40%) 155	(31%) 513	(39%) 3 593	0	(41%) 9 870 565
	Transportation	(-37%) 197	(-25%) 26 789	(-23%) 26	(24%) 57	(-23%) 630	0	(-42%) 2 796 061
	WZ Traffic Management	(-54%) 6 111	(-57%) 605 749	(-58%) 557	(-55%) 1 700	(-55%) 9 605	0	(-53%) 100 834 016
	Usage	(-28%) 112 926	(-27%) 19 912 635	(-27%) 19 467	(-28%) 44 745	(-27%) 267 081	0	(-29%) 2 321 530 245
	Total	**(-22%) 121 398**	**(-19%) 20 886 765**	**(-28%) 20 305**	**(-29%) 47 618**	**(-29%) 284 244**	**(-40%) 0. 0022727**	**(-31%) 2 466 662 453**
Traditional Reconstruction	Materials	(8%) 3 209	(-9%) 293 477	(-0.46%) 208	(-1%) 1 102	(-3%) 6 869	(8%) 0.0041290	(-10%) 56 252 998
	Construction and M&R	(-7%) 420	(-3%) 112 002	(-16%) 93	(-20%) 313	(-16%) 2 164	0	(-15%) 5 910 886
	Transportation	(99%) 620	(174%) 98 591	(193%) 100	(180%) 208	(195%) 2 417	0	(61%) 7 757 770
	WZ Traffic Management	(-51%) 6 551	(-72%) 396 568	(-54%) 602	(-51%) 1 847	(-51%) 10 461	0	(-49%) 106 993 480
	Usage	(-28%) 112 926	(-27%) 19 912 635	(-27%) 19 467	(-28%) 44 745	(-27%) 267 081	0	(-29%) 2 321 530 245
	Total	**(-21%) 123 727**	**(-19%) 20 813 273**	**(-28%) 20 471**	**(-28%) 48 213**	**(-28%) 288 991**	**(8%) 0.0041290**	**(-30%) 2 498 445 378**
Corrective Maintenance	Materials	2 982	323 871	209	1 118	7 094	0.0038097	62 375 100
	Construction and M&R	452	115 338	111	391	2 580	0	6 989 318
	Transportation	312	35 942	34	74	819	0	4 823 867
	WZ Traffic Management	13 292	1 409 130	1 310	3 766	21 529	0	221 728 627
	Usage	156 859	27 292 378	26 580	62 018	368 370	0	3 268 590 284
	Total	**173 898**	**29 176 659**	**28 245**	**67 368**	**400 392**	**0.0038097**	**3 564 507 198**

Acronyms: CC- climate change; AC- acidification; EU- eutrophication; HH- human health criteria air pollutants; PS- photochemical smog; ARD MR- abiotic resources depletion of mineral resources; ARD FF- abiotic resources depletion of fossil fuels; Sb- antimony.

Note 1: The potential environmental impacts in terms of CC were estimated for a 100-year time horizon.

Note 2: The numbers in brackets represent the reduction (negative values) or the increase (positive values) of the impact category indicator values with respect to the homologous phase of the corrective M&R strategy.

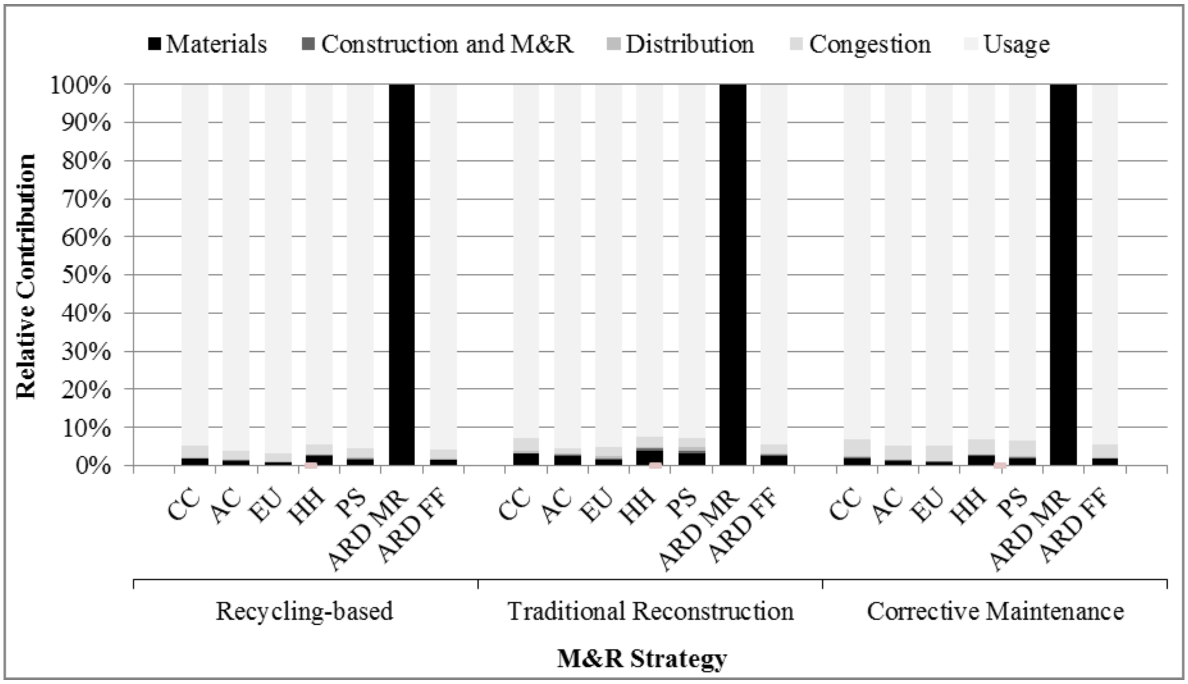

Figure 4-2 - Relative contributions to each impact category (percentage) per pavement life cycle phase of each M&R strategy. Impact category acronyms: CC- climate change; AC- acidification; EU- eutrophication; HH- human health criteria air pollutants; PS- photochemical smog; ARD MR- abiotic resources depletion of mineral resources; ARD FF- abiotic resources depletion of fossil fuels

Due to the relatively high influence of the usage phase on the overall environmental performance of the M&R strategies in comparison, it can be inferred that the M&R strategy with the worst environmental performance during the usage phase is simultaneously the least environmentally friendly overall. Therefore, it seems plausible to expect that the adoption of an M&R strategy that slows the deterioration rate of the pavement roughness would lead to valuable improvements in the life cycle environmental performance of a pavement system.

In response to the issues raised in the previous paragraph, this study demonstrated that by implementing a recycled-based M&R strategy, a reduction of approximately 30% in the overall life cycle impacts can be achieved relatively to those of a corrective M&R strategy. Moreover, in the case that only the materials and construction and M&R phases are considered in the LCA system boundaries, the recycling-based M&R strategy was still found to outperform the remaining M&R strategies in comparison.

Table 4-9 presents the feedstock, process and primary energy along with the CED Total corresponding to each M&R strategy, split up in fossil, nuclear and renewable resources. By definition, CED should account for the usage of any sort of energy, including direct and indirect energy, throughout the life cycle. That means that the feedstock energy of bitumen should also be included when accounting for CED. However, since the feedstock energy inherent to bitumen remains unexploited while used as a binder in a pavement, it was presented separately from the process and pre-combustion energy as recommended by the UCPRC Pavement LCA Guideline (Harvey et al., 2010).

Table 4-9 - Feedstock, process and primary energy and CED indicator values per pavement life cycle phase of each M&R strategy

M&R strategy	Life cycle Phase	Feedstock energy (MJ)	Process energy (MJ)	Primary energy (MJ)	CED F (MJ)	CED Nuc (MJ)	CED R (MJ)	CED Total (MJ)
Recycling-based	Materials	(-42%) 150 020 350	(-41%) 31 653 145	(-41%) 37 588 448	(-42%) 39 582 252	(-44%) 478 450	(-43%) 235 798	(-42%) 40 296 499
	Construction and M&R	0	(-33%) 1 854 509	(-33%) 2 226 086	(-33%) 2 374 473	(-33%) 3 974	(-33%) 2 487	(-33%) 2 380 933
	Transportation	0	(-59%) 2 473 366	(-59%) 2 968 939	(-59%) 3 166 843	(-59%) 5 300	(-59%) 3 316	(-59%) 3 175 460
	WZ Traffic Management	0	(-52%) 48 210 242	(-52%) 57 897 901	(-50%) 61 818 525	(-50%) 198 809	(-54%) 99 796	(-50%) 62 117 129
	Usage	0	(-29%) 1 938 650 938	(-29%) 2 327 831 483	(-29%) 2 484 626 344	(-29%) 4 157 553	(-29%) 2 601 593	(-29%) 2 491 385 490
	Total	**(-42%) 150 020 350**	**(-30%) 2 022 842 201**	**(-30%) 2 428 512 857**	**(-30%) 2 591 568 437**	**(-32%) 4 844 086**	**(-32%) 2 942 989**	**(-30%) 2 599 355 512**
Traditional Reconstruction	Materials	(-19%) 208 041 104	(-1%) 53 285 763	(-1%) 64 375 381	(-0.2%) 67 635 921	(6%) 901 930	(7%) 444 755	(-0.04%) 68 982 606
	Construction and M&R	0	(8%) 2 992 992	(8%) 3 592 680	(8%) 3 832 161	(8%) 6 414	(8%) 4 013	(8%) 3 842 588
	Transportation	0	(25%) 7 594 020	(25%) 9 115 587	(25%) 9 723 216	(25%) 16 273	(25%) 10 182	(25%) 9 749 672
	WZ Traffic Management	0	(-48%) 52 045 077	(-48%) 62 505 020	(-46%) 66 741 303	(-45%) 217 508	(-52%) 104 541	(-46%) 67 063 351
	Usage	0	(-29%) 1 938 650 938	(-29%) 2 327 831 483	(-29%) 2 484 626 344	(-29%) 4 157 553	(-29%) 2 601 593	(-29%) 2 491 385 490
	Total	**(-19%) 208 041 104**	**(-29%) 2 054 568 791**	**(-29%) 2 467 420 151**	**(-29%) 2 632 558 946**	**(-26%) 5 299 677**	**(-27%) 3 165 084**	**(-29%) 2 641 023 707**
Corrective Maintenance	Materials	257 799 624	53 857 196	63 930 785	67 741 997	847 904	417 166	69 007 067
	Construction and M&R	0	2 762 386	3 315 868	3 536 898	5 919	3 704	3 546 522
	Transportation	0	6 075 245	7 292 504	7 778 610	13 018	8 146	7 799 774
	WZ Traffic Management	0	100 376 784	120 542 044	123 082 069	397 567	217 687	123 697 322
	Usage	0	2 729 510 520	3 277 462 866	3 498 239 621	5 853 635	3 662 918	3 507 756 174
	Total	**257 799 624**	**2 892 582 130**	**3 472 544 067**	**3 700 379 196**	**7 118 043**	**4 309 621**	**3 711 806 860**

Acronyms: CED F- cumulative fossil energy demand; CED Nuc.- cumulative nuclear energy demand; CED R- cumulative renewable energy demand; CED Total- cumulative total energy demand.

Note 1: The feedstock energy, process energy and primary energy were computed through the GREET model's low heating values (LHV). The CED indicators values were computed through the GREET model's upper heating values (UHV).

Note 2: The numbers in brackets represent the reduction (negative values) or the increase (positive values) of the impact category indicator values with respect to the homologous phase of the corrective M&R strategy

Following the trend noticed for the remaining impact categories, the results presented in Table 4-9 show that the recycling-based M&R strategy is also the least harmful to the environment from the point of view of energy consumption. Overall, a reduction of about 32% in all the types of energy can be achieved as a result of implementing the recycling-based M&R strategy over the corrective maintenance one. Similar overall reductions might be obtained through the reconstruction M&R strategy, even though it denotes the most energy demanding transportation phase among the various strategies under assessment. This is because the reconstruction M&R activity requires the removal, and consequent transportation, of all the materials applied in the existing subgrade/base. The poor performance of the corrective M&R activity with respect to the CED indicator can be explained by the higher rate of change of IRI and pavement condition over the PAP, which requires vehicles to spend additional amounts of fuel to overcome the rolling resistance. Although less energy demanding than the usage phase, the WZ traffic management phase exhibit the second worst behavior, as a considerable amount of fuel is burned by the light vehicles while detouring the WZ.

When analyzing the relevance of each type of energy (fossil energy, nuclear energy and renewable energy) in the energy consumption, it can be seen that the nuclear and renewable energy sources are only consumed to power the pre-combustion energy-related processes. This fact explains the residual contributions of approximately 0.18% and 0.11% given by the CED Nuc. and CED R to the CED Total. The negligible role played by the nuclear and renewable energy sources can be seen as a mirror of a road transport mode, and particularly a road pavement construction and management sector, still excessively depending on the consumption of fossil fuels for energy sources. It is expected that the results would differ slightly if the introduction of alternative automotive fuels was taken into account in modeling the usage phase. However, there are both considerable uncertainties on how the rolling resistance effect would change the fuel consumption pattern of the vehicles propelled by alternative fuels, and the assumptions on the proliferation of alternative fuels in the long-term market.

Another notable result from Table 4-9 is that, excluding the case of the materials phase, approximately 17% of the primary energy attributable to each pavement life cycle phase is due to the pre-combustion energy for all M&R strategies. However, in the case of the remaining impact categories, the environmental impacts due to the upstream processes might be of such dimension that they turn out to be the main contributor to the global value of a determined impact category result. Thus, it is clear that the pre-combustion energy has a significant indirect impact on the environmental burdens of the several competing M&R strategies. Therefore, adopting narrowly defined system boundaries by neglecting supply-chain related impacts can result in underestimates of life cycle environmental footprint of pavement systems.

When comparing feedstock energy and CED F, Table 4-9 shows the feedstock energy of the bitumen to be almost three to five times the energy spent during the materials phase corresponding to the traditional reconstruction, recycling-based and corrective M&R strategies. This result is roughly 6%-9% of the CED Total for each of the strategies. If the energy spent during the usage phase were excluded from the CED indicator, the values would rise to be 96%-109% of the CED Total for the recycling-based, traditional reconstruction and corrective M&R strategies.

To further elaborate on the potential environmental differences arising from implementing the recycling-based activity as opposed to the traditional reconstruction activity, the results were separated into the materials, construction and M&R, transportation and WZ traffic management phases. In doing so, the environmental impacts assigned to the M&R activities that are expected to take place in the remaining years of the PAP were disregarded. The difference between the environmental impacts stemmed from the recycling-based activity and those arisen from the traditional reconstruction activity can be interpreted as "potential environmental impact savings", since the pavement is assumed to behave similarly after the initial recycling-based/traditional reconstruction. Figure 4-3 presents the impact of the two M&R activities on CC, with regard to materials, construction and M&R, transportation and WZ traffic management phases, respectively. Table 4-10 shows the changes in environmental impacts of each phase of the recycling-based activity relative to the traditional reconstruction M&R activity, presented in absolute value and percentage. Those results are to be understood as follows: negative relative numbers mean that the recycling-based M&R activity improves the LCIA results in relation to those associated with the traditional reconstruction M&R activity, while positive numbers represent a deterioration of the environmental profile. The CC impact category has been chosen to be analysed in more detail due to three main reasons: (1) it is the impact category with which most of the stakeholders tend to be more familiar with; (2) the majority of the measures aiming at reducing the environmental footprint of a process or an activity focus on attenuating the GHG emissions; (3) for both intervention strategies the relative contribution of each phase to the remaining impact categories is analogous to that observed in the case of the CC. Furthermore, the results were discretized in terms of the contributions given by the process energy and pre-combustion energy related processes.

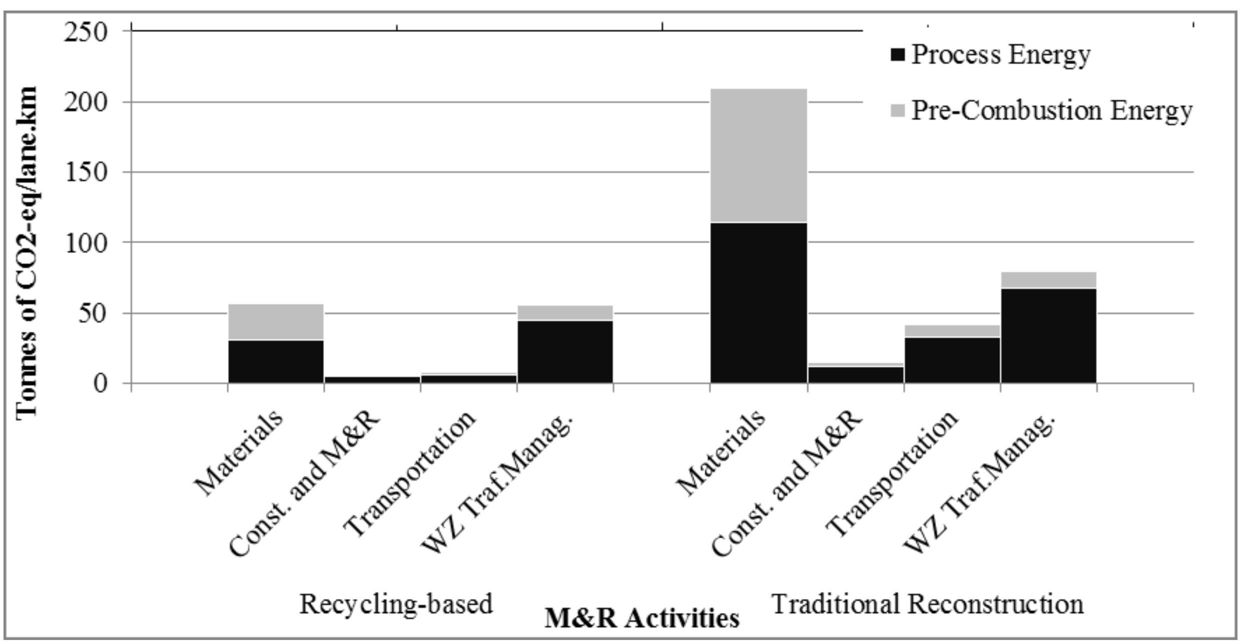

Figure 4-3 - Comparison of the global warming scoring associated with the application of the recycling-based and traditional reconstruction M&R activities

Table 4-10 - Changes in CC impact category indicator results of the recycling-based M&R activity relative to the traditional reconstruction M&R activity (absolute values in tonnes CO_2-eq/km.lane)

Pavement life cycle phase				Total
Materials	Construction and M&R	Transportation	WZ traffic management	
-150	26	-32	-30	-186
-80%	115%	-81%	-35%	-55%

As can be seen from Figure 4-3, the most meaningful environmental advantage obtained when applying the recycling-based M&R activity comes from the materials phase. A reduction of 150 tonnes of CO_2-eq/lane.km, meaning 80% of the emissions occurred during homologous phase of the traditional reconstruction M&R activity, is expected to be achieved if the recycling-based M&R activity is undertaken. However, this outcome must be interpreted having in mind that the reduction in CO_2-eq is not exclusively the reflection of the reduction of the virgin materials consumption. It also results from the fact that the production of the recycling-based mixtures (FDR, CCPR and CIR) taking place on the site are included in the construction and M&R phase, whereas the production of the asphalt mixtures applied in the traditional reconstruction activity are accounted for the materials extraction and production phase, namely the materials production sub-phase.

The WZ traffic management phase was found to have the second highest contribution for environmental impacts, behind the usage phase. Both the M&R strategies were modelled assuming the implementation of the same traffic management plan [as described in Diefenderfer at al. (2012)]. Therefore, the reduction of 30 tonnes of CO_2-eq/lane.km emissions obtained through the implementation of *in-place* recycling activity over the traditional reconstruction activity is due to the fact that the former M&R activity requires less time to be undertaken than the latter.

Finally, the recycling-based activity was found to have a much lower contribution from the transportation phase, bringing down the CO_2-eq/lane.km emissions from 40 tonnes to 7 tonnes. The cut in the CO_2-eq emissions was the result of a reduction in the total hauling movements from 50.490 giga tkm to 1.288 giga tkm. However, it should be noted that the transportation phase-related environmental benefits associated with the recycling-based activity would be greater if the quarry that supplied the aggregates consumed during the project was not inside the boundary of the asphalt drum plant facility.

Despite the recycling strategy's better overall environmental performance, not all the life cycle phases contribute positively to this achievement. The construction equipment required to implement the pavement recycling techniques were found to release 26 more tonnes of CO_2-eq/lane.km than what would be potentially released by the construction equipment used to carry out the traditional reconstruction activity. It is expected that this increase is due to the fact that the equipment producing the recycled materials (e.g., milling machine, reclaimer, cold-recycling mixing plant, cold recycler, etc.), along with the usage of construction equipment, possess engines with a greater power than those equipped by typical asphalt paving equipment (e.g., paver, rollers, etc.). However, the magnitude of this increase is not enough to offset the recycling strategy's better overall environmental performance obtained due to the improvements accounted for the remaining phases.

4.8. KEY FINDINGS

From the results presented and discussed in the previous section, the following findings are worth highlighting:

- the usage phase accounts for up to 96% of the overall life cycle environmental impacts of a pavement system;
- a significant decrease in environmental pollutants is realized by increasing the strength of the pavement, and thus decreasing the frequency of needed maintenance;
- the recycling-based M&R strategy significantly enhance the environmental performance of the pavements over the life cycle by improving the environmental impacts of the initial activity;
- the recycling-based M&R strategy reduce the overall life cycle environmental impacts and energy consumption by as much as 30 and 32 percent, respectively, when compared to the corrective M&R strategy;
- the pre-combustion energy represents approximately 17% of the primary energy consumed over the life cycle of a pavement system. However, regarding the remaining impact categories, this value might be of such dimension that they turn out to be the main contributor to the global value of a determined impact category result;
- a reduction of 80% in the environmental impacts occurring during the raw materials extraction and mixtures production can be achieved by undertaking the recycling-based M&R activity as an alternative to traditional reconstruction M&R activity;
- the recycling-based M&R activity allow savings of about 97% in the hauling movements, as measured by tonnes-kilometer, which represents a reduction of approximately 80% in the GHG emissions; and
- Even though it is not enough to offset its overall better environmental performance, in-place recycling activities are expected to lead to higher construction equipment-related emissions and fuel consumption when compared to those of traditional pavement M&R activities.

4.9. SUMMARY AND CONCLUSIONS

This paper presents the results of a comprehensive LCA of three M&R strategies for a pavement segment, and compares the relative environmental impacts of each strategy. A comprehensive pavement LCA model was developed that allows accounting for the environmental impacts resulting from the entire life cycle of a pavement system, including the upstream processes to the production and transportation of the energy sources. The pavement LCA model comprises six pavement life cycle phases: (1) materials extraction and production; (2) construction and M&R; (3) transportation of materials; (4) WZ traffic management; (5) usage and (6) EOL. In addition, an original methodology is implemented that easily combines the vehicle emissions model MOVES with the HDM-4 rolling resistance model calibrated to North American conditions, to estimate the additional fuel consumption, and consequently the environmental impacts, resulting from the deterioration of the pavement over the life cycle.

The results from this case study show that the usage phase is the phase of the life cycle with the greatest contribution across the majority of the impact categories. This outcome was found to be common to all M&R strategies, but with a greater impact, in absolute value, for the corrective M&R strategy. Consequently, this M&R strategy was also found to have an additional total energy consumption, as measured by the CED Total, of 44% and 42% relatively to the total energy consumed in the case that the recycling-based and traditional reconstruction M&R strategies are alternatively adopted.

When analyzing the relevance of each type of energy (fossil energy, nuclear energy and renewable energy) in the energy consumption, the nuclear and renewable energy sources were found to have residual contributions of 0.18% and 0.11% to the CED Total. Concerning the contribution given by the upstream processes in the production and transportation of the energy sources, it was shown that approximately 17% of the primary energy consumed during each pavement life cycle phase is due to energy source production. The magnitude of this value clearly suggests that the consumption of more sustainable energy sources may play an important role in lowering the life cycle environmental burdens of a road pavement.

By comparing the *in-place* recycling-based activity against the traditional reconstruction activity, a reduction of 150 tonnes of CO_2-eq/lane.km is expected to be achieved exclusively due to the materials phase if the recycling-based activity is undertaken. This value represents a reduction of 80% relatively to the CO_{2a}-eq emissions accounted for equal phase of the rehabilitation activity. Despite the lower impact when compared to the materials phase, the environmental benefits arisen from the WZ traffic management and transportation phases should also not be disregarded. However, it is important to note that the results may be strongly dependent on the traffic management and material location decisions made within this particular project. Consequently, generalizations of those results must be made carefully.

In spite of the exclusivity of each project, by implementing in-place recycling strategies the highway agencies are moving in the right direction towards reducing the overall life cycle environmental impacts related to the pavement construction and management practices. However, while the LCA is useful to increase the environmental consciousness of highway agencies, the environmental aspect is only one of the three elements that compose the triple bottom line that schematically represent the concept of sustainability.

To guide highway agencies towards complete life cycle thinking, future work on this topic should compare the various M&R strategies according to their performance in terms of the criteria addressed by the remaining branches of the sustainability concept.

4.10. ACKNOWLEDGEMENTS

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4.11. Chapter 4 References

Argonne National Laboratory. (2013, February). Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. Retrieved from GREET Life-Cycle Model User Guide: http://greet.es.anl.gov/

ASCE. (2013, April). American Society of Civil Engineering. Retrieved from 2013 Report card for America's infrastructure: http://www.infrastructurereportcard.org/a/#p/roads/overview

Bare, J. (2011). TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy,* 13, 687-696.

Bryce, J., Flintsch, G., Katicha, S. and Diefenderfer, B. (2013). Developing a network-level structural capacity index for asphalt pavements. *ASCE Journal of Transportation Engineering*, 139, 123-129.

Chatti, K., and Zaabar, I. (2012). Estimating the Effects of Pavement Condition on Vehicle Operating Costs. Washington, DC: Transportation Research Board of the National Academies.

Chiu, C.-T., Hsu, T.-H. and Yang, W.-F. (2008). Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resources, Conservation and Recycling*, 52, 545-556.

Dahlbo, H., Koskela, S., Pihkola, H., Nors, M., Federley, M. and Seppälä, J. (2013). Comparison of different normalised LCIA results and their feasibility in communication. *The International Journal of Life Cycle Assessment*, 18, 850-860.

Damas, L. (2005). *SQL- Structured Query Language*. FCA- Editora de Informática Lda, Lisboa.

Diefenderfer, B., Apeagyei, A., Gallo, A., Dougald, L., and Weaver, C. (2012). In-Place Pavement Recycling on I-81 in Virginia. Transportation Research Record: Journal of the Transportation Research Board, 2306, 21–27.

Eurobitume (2011). *Life cycle inventory: bitumen*. Retrieved from Eurobitume website: http://www.eurobitume.eu/hse/sustainability

Federal Highway Administration (2011). *Our nation's highway 2011* (Publication No. FHWA-PL-11-028). Retrieved from Federal Highway Administration website: https://www.fhwa.dot.gov/policyinformation/pubs/hf/pl11028/

Guinée, J.B. (Ed.). (2002). *Handbook on life cycle assessment: operational guide to the ISO standards. Series: eco-efficiency in industry and science*. Kluwer Academic Publishers, Dordrecht.

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. and Wang, T. (2010). *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Retrieved from University of California Pavement Research Center website: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., …Nemecek, T. (2010). *Implementation of life cycle impact assessment methods* (ecoinvent report No. 3, v2.2). Retrieved from ecoinvent Centre website: http://db.ecoinvent.org/files.php?area=463ee7e58cbf8&action=list

Huang, Y., Bird, R. and Heidrich, O. (2009). Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production*, 17, 2, 283-296.

International Standard Organization (2006a). *ISO 14040:2006 – environmental management – life cycle assessment – principles and framework*. ISO 14000 International Standards Compendium, Geneva, Switzerland.

International Standard Organization (2006b). *ISO 14044:2006 – environmental management – life cycle* *assessment – requirements and guidelines*. ISO 14000 International Standards Compendium, Geneva, Switzerland.

Jullien, A., Monéron, P., Quaranta, G. and Gaillard, D. (2006). Air emissions from pavement layers composed of varying rates of reclaimed asphalt. *Resources, Conservation and Recycling*, 47, 356-374.

Karlsson, R., Carlson, A. and Dolk, E. (2012). *Energy use generated by traffic and pavement maintenance. Decision support for optimization of low rolling resistance maintenance* (VTI Report 36A–2012).

Kendall, A. (2012). Time-Adjusted Global Warming Potentials for LCA and Carbon Footprints. International Journal of Life Cycle Assessment, 1042-1049.

Loijos, A., Santero, N. and Ochsendorf, J. (2013). Life cycle climate impacts of the US concrete pavement network. *Resources, Conservation and Recycling*, 72, 76-83.

Loureiro, H. (2010). *Visual Basic- curso completo* [Visual Basic- Complete Course]. FCA- Editora de Informática Lda, Lisboa (in Portuguese).

Marceau, M. L., Nisbet, M. A. and VanGeem, M. G. (2006). *Life cycle inventory of portland cement manufacture* (PCA R&D Serial No. 2095b). Retrieved from Portland Cement Association website: http://www.cement.org/bookstore/profile.asp?store=&pagenum=1&pos=0&catID=&id=11004

Miliutenko, S., Björklund, A. and Carlsson, A. (2013). Opportunities for environmentally improved asphalt recycling: the example of Sweden. *Journal of Cleaner Production*, 43, 156-165.

Park, K., Hwang, Y., Seo, S., and Seo, H. (2003). Quantitative Assessment of Environmental Impacts on Life Cycle of Highways. ASCE Journal of Construction Engineering and Management, 25-31.

Rubio, M. C., Moreno, F., Martínez-Echevarría, M. J., Martínez, G. and Vázquez, J. M. (2013). Comparative analysis of emissions from the manufacture and use of hot and half-warm mix asphalt. *Journal of Cleaner Production,* 41, 1-6.

Sandberg, U., Haider, M., Conter, M., Goubert, L., Bergiers, A., Glaeser, K.-P., … Harvey, J.T. (2011). *Rolling resistance - basic information and state-of-the-art on measurement methods* (Report MIRIAM SP1 01). Retrieved from MIRIAM project website: http://www.miriam-co2.net/Publications/Publications.htm

Santero, N., Masanet, E., and Horvath, A. (2011). Life-cycle assessment of pavements. part I: critical review. *Resources, Conservation and Recycling*, 55, 801-809.

Sayagh, S., Ventura, A., Hoang, T., François, D. and Jullien, A. (2010). Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures. *Resources, Conservation and Recycling,* 54, 348-358.

Stripple, H. (2001). *Life cycle assessment of road: a pilot study for inventory analysis* (Swedish Environmental Research Institute (IVL) report B 1210 E, 2nd revised ed.). Retrieved from Swedish Environmental Research Institute website:

Tatari, O., Nazzal, M. and Kucukvar, M. (2012). Comparative sustainability assessment of warm-mix asphalts: a thermodynamic based hybrid life cycle analysis. *Resources, Conservation and Recycling*, 58, 18-24.

The Freedonia Group (2011). *Asphalt: US Industry Study with Forecasts for 2013 and 2018.* (Study number No. 2544). Retrieved from the The Freedonia Group website: http://www.freedoniagroup.com/industry-study/2544/asphalt.htm

Thenoux, G., González, A. and Dowling, R. (2007). Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile. *Resources, Conservation and Recycling*, 49, 325-339.

Transportation Research Board. (2000). *Highway Capacity Manual 2000.* Transportation Research Board, Washington, D.C.

United States Energy Information Administration (2012). *State electricity profiles 2010* (Report DOE/EIA-0348(01)/2). Retrieved from United States Energy Information Administration website: http://www.eia.gov/electricity/state/

United States Environmental Protection Agency (2004). *AP-42: compilation of air pollutant emission factors* (Volume 1: Stationary point and area sources, Chapter 11: Mineral products industry, 11.1). Retrieved from US EPA website: http://www.epa.gov/ttn/chief/ap42/ch11/index.html

United States Environmental Protection Agency (2008). *Direct emissions from mobile combustion sources. climate leaders GHG Inventory protocol core module guidance* (Report EPA430-K-08-004). Retrieved from US EPA website: http://www.epa.gov/climateleadership/index.html

United States Environmental Protection Agency (2010a). *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Retrieved from US EPA website: http://www.epa.gov/otaq/models/moves/index.htm#user.

United States Environmental Protection Agency (2010b) *Exhaust and crankcase emission factors for nonroad engine modeling- compression- ignition* (Report No. NR-009d). Retrieved from US EPA website: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Geologic Services (2013). *2011 minerals yearbook: Stone, crushed*. Retrieved from United States Geologic Services website: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/

Vidal, R., Moliner, E., Martínez, G. and Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling,* 74, 101-114.

Virginia Department of Transportation (2011). Life cycle costs analysis. Virginia Department of Transportation Materials Division. Retrieved from Virginia Department of Transportation website: http://www.virginiadot.org/business/materials-download-docs.asp

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B., and Kim, C. (2012). Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production*, 86-96.

Yu, B. and Lu, Q. (2012). Life cycle assessment of pavement: methodology and case study. *Transportation Research Part D: Transportation and Environment*, 17, 380-388.

Zapata, P., and Gambatese, J. (2005). Energy consumption of asphalt and reinforced concrete pavement materials and construction. *ASCE Journal of Infrastructure Systems*, 11, 9-20.

Chapter 5.
A Multi-Criteria Decision Analysis Technique for Sustainable Infrastructure Management Business Practices[6,7]

James Bryce[1]; Gerardo Flintsch[2], PhD, P.E., M.ASCE; Ralph P. Hall[3], MEng, SM, PhD

[1] Graduate Research Assistant, Virginia Tech Transportation Institute, Department of Civil and Environmental Engineering, Virginia Tech, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Phone: (573) 289-9236, Email: jmbp54@vt.edu

[2] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, 3500 Transportation Research Plaza, Virginia Tech, Blacksburg, VA 24061-0105, Phone: (540) 231-9748, Email: flintsch@vt.edu

[3] Assistant Professor, School of Public and International Affairs, 207 Architecture Annex, 140 Otey Street, Virginia Tech, Blacksburg, VA 24061, Email: rphall@vt.edu

5.1. ABSTRACT

This paper presents a decision analysis technique to allow highway agencies to assess the tradeoffs between costs, condition and energy consumption. It is shown how the entire feasible solution space can be evaluated between multiple stakeholders with differing values to assess the desirability of the outcomes resulting from infrastructure management decisions. Furthermore, an example network-level analysis is presented using data from the Virginia Department of Transportation. The example analysis clearly shows a tradeoff between the most cost effective outcomes (i.e., minimizing the cost divided by the condition) and the outcomes where the cost is minimized relative to the condition, and how decision analysis should account for this tradeoff. The results of the method presented show that various pavement management alternatives can be represented in terms of desirability, and that this desirability can assist the decision maker with making decisions about performance goals and targets.

5.2. INTRODUCTION

A key aspect of sustainable development is understanding the tradeoffs that exist between maintaining quality and cost effective infrastructure while also mitigating adverse impacts on social and environmental systems (ASCE 2012). However, many long term environmental and social impacts related to infrastructure still contain a relatively high level of uncertainty. As a framework to build policy decisions around high levels of uncertainty pertaining to environmental and social impacts, many countries have adopted versions of the precautionary principle (Gollier et al. 2000; Kriebel et al. 2001). The precautionary principle employs an anticipatory attitude towards irreversible and potentially harmful environmental and social impacts, such

[6] The MATLAB® code used to obtain the results in this chapter is given in Appendix B.
[7] This paper has been submitted for publication to *Transport Research Part D*. Permission for reproduction of this work can be found in Appendix G.

as the current rate of unsustainable consumption of non-renewable energy. The precautionary principle states that a lack of full scientific certainty should not preclude actions towards mitigating potential harms caused by actions resulting in such impacts. A major component of the precautionary principle is the idea that scientific uncertainties are resolved over time, and that policy makers should adapt their method of decision making such that they continually learn about and update the potential solution space regarding their specific objectives.

It has been proposed that a key component of the precautionary principle, an evaluation of an entire feasible solution space including all potential outcomes, can be applied to enhance sustainable development in the face of long-term uncertainties about adverse impacts (Steele 2006). Inherent in this approach is the idea that sustainable development must be evaluated as a multi criteria problem, and that policy makers should be presented with a solution space of many feasible outcomes, as opposed to a single optimal solution. Many researchers have proposed multi criteria decision analysis approaches with the goal of seeking an optimum, or most desirable solution given the tradeoffs in various infrastructure management criteria (Li and Sinha 2004; Zietsman et al. 2006; Smith and Tighe 2006; Stich et al. 2011). However, a method to present the entire solution space in terms of the optimality or desirability of various outcomes in relation to commonly used variables in infrastructure management (e.g., cost or infrastructure condition) has yet to be developed. In light of this, a method to evaluate and represent a multi criteria decision problem over an entire solution space is presented in this paper. The analysis is presented in terms of pavement management and energy consumption, but it is expected that the techniques presented will be applicable to many fields.

5.3. OBJECTIVE

The objective of this paper is to present a practical multi-criteria decision making technique for pavement management applications. The technique focuses on representing the desirability or optimality of a set of potential outcomes in terms of commonly used variables in pavement management (i.e., cost of maintenance and condition of the pavement). The variable used in this analysis to represent adverse environmental impacts is energy consumption. The anticipated benefit of the methodology presented in this paper is that it will result in an adaptive decision-analysis tool that policy makers can use to *learn* about feasible outcomes and the resulting impact of weights they place on certain variables (e.g., costs, energy consumption, etc.). It is also expected that the decision method presented in this paper will assist agencies in working with the public when setting policy decisions regarding tradeoffs to adverse environmental impacts, as recommended by the National Academies of Sciences (Dietz and Stern, 2008).

5.4. BACKGROUND

Sustainable pavement management is an emerging area of research that is concerned with maintaining acceptable condition of pavements while also considering the tradeoffs between cost, environmental impacts and social impacts of pavement investments. Generally the tradeoffs between economic, environmental and social factors require that (1) the agency in charge of managing pavements maintains an accurate database that includes the pavement condition and (2) models to predict the resulting impacts of pavement management decisions on each sustainability factor. Most efforts to date have focused on defining pavement sustainability and sustainable performance measures. However, a next critical step is implementing sustainability into the pavement management decision-making process. This includes incorporating sustainability as a fundamental business practice within the agency where considerations about project selection, treatment type selection, lifecycle management, and triple bottom line (economic, environmental and social) tradeoffs are addressed in the initial decision processes.

The multi-objective decision problem arising from sustainable pavement management is generally converted to a single objective problem by treating some of the objectives as the constraints (Wu and Flintch 2009). In this way, an agency seeks to maximize or minimize one particular objective (e.g., minimizing the cost divided by the performance of the pavement condition) subject to constraints that arise from the original objectives. A shortcoming with the single criterion approach is that when objectives are reformulated as constraints, the resulting analysis becomes non-compensatory (Goodwin and Wright 1998). In other words, undesirable values in the newly formulated constraints are no longer compensated for by highly desirable values in the objective values. Consequently, there is no longer a guarantee that the selected value is non-dominated, and a more optimal value may exist depending on the extent to which the constraints are relaxed. Secondly, the non-compensatory analysis tends to bias the results to the parameter that is chosen as the objective function, thus rendering other objectives as lower level considerations.

Many methods have been proposed for finding solutions to the multi-objective problems encountered in the transportation setting, such as utility theory (Li and Sinha 2004; Zietsman et al. 2006), the analytical hierarchy process (Smith and Tighe 2006) as well as rank aggregation methods when limited alternatives are presented (Stich et al. 2011). Each method has demonstrated advantages and shortcomings, and thus no widely accepted method has been adopted by the transportation sector. This paper will demonstrate a method for finding solutions to the multi-criteria problem posed by sustainable pavement management by combining the benefits cited for other proposed methods into the development of a novel new technique. Pavement management includes analysis at multiple levels, generally divided into the strategic level, network level and project level, which are described in more detail by Butt et al. (1994). The method demonstrated in this paper is expected to be most applicable to the network-level (e.g., for setting objectives for the project selection process) and strategic-level (e.g., for setting targets for performance levels). Therefore, the solution space is expected to be relatively large, and the direct comparison of alternatives may not be feasible.

5.5. MULTI-ATTRIBUTE DECISION ANALYSIS IN INFRASTRUCTURE MANAGEMENT

Given the multiple objectives presented in sustainable pavement management, an important tool to consider for applying sustainable pavement management in decision making is multi-attribute decision making. Important aspects in multi-attribute decision problems are multiple objectives (i.e., multiple criteria and desired levels of attainment for each criteria), constraints for the criteria and preference functions or weighting values used to compare the criteria. Solutions for multi-criteria problems are given by a set of non-dominated solutions (as opposed to a single optimal solution), and thus some judgment or preference function must be evaluated to select the preferred solution from amongst the non-dominated set.

Several methods exist for solving multi-attribute problems. For example, Wu and Flintsch (2009) present a method for replacing traditional deterministic constraints with stochastic constraints before developing the set of non-dominated solutions. Giustozzi et al. (2012) proposed a method of rescaling each criteria between zero and one, weighting each criteria in terms of preference, and then summing the product of each rescaled criteria and criteria weight to determine the best alternative. Li and Sinha (2004) presented a method for using utility theory in transportation asset management decision making. Another application of utility theory in transportation decision making was presented by Zietsman et al. (2006).

One important aspect of multi-criteria problems is the aggregation of preferences among many decision makers who might consider different solutions optimal. Identifying a preferred set of solutions using multi-criteria techniques can support more effective decision-making and promote learning among those engaged in the decision process. As an example, Stich et al. (2011) developed a number of proposed highway alignment alternatives using GIS tools, and then utilized a public informational meeting to have the voters rank the projects given all of the relevant information (i.e., wetland impact, noise and air pollution, etc.) about each alternative. Preference rank aggregation techniques were then used to combine the input to inform the final decision. One policy related benefit that the research cited about gathering the stakeholder's preferences was the possibility of streamlining project delivery times by addressing concerns of the public before they arise, instead of retroactively trying to mitigate the problems and concerns. Lahdelma et al. (2000) describes the use of ranking alternatives among the many stakeholders as an important key to environmental decision making.

Another example of ranking is the analytical hierarchy process (AHP). Smith and Tighe (2006) describe using AHP as a tool for assessing user preferences for maintenance or rehabilitation decisions in the context of transportation asset management. A large subset of road users were identified and surveyed to determine their preferences for many different criteria related to road maintenance and rehabilitation. The preferences were then aggregated by using a simple averaging technique, and the AHP technique was used to evaluate the criteria that were considered most important by user groups, and how the user groups would weight various alternatives.

5.5.1. Reference Point Programming

A multi-criteria technique that is used in business decisions is the reference point method, also known as reference point programming. Reference point programming falls within a family of decision analysis tools that also includes goal programming, where the programmers are attempting to minimize the deviation from the ideal solution (Romero et al. 1998). Reference point programming as described by Eiselt and Sandblom (2007) is a way of trying to maximize the distance between the worst outcome (or minimize the distance between the ideal point) and the many alternatives. Reference point programming shares many similarities with another common multi-criteria method, the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method. In TOPSIS, the alternatives are ranked by comparing their distances to the most ideal solution, as well as their distances from the least ideal solution (Lai et al. 1994). One difference is that TOPSIS is a method that is used when finite alternatives are presented, whereas the reference point method is more readily generalized over a continuous solution space.

An advantage cited by Eiselt and Sandblom (2007) is that reference point programming provides an interactive method where the decision maker can assess the tradeoff at many points along the pareto frontier. One of the major advantages of reference point programminng is that the decision maker works directly with real values, as opposed to proxy values or weights (Bogetoft et al. 1988). Furthermore, given the interactivity of the reference point method, the decision maker is expected to learn about the problem during the process (e.g., the tradeoff between the variables becomes more evident) (Luque et al. 2009). One of the challenges with using reference point programming relates to the assesment of the distance function. Eiselt and Sandblom (2007) discuss how the optimal soultion is impacted by the use of the distance function, be it Euclidean (straight line) distances or other metrics, such as *Chebyshev* distances.

5.5.2. Utility Theory

Utility theory is a method in which a decision makers values are quantified over a range of feasible outcomes, then the values are combined with the corresponding probabilites of each outcome to form a set of utility values. The motivating factor behind utility theory is that if an appropriate utility is assigned to each possible outcome, and the expected utility of each alternative is calculated, the best alternative is the one that maximizes the overall utility (Keeney and Raiffa 1993). The strength of utility theory is that the relative scale of preference between possible outcomes for each variable is used to determine the best alternative from the set of possible alternatives. In other words, the range of values and differences in potential values are used to scale preferences. For example, it is not assumed that increasing a variable four times the original amount is preferred twice as much as increasing by two times the original amount.

Utility theory states that given an action a' that results in consequence x_i with a probability p'_i, we can determine a set of π_i's such that the decision maker is indifferent between the following two options (Keeney and Raiffa 1993);

1. Certain Option: Receive x_i with certainty
2. Risky Option: Receive x_n (best consequence) with probability π_i and x_1 (worst consequence) with probability $(1- \pi_i)$

Then the expected values of π_i's can be used to numerically scale the probability distribution over x_i's such that;

$$\bar{\pi}' = \sum_i p_i' \pi_i$$

Suppose we have two acts a' and a'' with associated $\bar{\pi}'$ and $\bar{\pi}''$, there is good reason to expect that the decision maker should rank the order of preferences of a' and a'' based on the values of $\bar{\pi}'$ and $\bar{\pi}''$ (Keeney and Raiffa 1993). Finally, the π's can be translated to u's by means of a positive linear transform such that the preferences for the probabilistic alternatives is maintained as follows:

$u_i = a + b\pi_i$ For b > 0 and i=1,2…n

For uni-dimensional utility theory, the consequence x_i describes one attribute, such as pavement condition. However, the condition of a transportation corridor is generally defined by many attributes taken together. Thus, multi-dimensional utility theory is employed, and the consequence x_i is used to describe multiple attributes in given states.

One drawback to utility theory is that proxy values (utilities) are used instead of real values, which opens the possibility of misconceptions between changes in real value and changes in utilities. Secondly, it is expected that since the objective is maximizing overall utility, the decision maker is biased to think that the corresponding alternative is optimal, instead of taking time to learn about other alternatives with high overall utilities.

5.6. PROPOSED METHODOLOGY

Drawing on strengths and drawbacks of the reference point method and utility theory, the proposed decision analysis method is a combination of the two methods. More precisley, it will be shown how the method introduces utility functions into the reference point method as an impedance field or a force field, and the distance vector can be described as the work required to go from the most desirable point (i.e., the reference point) to each point in the feasible set. The work represented in the decision analysis technique is the combination of the distance of any given point in the solution space from the most ideal point, and the value gained (in terms of utility) by travelling to the given point on the solution space from the most ideal point.

First the problem can be stated as;

$$\mathbf{Min}\left[y_1, y_2 \ldots y_k\right], \mathit{for}\ k = 1, \ldots q$$

Where y are the values for k objective functions. It will be assumed for this case that the feasible set was determined satisfying all constraints (e.g., any solution alternative can be achieved with given budget), and contains the set of non-dominated (Pareto) points. A reference point can be described as the most desirable outcome from the point of view of the decision maker for each objective as:

$$y^* = \left[y_1^*, y_2^* \ldots y_k^*\right]$$

An example of a reference point given cost and condition is [0, 100], where zero represents no cost and 100 represents perfect condition. Although this is not achievable in practice, it is defined as the most desirable outcome. Given y and y^*, each feasible outcome (y) can be compared to the most desirable outcome (y^*). Traditionally, the objective of reference point programming is written as:

$$\mathbf{min}\, d(y, y^*)$$

Where d is a distance function, generally taken as one of the p-norm distances such that:

$$d(y, y^*) = \left(\sum_{k=1}^{q} \left|y_k - y_k^*\right|^p\right)^{1/p}$$

Where a value of p equal to two gives the Euclidean distance. However, defining the distance vector in terms of the work required to move through a field (Corwin and Szczarba 1995) yields:

$$d(y, y^*) = \int_{y^*}^{y} \mathbf{F}(\alpha(t)) \cdot \alpha'(t)\, dt$$

Where $\mathbf{F}(\alpha(t_i))$ is the magnitude of the field at location α and t_i defines the interval over which the sum is taken such that $0 \le i \le m$. The field at location α can be described using the utility functions evaluated at location α in the direction opposite of the vector defined by $(\alpha(t_{i-1}), \alpha(t_i))$. The distance function can be numerically approximated by:

$$d(y, y^*) \approx \sum_{i=1}^{m} \left[\mathbf{F}(\alpha(t_i)) \cdot \alpha'(t_i)\right](t_i - t_{i-1})$$

Two important concepts must be addressed at this point. First, the utility functions should be scaled such that the maximum utility value corresponds to the least desirable choice so that the maximum work vector corresponds to the least desirable alternative. This is because the work done is a product of the force applied to the vector and the total distance travelled along the vector. Secondly, the values for each variable and utility values should be scaled similarly so that neither dominate the analysis. This will be demonstrated futher in an example analysis.

5.7. Analysis Using Cost, Condition and Energy Consumption of a Road Network

In order to demonstrate the concept discussed in the previous section, an example problem will be presented. Three objectives will be considered in this example as follows:

$$\left[\mathbf{Min}(\mathbf{Cost}), \mathbf{Max}(\mathbf{Condition}), \mathbf{Min}(\mathbf{Energy})\right]$$

The data for this example was obtained by analyzing a subset of flexible pavements along Interstate 81 in the Virginia Department of Transportation's (VDOT's) Salem District. The total length of the pavements was approximately 291 lane-miles (468 lane-km), and the pavements were broken into 65 different segments, ranging in length from 0.5 lane-miles (0.8 lane-km) to 16 lane-miles (26 lane-km), based on the segments defined by the 2012 VDOT pavement management system (PMS). The condition and roughness data was obtained from the VDOT PMS for each pavement segment. The condition was reported in terms of the Critical Condition Index (CCI), a value ranging from 0 (impassible) to 100 (perfect condition). The roughness was reported in terms of the international roughness index (IRI). Finally, the traffic was obtained from the VDOT traffic count website, where it is stored in Microsoft Excel files, and the traffic in terms of average annual daily traffic (AADT) and percent trucks was extracted for each pavement segment. Summary plots of the traffic, CCI and pavement roughness (in terms of IRI) are shown in Figure 5-1.

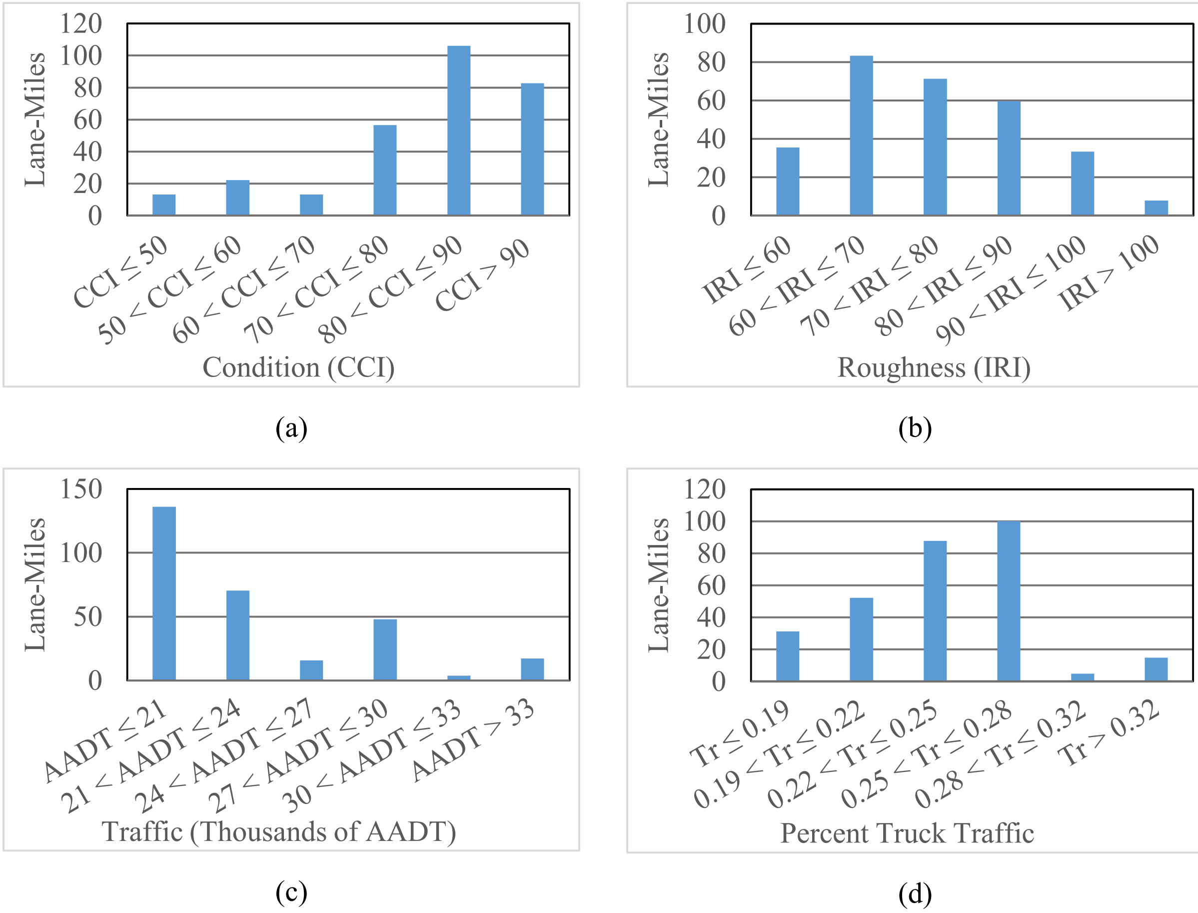

Figure 5-1. Network Condition, Roughness and Traffic Data

5.7.1. Multi Year Analysis

A five year network level analysis was conducted on the pavement network to determine the cost, average condition and energy consumption resulting from a range of different maintenance actions. The maintenance actions were based on VDOT (2011), and defined as Do Nothing (DN), Preventive Maintenance (PM), Corrective Maintenance (CM), Restorative Maintenance (RM) and Reconstruction/Rehabilitation (RC). The maintenance actions were triggered based on condition, such that pavements with condition greater than 90 were set as DN, PM was triggered at condition less than 90 and greater than 80, CM was triggered at condition less than 80 and greater than 65, RM was triggered at condition less than 65 and greater than 45, and RC was triggerred at condition less than 45. It was assumed that PM did not impact pavement roughness, and that the condition was increased by 8 points, which adds approximately 3 years of life within the condition range specified. When CM, RM and RC were applied, the IRI was set to 55 in/mile (0.87 m/km) and the CCI was set to 100.

The deterioration model used for the pavement condition was taken from the model used by the VDOT PMS as discussed in (Stantec and Lochner 2007). IRI growth was assumed at 5 in/mile/year (0.08 m/km/yr). This is higher than the mean value reported by McGhee and Gillespie (2006), and is closer to the value representing a 95 percent certainty given the data reported. The expected energy consumption for each of the maintenance actions was taken from Bryce et al. (2014). The energy consumption due to the vehicles was taken as a function of the IRI, and the models developed by Chatti and Zaabar (2012) were used to obtain the fuel consumption values. Finally, the expected costs for each maintenance action was obtained from VDOT (2011).

5.7.2. Analysis Methodology

In order to obtain the range of energy consumption, average condition and cost values for the five year analysis of the pavement network, a non-linear binary optimization program was set up in MATLAB™. The objective of the optimization was to minimize the energy consumption for given targets of cost and condition throughout the feasible solution space. The problem setup was similar to the methodology presented by Smadi and Maze (1994), with the exception that pavement roughness was also a variable that was tracked. Therefore, the procedure was: (1) determine the condition of the pavement given the pavement age; (2) determine the appropriate treatment given the condition; (3) determine the condition and pavement roughness in the year following the treatment given the treatment type; (4) determine the energy consumption value and cost associated with the treatment type and (5) determine the energy consumption due to the vehicles travelling along the pavement as a function of the pavement roughness, number of trucks and total AADT. Mathematically, the binary optimization of the energy consumption values can be expressed as:

$$e_i^j = F\left(X_i^j, Y_i^j, CCI_i^j, IRI_i^j\right)$$

Where e_i^j is the energy consumption attributed to pavement section i in year j, X_i^j is the binary variable representing whether pavement section i is selected for treatment in year j, Y_i^j is the binary variable representing whether pavement section i is selected for PM in year j, CCI_i^j is the condition for pavement section i in year j, IRI_i^j is the roughness for pavement section i in year j.

Finally, the genetic algorithm tool built into the MATLAB™ global optimization toolbox was used to find the non-dominated surface that relates cost, condition and energy consumption. A discussion of genetic algorithms as they relate to pavement management can be found in Pilson et al. (2007) and Gao and Zhang (2008). The resulting pavement surface is shown in Figure 5-2.

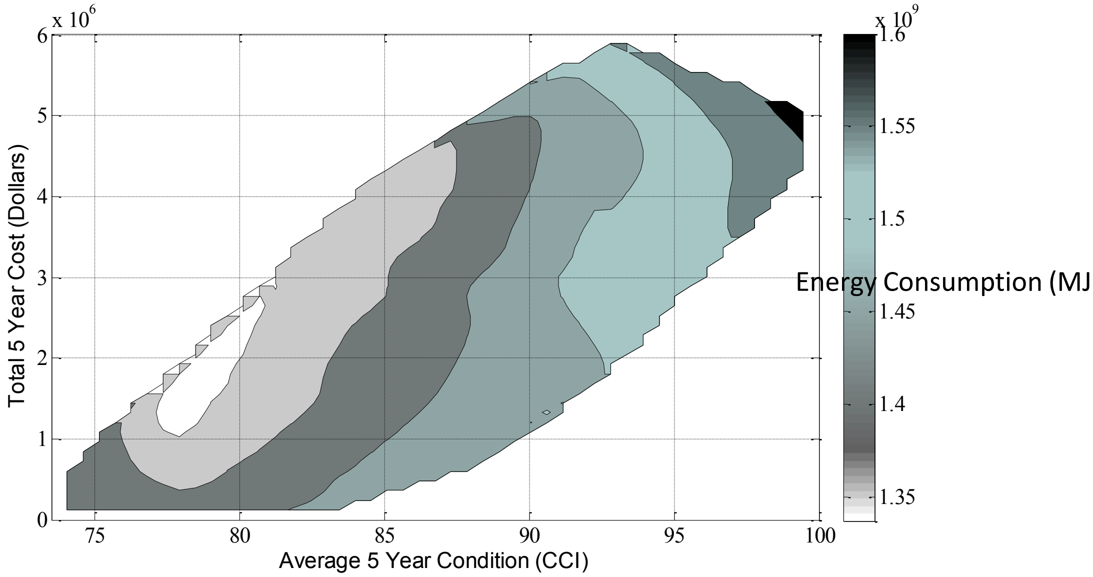

Figure 5-2. Solution space With Energy Consumption (MJ) as the Elevation Contour

The first thing to note from Figure 5-2 is that the range of condition in which the energy consumption is minimized (i.e., a CCI of 77 to 82) includes the current weighted averaged condition of the pavement network (81.4). Furthermore, if the pavement is allowed to deteriorate for the first year with no intervention, the weighted average condition for the second year becomes 76 (assuming VDOT's deterioration model), which falls outside the range of minimizing the energy consumption. With no work performed, the condition of this pavement network would fall to 67, and the energy consumption (which would consist purely of rolling resistance energy) would be 1.44×10^9 MJ. Secondly, the minimum energy consumption does not follow the contour with the best cost benefit (i.e., the contour defining the lower bound of the solution space).

5.7.3. Applying the Decision Analysis Technique

The first step will be to rescale each variable for the j^{th} alternative such that they fall between zero and one, and define proxy variables for *x, y* and *z* such that the most desirable point (also called the utopia point (Luque et al. 2009)) corresponds to values of *x, y* and *z* all equal to zero (and the least desirable corresponds to a value of 1);

$$x_j = \frac{\text{Energy}_{\text{j}} - \text{Energy}_{\text{Utopia}}}{\text{Energy}_{\text{Max}} - \text{Energy}_{\text{Utopia}}}, y_j = \frac{\text{Condition}_{\text{Utopia}} - \text{Condition}_{\text{j}}}{\text{Condition}_{\text{Utopia}} - \text{Condition}_{\text{Min}}}, z_j = \frac{\text{Cost}_{\text{j}} - \text{Cost}_{\text{Utopia}}}{\text{Cost}_{\text{Max}} - \text{Cost}_{\text{Utopia}}}$$

Note that one valuable benefit of rescaling each value such that the utopia point corresponds to *x, y* and *z* all equal to zero and keeping the interval constant is that the work vector is always beginning at values of zero, thus $\alpha(t) = \left(\left(t_x - t_{x-1}\right) + t_x, \left(t_y - t_{y-1}\right) + t_y, \left(t_z - t_{z-1}\right) + t_z\right) \approx \left(0 + t_x, 0 + t_y, 0 + t_z\right)$, and $\alpha'(t) = (1,1,1)$. The reference point was chosen as 100 for condition, 0 for cost, and 0 for energy. Next, the vector of the force field that is directly counteracting the vector defined by (*y, y**) can be described as $\mathbf{F}_j = \left(u_E \rho_j, u_C \beta_j, u_M \gamma_j\right)$ where u_E, u_C and u_M are the utility functions corresponding to energy, condition and cost (respectively), and;

$$\rho_j = \frac{x_j}{\sqrt{x_j^2 + y_j^2 + z_j^2}}, \beta_j = \frac{y_j}{\sqrt{x_j^2 + y_j^2 + z_j^2}}, \gamma_j = \frac{z_j}{\sqrt{x_j^2 + y_j^2 + z_j^2}}$$

The utility functions used in this case were assumed, and were developed such that the decision maker is risk neutral towards increases in energy consumption, slightly risk averse towards condition and relatively highly risk averse for cost (Figure 5-3). The utility functions were then rescaled such that the least preferable option corresponded to the highest utility value. Finally, the work required to travel from the utopia point (chosen as the reference point) to the location of each of the alternatives was calculated and the results, along with the contour plot representing the alternatives, are shown in Figure 5-4. The results in Figure 5-4 are representative of the case that cost, condition and energy consumption are weighted equally.

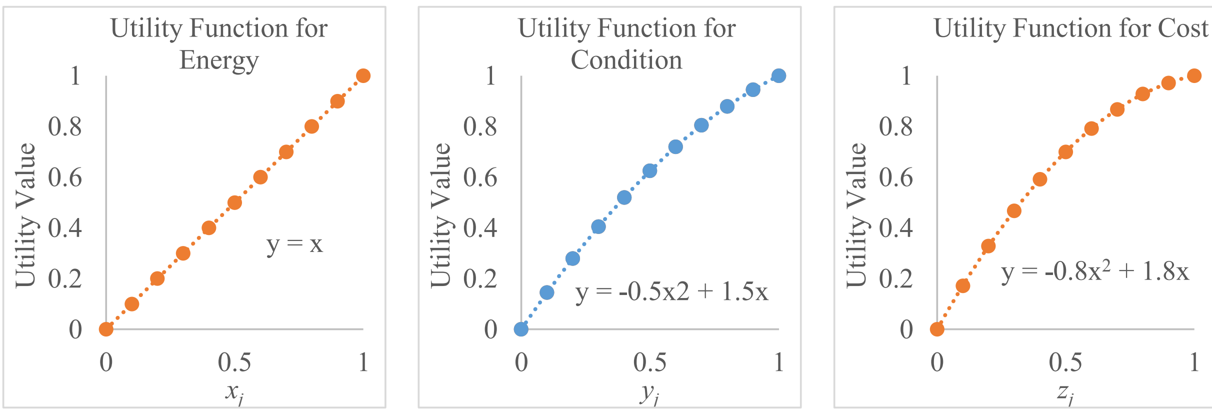

Figure 5-3. Utility Function Assumed for Example Analysis

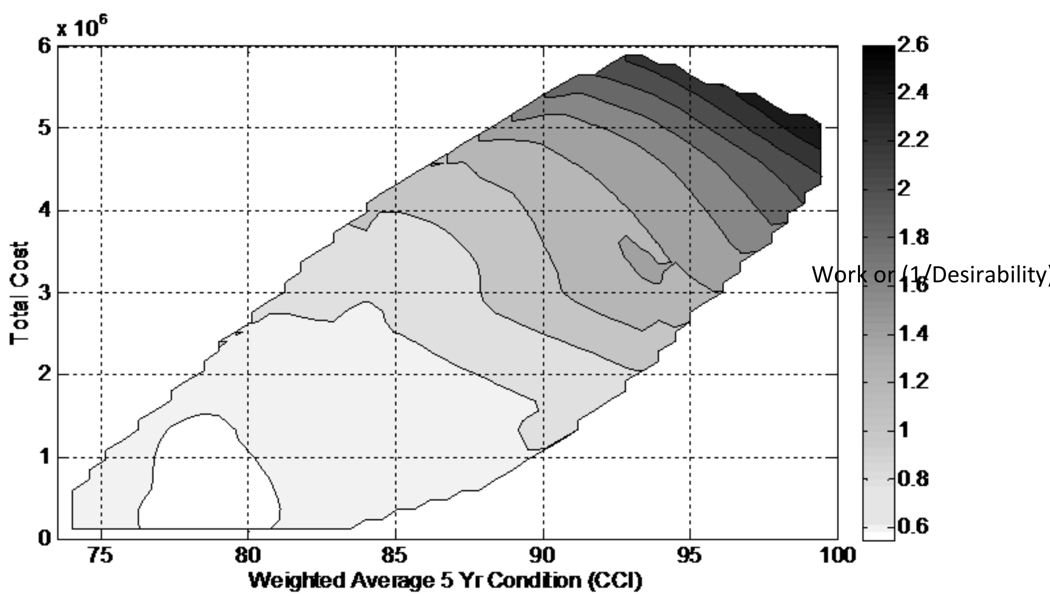

Figure 5-4. Contour Plot of Work Representing the Desirability of the Alternatives, Lower Elevations Represent Greater Desirability

It can be seen from Figure 5-4 that the options representing the minimum work (i.e., the most desirable alternatives) follow very closely to the contours representing minimizing energy consumption. This is because the costs are also relatively low for the alternatives with low energy consumption, even though the condition is also relatively low. Recall that, the condition of this pavement network would fall to 67 with an energy consumption of 1.44×10^9 MJ (purely due to rolling resistance) with no maintenance performed throughout the five year time frame. This energy consumption is approximately eight percent higher than the minimum energy consumption case (with the worst case being approximately 19 percent higher than the minimum energy consumption case). Thus, some maintenance is required to reduce the rolling resistance. However, as the extent of the maintenance performed over the five year time frame is increased, the benefits from the marginal reduction in energy consumption due to rolling resistance are negated by the increased energy consumption due to maintenance actions. Even though the total energy consumption due to the use phase far exceeds that of any other phase, the net energy consumption (i.e., the energy consumption of pavement with high rolling resistance minus the energy consumption of pavement with low rolling resistance) must be used when comparing potential maintenance strategies. This is because vehicle fuel consumption can only be reduced by a marginal amount by reducing rolling resistance, assuming the same type and number of vehicles in the before and after case.

By representing the solution space as a continuum, it can be seen that the level of desirability for the alternatives changes as a function of costs incurred and average condition. Finally, the representation of the desirability of outcomes (Figure 5-4) is represented relative to cost and condition, which are two variables that are nearly ubiquitous among pavement management personnel, meaning that the impact of decisions (and variability of the desirability of possible outcomes) can easily be discussed among many people with little loss of information.

5.8. COMPARISON OF MANY STAKEHOLDERS

The results shown in Figure 5-4 represent the desirability of all potential outcomes, given a decision maker with specific preference functions (Figure 5-3) and equal weights for all criteria. Given the framework from the previous example, it is possible to represent the most desirable outcome of many stakeholders on the same figure. In this example, four stakeholders were assumed to all have the same risk preferences (given in Figure 5-3). The primary concern was minimizing cost for stakeholder 1, minimizing cost while maximizing benefit for stakeholder 2, minimizing energy consumption for stakeholder 3 and maximizing condition for stakeholder 4. The AHP (Saaty 1980) was used to elicit weights for each of the criteria. Stakeholder 1 is assumed to consider cost moderately more important than condition and strongly more important than energy, while considering condition moderately more important than energy. Stakeholder 2 is assumed to consider cost and condition equal with both strongly more important than energy consumption. Stakeholder 3 is assumed to consider condition as important as energy, condition moderately more important than costs and energy consumption strongly more important than costs. Stakeholder 4 is assumed to consider condition moderately more important than costs and strongly more important than energy consumption, while considering cost strongly more important than energy consumption. The resulting plots of work (with minimum work representing maximum desirability) are given in Figure 5-5.

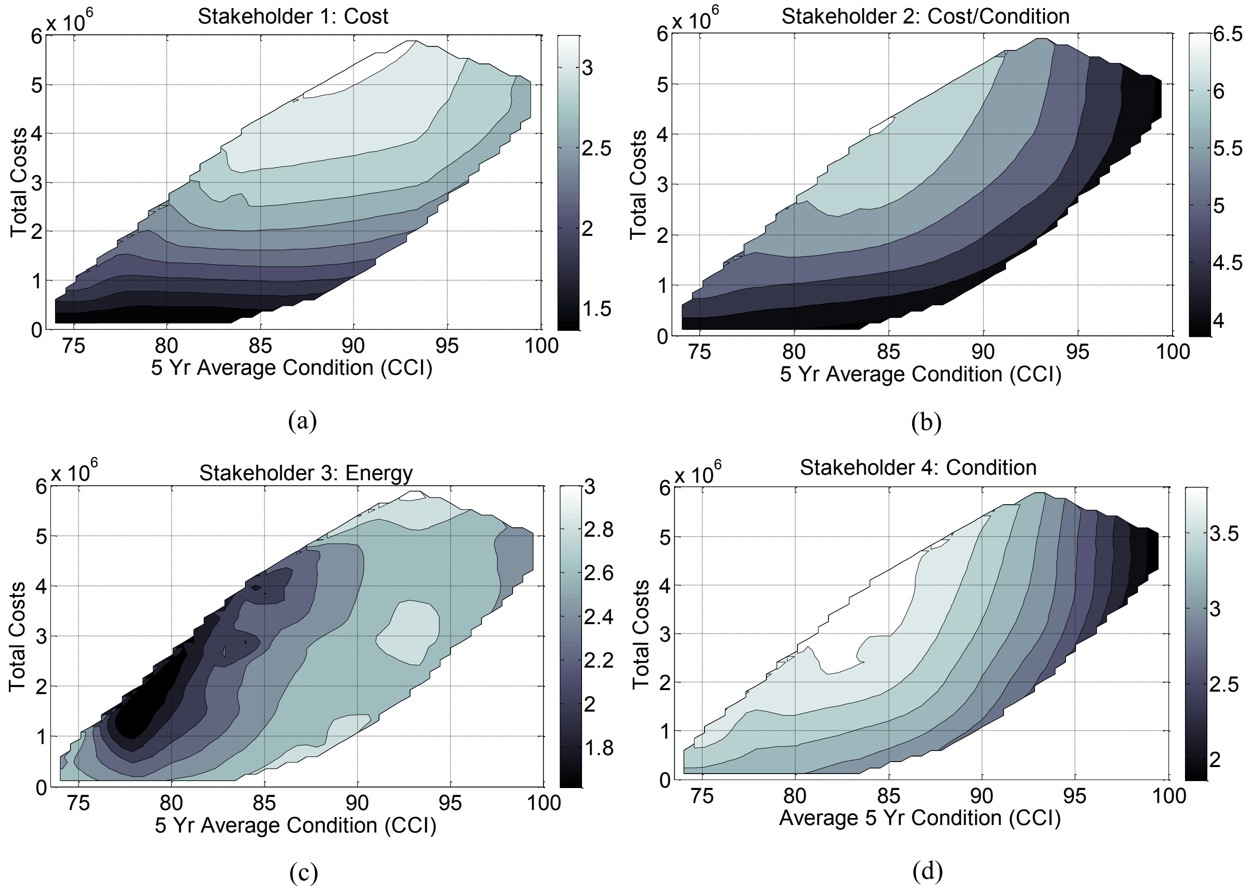

Figure 5-5. Desirability from Stakeholders, Lower Elevations Represent Greater Desirability

5.9. DISCUSSION

The different preferences among stakeholders can clearly be seen in each plot in Figure 5-5. For example, stakeholder 2 (Figure 5-5(b)) considered costs and condition equal while considering energy consumption of considerably less importance. Therefore, the plot of desirability of stakeholder 2 follows contours associated with the most cost effective strategies (i.e., minimizing costs divided by average condition). However, stakeholder 3 considers energy consumption the most important factor, and thus Figure 5-5(c) follows closely with Figure 5-2 in that the strategies that minimize energy consumption are the most desirable. Revealing stakeholders preferences in this way could promote learning among those engaged in the decision-making process, as well as help facilitate public involvement when developing policies regarding tradeoffs of environmental factors. As individuals begin to comprehend the broader implications of their preferences, these preferences may change as a deeper appreciation of the decision landscape emerges. Further, the data (or contour plots) from this approach could become ‘boundary objects’, mechanisms that promote “dialogue, information sharing, learning and consensus-building across different policy boundaries: between experts and non-experts, formal government and different nongovernment actors, higher-order governments and lower-order governments” (Holden 2013, p. 89).

An important implication of representing the decision space in terms of desirability among many stakeholders is that the agency can directly evaluate how the final decisions vary from the preferences of the stakeholders. It is clear in Figure 5-5 that the tradeoffs that are inevitable in the final decision made by the agency can only be seen as optimal by a maximum of two of the four stakeholders. In other words, if an optimal decision is chosen from one of the plots in Figure 5-5, at least two of the stakeholders will not see the final outcome as optimal. Furthermore, visualizing the tradeoffs of many stakeholders can serve as a platform for informing change within the agency, in terms of the agencies strategic goals and objectives. This is because many transportation agencies are in charge of managing public assets, and the goals and objectives of the agency must reflect the goals and objectives of the travelling public. Finally, it is possible to combine all of the stakeholders on one plot by calculating the average work to get to each point in the solution space. It was assumed that all stakeholders are weighted equally. The results are shown in Figure 5-6, where the lowest elevation represents the most desirable combined outcomes for all stakeholders.

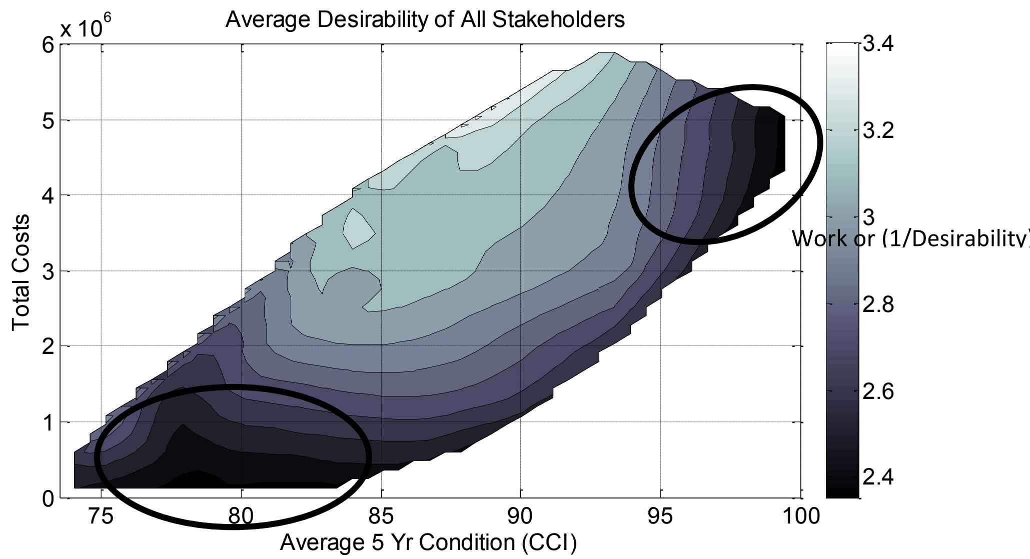

Figure 5-6. Average Desirability from Stakeholders, Lower Elevations Represent Greater Desirability

From the results in Figure 5-6, it can be seen that any optimal decision strategy should be chosen so that the total 5 year costs fall below 1 million dollars, or the average 5 year condition falls above 95. Furthermore, it can be seen in that the optimal sets of outcomes for the given set of stakeholders follows the most cost effective outcomes. This can be attributed to the fact that three of the four stakeholders weighted their most desirable outcome as one which falls along the contour also defined by the most cost effective outcome (Figure 5-5).

5.10. Conclusions

The decision analysis technique presented in this paper provides decision makers with the tools necessary to support complex, multi objective problems while also learning about the tradeoff by evaluating the solution space for the variables of concern among many stakeholders. One important finding in this paper is that the most cost effective maintenance alternatives may tend to correspond to alternatives with a much higher level of energy consumption than the maintenance alternatives not considered the most cost effective (in terms of only cost and condition). This is because a tradeoff exists between the energy consumed when maintenance actions are performed and the energy consumed by vehicles travelling on the pavement (which increases with increasing pavement roughness). Preventive maintenance actions are known to be a less energy intensive and a more cost effective treatment, which does not improve pavement roughness or the energy consumed by vehicles travelling on the pavement. Therefore, a decision maker who is more concerned with cost effectiveness may tend to employ more preventive maintenance activities than a decision maker who also takes environmental considerations (e.g., reducing energy consumption) into account.

The proposed decision analysis technique advocates the evaluation of the entire solution space which presents many potential benefits, including providing the ability to combine the desirability of the outcomes for all potential solutions (as opposed to only optimal solutions) for many stakeholders. Secondly, by visualizing the solution space for each stakeholder, those engaged in the decision-making process have the opportunity to understand the relationship between their preferences and the viability of potential solutions. This feedback may result in the adjustment of preferences based on a deeper understanding of the tradeoffs, promoting a dynamic process that better reflects real-world decision making. Furthermore, decision-makers could evaluate the impact of potential outcomes on certain stakeholders, and potentially modify the weights given to particular attributes based on this. By considering how all stakeholders view the tradeoffs in the feasible solution space, as opposed to only evaluating optimal outcomes among the many stakeholders, a more complete assessment can be made of which solutions are likely to receive broad support and, thus, less resistance in their implementation.

It has long been recognized that decision making within pavement management includes tradeoff between many competing objectives (Wu and Flintsch 2009; Gurganus and Gharaibeh 2012), as well as between many stakeholders (Smith and Tighe 2006; Stich et al. 2011). Furthermore, environmental considerations in pavement management such as reducing overall energy consumption have come to the forefront of concerns in recent years (FHWA 2014). To address these considerations, new business practices will have to emerge in pavement and infrastructure management for policy and decision makers, and public engagement must also be considered as a factor when setting policies (Dietz and Stern, 2008). This paper represents one step in the process towards more sustainable pavement management business practices.

5.11. Acknowledgments

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5.12. References

ASCE, 2012. American Society of Civil Engineers. Available at: www.asce.org/sustainability/ [Accessed 8 October 2012].

Bogetoft, P., Hallefjord, A. and Kok, M., 1988. On the Convergence of Reference Point Methods in Multiobjective Programming. European Journal of Operational Research, Volume 34, pp. 56-68.

Bryce, J. et al., 2014. Probablistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements. Washington, DC, 93rd Annual Meeting of the Transportation Research Board of the National Academies.

Butt, A., Shahin, M., Carpenter, S. and Carnahan, J., 1994. Application of Markov Process to Pavement Management Systems at the Network Level. San Antonio, TX, 3rd International Conference on Managing Pavements.

Chatti, K. and Zaabar, I., 2012. Estimating the Effects of Pavement Condition on Vehicle Operating Costs, Washington, DC: Transportation Research Board of the National Academies.

Corwin, L. and Szczarba, R., 1995. Calculus in Vector Spaces. New York, New York: Marcel Dekker.

Dietz, T. and Stern, P. C., 2008. Public Participation in Environmental Assessment and Decision Making. Washington, DC: National Research Council.

Eiselt, H. and Sandblom, C., 2007. Linear Programming and its Applications. Berlin: Springer.

FHWA, 2014. Federal Highway Administration. [Online] Available at: https://www.fhwa.dot.gov/environment/climate_change/energy/

Gao, J. and Zhang, Z., 2008. Robust Optimization for Managing Pavement Maintenance and Rehabilitation. Transportation Research Record: Journal of the Transportation Research Board of the National Academies, No. 2084, pp. 55-61.

Giustozzi, F., Crisino, M. and Flintsch, G., 2012. Multi-attribute Life Cycle Assessment of Preventive Maintenance Treatments on Road Pavements for Achieving Environmental Sustainability. International Journal of Lifecycle Assessment, Volume 17, pp. 409-419.

Gollier, C., Jullien, B. and Treich, N., 2000. Scientific progress and irreversibility: an economic interpretation of the 'Precautionary Principle'. Journal of Public Economics 75, pp. 229-253.

Goodwin, P. and Wright, G., 1998. Decision Analysis for Management Judgment, 2nd ed.. West Sussex: John Wiley & Sons,.

Gurganus, C. and Gharaibeh, N., 2012. Project Selection and Prioritization of Pavement Preservation. Volume No. 2292, pp. 36-44.

Holden, M., 2013. Sustainability indicator systems within urban governance: Usability analysis of sustainability indicator systems as boundary objects.. Ecological Indicators, Volume 32, p. 89– 96.

Keeney, R. and Raiffa, H., 1993. Decisions With Multiple Objectives: Preferences and Value Tradeoffs. Cambridge, UK: Cambridge University Press.

Kriebel, D. et al., 2001. The Precautionary Principle in Environmental Science. Environmental Health Perspectives, Vol. 109 No. 9, pp. 871-876.

Lahdelma, R., Salminen, P. and Hokkanen, J., 2000. Using Multicriteria Methods in Environmental Planning and Management. Environmental Management Vol. 26, No. 6, pp. 595-605.

Lai, Y., Liu, T. and Hwang, C., 1994. TOPSIS for Multi Objective Decision Making. European Journal of Operational Research Vol. 76 No. 3, p. 486–500.

Li, Z. and Sinha, K. C., 2004. Methodology for the Development of a Highway Asset Management System for Indiana: Publication FHWA/IN/JTRP-2003/21, West Lafayette, Indiana: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University.

Luque, M., Miettinen, K., Eskelinen, P. and Ruiz, F., 2009. Incorporating Preference Information in Interactive Reference Point Methods for Multiobjective Optimization. The International Journal of Management Science, Volume 37, pp. 450-462.

McGhee, K. K., and Gillespie, J. S. (2006). *Impact of a Smoothness Incentive/Disincentive on Hot-Mix Asphalt Maintenance Resurfacing Costs.* Charlottesville, VA: Virginia Transportation Research Council.

Pilson, C., Hudson, R. and Anderson, V., 2007. Multi Objective Optimization in Pavement Management by Using Genetic Algorithms and Efficient Surfaces. Transportation Research Record: Journal of the Transportation Research Board of the National Academies No. 1655, pp. 42-48.

Romero, C., Tamiz, M. and Jones, D., 1998. Goal Programming, Compromise Programming and Reference Point Method Formulations: Linkages and Utility Interpretations. The Journal of The Operational Research Society, Volume 49, pp. 986-991.

Saaty, T., 1980. The Analytic Hierarchy Process. 1 ed. New York, NY, U.S.A.: McGraw-Hill International.

Smadi, O. and Maze, T., 1994. Network Pavement Management System Using Dynamic Programming: Application to Iowa State Interstate Network. San Antonio, TX, Transportation Research Board of th National Academies, pp. 195-204.

Smith, J. and Tighe, S., 2006. The Analytical Hierarchy Process as a Tool for Infrastructure Management. Transportation Research Record, Journal of the Transportation Research Board, Volume 1974.

Stantec Consulting Services, Inc; H.W. Lochner, Inc. , 2007. Development of Performance PRediction Models for Virginia Department of Transportation Pavement Management System, Richmond, VA: Virginia Department of Transportation.

Steele, K., 2006. The precautionary principle: a new approach to public decision making?. Law, Probability and Risk Vol. 5, pp. 19-31.

Stich, B., Holland, J. H., Noberga, R. A. and O'Hara, C. G., 2011. Using multi-criteria decision making to highlight stakeholders' values in the corridor planning process. The Journal of Transport and Land Use, 4(3), pp. 105-118.

VDOT, 2011. Supporting Document for the Development and Enhancement of the Pavement Maintenance Decision Matrices Used in the Needs Based Analysis, Richmond, VA: Virginia Department of Transportation Maintenance Division.

Wu, Z. and Flintsch, G., 2009. Pavement Preservation Optimization Considering Multiple Objectives and Budget Variability. ASCE Journal of Transportation Engineering, 135(5), pp. 305-315.

Zietsman, J., Rilett, L. and Kim, S.-J., 2006. Transportation Corridor Decision Making with Multi Attribute Utility Theory. International Journal of Management and Decision Making, 7(2/3), pp. 254-266.

Chapter 6.
Evaluating Stakeholder Values for Sustainable Infrastructure Management[8, 9]

James Bryce[1] SM.ASCE; Gerardo Flintsch[2], PhD, P.E., M.ASCE; Christian Wernz[3], PhD

[1] Graduate Research Assistant, Virginia Tech Transportation Institute, Department of Civil and Environmental Engineering, Virginia Tech, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Phone: (573) 289-9236, Email: jmbp54@vt.edu

[2] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, 3500 Transportation Research Plaza, Virginia Tech, Blacksburg, VA 24061-0105, Phone: (540) 231-9748, Email: flintsch@vt.edu

[3] Assistant Professor, Grado Department of Industrial and Systems Engineering, Virginia Tech, 205 Durham Hall
MC 0118, Virginia Tech, Blacksburg, VA 24061-0105, Phone: (540) 231-9772, Email: cwernz@vt.edu

6.1. Abstract

Researchers and policy makers have recognized that sustainable infrastructure management requires a paradigm shift for the agencies that manage transportation infrastructure. Decision-making for infrastructure management is a multi-criteria decision problem that impacts many stakeholders, and responsible agencies should recognize their impact on the larger social and environmental system. An important part of understanding the shift towards sustainable decision-making within infrastructure management is understanding the preferences of transportation professionals. This paper presents an attempt to measure the preferences of transportation professionals using of utility theory and the Analytical Hierarchy Process. We determined that a platform that provides real-time feedback to respondents would be a more appropriate approach over the static platform used in this work. We also determined that people who work within infrastructure management tend to be considerably more concerned with condition than costs and energy consumption, although this could be due to the strong correlation between costs and condition.

6.2. Introduction

The sustainable management transportation infrastructure has required a paradigm shift from traditional decision-making techniques based mainly on economics to methods which account for the resulting impacts on environmental and social systems (Mansfield & Hartell, 2012). This also includes modifying agency policies to reflect sustainability in the strategic objectives of the Departments of Transportation (DOTs). The European Conference of Ministers of Transport (ECMT) described the paradigm shift more broadly as treating the transportation sector as a means of promoting political objectives (e.g., promoting sustainable development), as opposed to treating it as a self-contained sector within the agency (ECMT 2004). This shift requires active cooperation from both the political sectors and the transportation agencies in charge of

[8] Approval was obtained from the Virginia Tech Institutional Review Board (IRB) before gathering the data that is analyzed in this chapter. The IRB approval form is provided in Appendix C.
[9] The survey that was distributed is presented in Appendix D

managing the infrastructure. Holden (2013) discussed the relationship between the technical sector, public sector and the political sector, and how the implementation of sustainable management should include indicators to act as boundary objects between the sectors. The boundary objects are indicators that act as intermediary communication tools between the different sectors.

Several tools exist for use by DOTs when developing and implementing plans for sustainability. For example, the Federal Highway Administration (FHWA) released the Transportation Planning for Sustainability Guidebook in 2011 (FHWA 2011). The FHWA report also presents the results of a survey designed to gauge the level of implementation of sustainable practices at each state DOT, and several case studies related to the development and implementation of methods and tools to support sustainability. Another method to guide development and implementation of sustainable practices is presented in Barrella et al. (2013). An important aspect that is addressed in Barrella et al. (2013) is the concept of organizational design, and how the structure of an organization can influence the outcomes of implementing sustainable practices. Furthermore, Mansfield and Hartell (2012) evaluated sustainability plans from several DOT's in the United States, and found that the majority of the implementations that were studied have had positive impact related to sustainable outcomes when compared to the alternative of no plan being implemented.

An important property of sustainability is that it is a multi-objective problem. Given that the optimality of solutions to functions with multiple objectives is generally not unique, some preferences must be expressed by decision makers in order for a final solution to be reached (Keeney and Raiffa, 1993). In terms of the three main objectives associated with sustainability, the preferences result in a tradeoff between economic, social and environmental objectives such that one or more objectives are made worse in order to improve the other objectives. Therefore, this paper presents an attempt to measure, on a large scale, the risk preferences and weights associated with three pavement management objectives for use in multi criteria decision analysis for a specific network level pavement analysis. The network level pavement analysis is presented in Bryce et al. (2014a), and demonstrates the tradeoff between maintenance costs for a five year period, the resulting average pavement condition and the total energy consumption of the pavement system.

6.3. OBJECTIVE

The objective of this paper is to present the results from collecting and aggregating the risk preferences and relative weights for many asset management criteria across a group of stakeholders. The results were obtained from a survey designed to collect certainty equivalents and parameter weights of transportation professionals. Utility theory was used to assess the certainty equivalents and develop value functions, and weights were established using the analytical hierarchy process (AHP). The AHP was chosen for the criteria weighting because it is a widely used process that provides for a method of translating relative weights (e.g. the variable a is strongly more important than variable b) into numerical weights (e.g. a = 5*b), which is beneficial when assessing stakeholder weights.

Sustainability includes considerations for economic systems, social systems and environmental or ecological systems. The three objectives considered constitute what is referred to as the triple bottom line of sustainability. This paper focuses on two aspects of the triple bottom line of sustainability, economic and environmental impacts. The third aspect of the triple bottom line, social impacts, is not explicitly discussed in this paper, but it is recognized that transportation facilities are directly correlated to the quality of life of developing and developed communities (Chamorro & Tighe 2009).

6.4. BACKGROUND

Davis et al. (2010) demonstrated that current and future transportation infrastructure investments have the potential to significantly impact global climate change. Thus, the public has a vested interest in future goals and decisions made about infrastructure beyond such attributes as capacity expansion or condition. Furthermore, Bryce et al. (2014a) demonstrated that management alternatives that minimize the energy consumption (and consequently reduces emissions) of infrastructure management alternatives do not necesarilly correspond to the most cost effective alternatives. Therefore, traditional infrastructure management techniques based on minimizing costs for a given level of performance of a network of assets should be revisited and revised to include objectives deemed important among many stakeholders. One important role that public stakeholders play in the sustainability of pavement networks is advocating for policy implementations that drive agencies towards more sustainable outcomes.

One example of including the input of various stakeholders into policy decisions is discussed in Ananda and Herath (2005), which presented a method for assessing stakeholder risk preferences when evaluating land use alternatives for forest management. The methodology used was utility theory, and risk preferences were evaluated over three criteria; one related to economic, one related to recreation, and on related to ecological consideration. A benefit cited by the researchers was that the risk preferences of the many stakeholders could lead to a better understanding of conflicts in preferences as management decisions a being considered. Many more papers relating to transportation infrastructure have proposed techniques to combine stakeholder preferences in terms of maximizing overall utility (Li and Sinha 2004; Zietsman et al. 2006) or by using weighting and preference rank aggregation (Smith and Tighe 2006; Stich et al. 2011). The analysis in this paper differs in that the methodology is generalized so that a wider audience can be reached (i.e., through an online survey system as opposed to direct interviews), and that the objective of the decision analysis is to evaluate the entire feasible solution space for each stakeholder as opposed to only the optimal decisions for the stakeholders. The resulting solution space is expected to act as the boundary objects (Holden 2013) for more clear communication between stakeholders. The analysis in this paper will be conducted in terms of infrastructure asset management, and more specifically in terms of pavement management. However, the methodology presented for assessing and evaluating stakeholder preferences is expected to be applicable across a wide range of disciplines, particularly when minimizing environmental impacts requires a tradeoff in terms of economic considerations.

6.4.1. Stakeholder Involvement in Sustainable Decision Making

Although the objective of this paper is to evaluate the preferences of transportation professionals regarding the tradeoff in economic and environmental considerations, it is important to understand that the transportation network is a system that impacts the entire society. The need to involve input from many stakeholders in environmental decision-making and resulting benefits from doing so have been demonstrated through several undertakings (Dietz and Stern 2008; Stich et al. 2011; Committee on Sustainability Linkages in the Federal Government 2013). However, some challenges have been recognized when involving some stakeholders in technical decisions, such as clearly conveying the problem and transparently stating the uncertainties to a general audience. In order to address the varying challenges to public involvement in environmental policy and decision-making, the National Academies of Science sponsored a study conducted through the National Research Council (NRC) that culminated in a report with several recommendations (Dietz and Stern 2008). The first recommendations from the NRC report is that public involement should be fully incorporated within environmental assessment and decision-making. Building on the recommendations from the NRC report, this paper presents a method of evaluating stakeholder values when incorporating environmental decision-making into infrastructure management processes. The stakeholders included in this paper are transportation professionals, however the results are expected to be used to develop communication tools among other stakehoder groups.

6.4.2. Tradeoffs Considered in Analysis

Three criteria are considered in this analysis; total maintenance costs, average pavement condition and energy consumption due to maintenance and vehicles travelling on the pavement. The network analyzed in Bryce et al. (2014a) is used to assess the range of values for each of the criteria. The network analyzed in consists of 291 lane-miles (468 lane-km) of asphalt pavements, and maintenance alternatives were evaluated over a five year period. The optimization was conducted using a non-linear binary optimization scheme, and employed genetic algorithms to determine the non-dominated surface associated with the three criteria. Costs ranged from 0 to 6.02 million dollars, condition ranged from 73 to 100 and energy consumption ranged from $1.34x10^9$ to $1.63x10^9$ Mega Joules. Condition values were reported in terms of the Critical Condition Index (CCI) which ranges from 0 (worst case condition) to 100 (no distresses).

One important consideration is that the outcomes each have a level of uncertainty, as demonstrated in Bryce et al. (2014b). This is due both to the fact that the outcomes are analyzed using network-level data, and the energy consumption values are based on a range of values found in literature. This is important given that utility theory is used to analyze preferences, as opposed to other methods which are used when outcomes are certain. The outcomes represented in this paper are the mean values of the distribution of potential outcomes.

6.5. Assessment Methodology

A survey was designed and distributed among transportation professionals that work within the field of infrastructure management in order to capture their preferences. The survey was built using an online based platform so that the survey could be distributed via email using a link to a particular website which contained the survey questions. The answers were recorded anonymously and stored in a database. The survey was designed in four sections. The first section was one question to determine the approximate length of time the respondent has worked in the field of infrastructure management. The second section included two questions related to obtaining weights for each of the three parameters. The first question of section two simply asked the respondent to rank the three criteria in order from most important to least important. The second question (Figure 6-1) was designed to gauge the relative weights of each criterion using the AHP. The third section consisted of four questions to obtain certainty equivalents for each of the criteria. The questions in the third section were more time intensive, and discussed scenarios in which the respondent was asked to choose a certain value that would make them indifferent between their choice, and a risky choice. An example question designed to determine the certainty equivalent of energy consumption is shown in Figure 6-2. When asking questions related to the certainty equivalent, all attempts were made to avoid presenting information in the question to avoid biases (e.g. anchoring biases) in the responses. The final section included one question which asked the respondent to indicate their level of confidence in their responses, as well as a comment box for further input.

Please compare your preferences about the costs of maintenance related to condition and energy consumption (used to determine global climate change impacts).

Choose the option that best fills in the blank for the corresponding statement

	Extremely less important	Very Strongly less important	Strongly less important	Moderately less important	As Important	Moderately More Important	Strongly more important	Very Strongly more important	Extremely more important
I consider costs (blank) related to energy consumption.	○	○	○	○	○	○	○	○	○
I consider condition (blank) related to costs.	○	○	○	○	○	○	○	○	○
I consider energy consumption (blank) related to condition	○	○	○	○	○	○	○	○	○

Figure 6-1. Question to Weight Using the AHP

The agency you manage has decided to track energy consumption from maintenance and from vehicles using the network using updated models. In order to do this, you form two design teams to propose maintenance plans given a specified condition and cost constraint.

Design team 1 proposes an innovative (but uncertain) plan that meets cost and condition constraints. The uncertainty is simplified as follows: a 50 percent probability an energy consumption value of 1.3e9 Megajoules (equivalent energy to power ~34,000 average American homes), or a 50 percent probability of 1.7e9 Megajoules (equivalent energy to power ~43,000 average American homes).

Design team 2 meets the same cost and condition, but delivers a certain value 'x' (assume ~100 percent certainty) for a value of energy consumption.

What value of 'x' would make you indifferent to choosing either design team. In this case, increasing 'x' would make you tend to choose design team 1, whereas decreasing 'x' would make you tend towards design team 2.

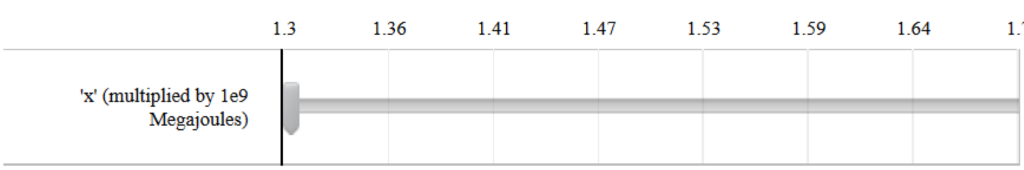


Figure 6-2. Question to Determine the Certainty Equivalent for Energy Consumption

6.5.1. Developing Utility Curves

There is no standard method for developing utility curves, but there are a number of steps that can help guide the procedure. The analysis presented in this paper follows Keeney and Raiffa (1993) which presents the following five step procedure to help guide the process: (1) prepare for the assessment, (2) identify the relevant qualitative characteristics of the utility curves, (3) specify quantitative restrictions to the curves (e.g., determine specific values along the curve), (4) choose a utility function, and (5) check for consistency in the responses. Generally, utility curves are refined by presenting the respondent with feedback regarding the implied preferences given their response, and allowing the respondent to adjust their responses. In this case the survey is anonymous, so the respondent will not have a chance to refine their preferences. The implications of this type of static system with no feedback will be discussed later in this paper.

A key aspect of developing the utility functions is defining the range over which the preferences will be evaluated. The range of values is critical, because a range that is much larger than the scale of achievable values will minimize the effect of the achievable values in the decision process. However, it is important to note that the upper bound on the utility function does not necessarily need to reflect what is currently achievable, all that is important is that the scale is preserved. An example given in Keeney and Raiffa (1993) is that given a range of criteria from 0 to 8.75, setting the bounds of the utility function at 0 and 10 is reasonable, whereas setting the upper bound at 10,000 would have very little meaning to the decision maker.

The bounds for condition were 70 and 100, corresponding to the minimum and maximum feasible conditions (respectively). The bounds for costs were zero and 7 million dollars for the minimum and maximum (respectively). It was decided to present energy consumption both in terms of the absolute value and in terms of a proxy value in order to increase understanding about the meaning of energy consumption. This follows recommendations from Dietz and Stern (2008) and The Committee on Sustainability Linkages in the Federal Government (2013) that the data be clearly presented and understandable by a wide audience. The proxy variable was chosen as the energy consumed by an average US home in 2012 as obtained from the US Energy Information Administration (2014). The bounds for energy consumption were taken as 1.3x109 Mega Joules or the amount of energy to power approximately 34,000 average American homes for a year as the minimum, and 1.7x109 Megajoules or the amount of energy to power approximately 43,000 average American homes for one year as the maximum.

Some important steps for identifying the relevant qualitative criteria of the utility curves are to determine whether the utility curve is monotonic, and the risk preferences of the decision maker. Given the criteria used in this assessment, we deemed reasonable to assume the utility curves are monotonic. In other words, given all else equal and independent, lower cost is always preferred over higher costs, higher condition is always preferred to lower condition, and lower energy consumption is always preferred to higher energy consumption. Another assumption that had to be made was that of mutual utility independence. This assumption states that the range of utilities assigned to one criteria is independent of the values of the other criteria. As an example, it is reasonable to assume that the stakeholder would assign the same relative utilities to all values of energy consumption regardless of the value of costs when given the information that the energy consumption is independent of costs. It is important to recognize that all of the transportation infrastructure management criteria are correlated (e.g. increased cost typically relates to increased condition), but the questions were designed so that the certainty equivalents for a given criterion did not impact the outcomes in the other criteria.

Determining quantitative restrictions of a utility functions includes fixing many points along the utility curve by using techniques such as 50-50 lotteries, and determining the respondent's certainty equivalent for these lotteries. A certainty equivalent is the value that a decision maker would take such that they are indifferent between the risky decision and the certain value. For example, if presented with two options; (1) a 50 percent chance of winning 100 dollars and a 50 percent chance of no winnings, or (2) a 100 percent chance of x dollars, the certainty equivalent is the x amount of dollars that would make the decision maker indifferent to either option. If the decision maker choose an x of 50 dollars, they are said to be risk neutral.

A higher value for x would indicate risk proneness (or risk seeking), and a lower value for x would indicate risk averseness.

The final steps are to choose the utility function and check for consistency. A utility function is the mathematical representation of the relative preferences (i.e., utilities) of a decision maker or stakeholder over a given range of outcomes. Choosing a function that fits the data, as well as fits the risk preferences is important to the assessment. For example, if the decision maker is constantly risk averse, a negative exponential function may be used, and the responses can be used to fit the constant value to the curve (Keeney and Raiffa 1993).

6.5.2. Weighting Criteria

A number of methods are available that can be used to evaluate the weights applied to the various criteria, and an overview of many of the techniques can be found in Choo et al. (1999). We decided to use weighting technique associated with the AHP developed by Saaty (1977, 1980) to determine the relative criteria weights for this work. The AHP has proven to be a powerful and thorough method when comparing multiple criteria across multiple people in business and economic decisions, particularly when little prior information is known regarding some criteria (e.g. environmental sustainability) (Handfield et al. 2002). The basis for AHP is the pairwise comparisons made through the various criteria and measures. Table 6-1 shows the values for the relative weighting of the importance between comparisons.

Table 6-1. Relative Rating Values for Comparison

Relative Importance	Definition
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2,4,6,8	Compromises Between Above

After the relative weights are determined, they are put in matrix form and the normalized principal eigenvector is calculated in order to determine the weighting values. The next step is to check for consistency among the responses. Consistency can be seen in terms of the following example; if I prefer ***a*** 2 times more than ***b***, and I prefer ***b*** two times more than ***c***, it goes to follow that I should prefer ***a*** four times more than ***c***. Thus, saying I prefer ***a*** three time more than ***c*** would be considered inconsistent. However, because not every decision maker can be expected to follow perfectly rational preference values, some level of inconsistency is allowable. The consistency can be checked as follows;

$$CR = \frac{CI}{RI} \tag{6-1}$$

Where CR is the Consistency Ratio, RI can be obtained from Table 6-2 using the size of the comparison matrix, and CI can be calculated using equation 6-2. A value of less than 0.1 for CR is generally determined to be acceptable.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{6-2}$$

Where λ_{max} is the principal Eigen value of the comparison matrix, and *n* is the size of the comparison matrix.

Table 6-2. RI Values for Equation 6-1

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

6.6. RESULTS

The survey was distributed to approximately 60 DOT personnel that work within pavement and infrastructure management, with at least one person in each state DOT contacted. The survey was also distributed to approximately 20 researchers and consultants in the field of infrastructure management. Of the potential respondents that were contacted, only 38 responded to the survey. Upon review of the results, only 16 of the 38 respondents completed the survey in full. Thirty of the respondents completed the first two sections, and the remainder of the respondents only completed the first section. Many of the respondents who did not complete the survey indicated that the length of the questions was an issue to them, although the respondents who completed the survey did so in an average of approximately 17 minutes. Of the respondents who completed the survey in its entirety, the average respondent recorded between five and ten years' experience in pavement management, with the minimum being 5 years and the maximum being greater than 15 years.

6.6.1. Ranking and Weighting the Criteria

Of the 38 respondents, 30 completed the portion of the survey related to the criteria ranking and weighting. The results for the ranking and weighting of the criteria are shown in Figure 6-3 and Figure 6-4. In general, condition was ranked and weighted the highest. An interesting result was can be seen is that cost was ranked the second most important by a significant margin, but the mean of the weights of cost and energy consumption are very similar (0.37 and 0.33, respectively). This demonstrates the fact that ranking relative criteria does not necessarily preserve the range of preferences in the outcomes (i.e., preferring one objective more than the other does not provide a measure of preference between the two).

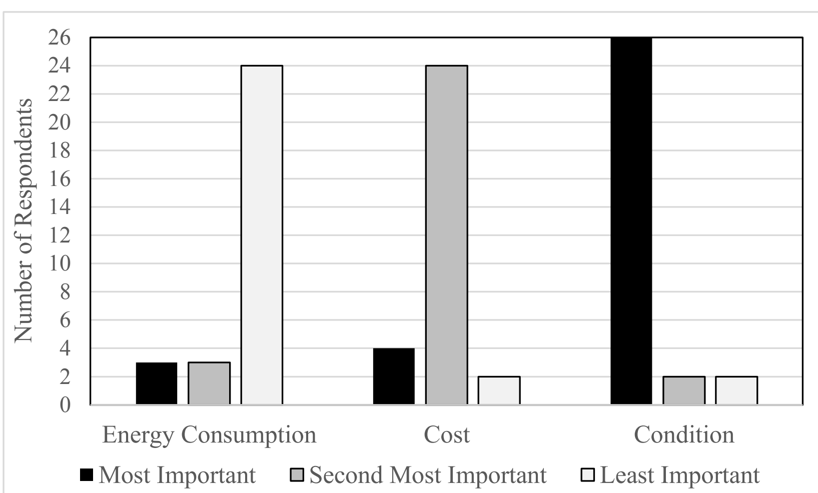


Figure 6-3. Results of Directly Ranking the Criteria

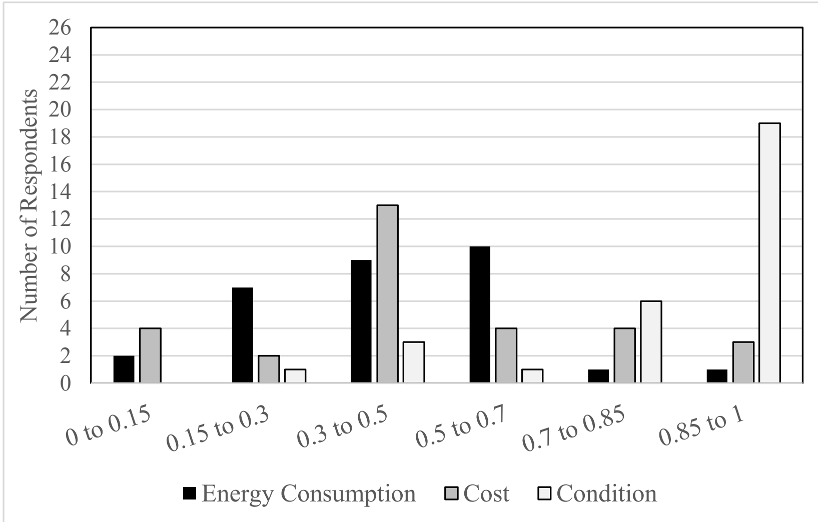


Figure 6-4. Results of Weighting the Criteria Using the AHP

Consistency of the responses were checked in two ways. First, the direct ranking of the importance of the three criteria was compared to the relative weighting (i.e. the results of the weighting using the AHP) to make sure that the rankings matched the weighting. Secondly, the consistency ratio was calculated using equation (1) to ensure the relative weightings were consistent. It is worth noting that many of the respondents indicated having trouble understanding the questions regarding the weighting, particularly given the relatively large number of options to choose from. This could be a factor that contributes to relatively high levels of inconsistency. One way to counteract this in future studies would be to use a dynamic platform that presents real time feedback to the respondents. The benefits of providing real time feedback to respondents has been described as a way to increase participation, as well as increase information gained by the respondent (Robbins et al. 2008).

When comparing the ranking of the three criteria to the weighting, and interesting pattern emerged. Twenty three of the 30 respondents (77 percent) ranked condition as the most important criteria, followed by cost, and then energy consumption. However, when determining the weights based on the scale for the AHP, the final values indicated that the 11 of the 23 respondents who ranked cost higher than energy consumption had final weights that indicated the opposite. For example, one respondent ranked the criteria in the following order: condition as the most important, cost as the second most important, energy consumption is the least important. When the same respondent answered the question related to the weighting of they responded as follow: energy consumption is strongly more important when compared to cost, condition is extremely more important related to costs, and condition is strongly more important when compared to energy consumption. This equates to weights for cost, condition and energy consumption as 0.08, 1 and 0.28, respectively. The principal eigenvector for the comparison matrix is 3.117, which equates to a consistency ratio of 0.1 (generally seen as acceptable).

The consistency ratio for each respondent was calculated, and the majority of the consistency ratio's had values greater than 0.1. Therefore, it was decided to investigate the reasons why each consistency ratio was greater than 0.1 before determining whether the responses were too inconsistent to be considered usable. For example, one respondent labeled cost as extremely more important that energy consumption and condition as extremely more important than costs. Based on these two, the highest level of consistency achievable would be 0.18, and would be the case that they considered energy consumption extremely less important than condition. However, the respondent indicated that energy consumption is very strongly less important that condition, which resulted in a consistency ratio of 0.61. Thus, it was decided that the inconsistencies in this particular respondents weights were acceptable given that the overall trend in the preferences was maintained.

To further explore the weighting of the criteria, the decision process was broken into several decision paths. The paths were defined as the combination of decisions made by each respondent. For example, a particular path may begin with costs as more important than energy consumption, then move to condition more important than costs, and finally end up at energy consumption is less important than condition. By defining paths in this way, there are 33=27 possible decision paths for each decision maker to follow. Also, by defining paths in this way, we demonstrated that there are only 13 decision paths that can be taken to provide valid weighting. An example of an invalid decision path is: Cost is More Important than Energy Consumption → Condition is More Important than Cost → Energy Consumption is More Important than Condition. Seven respondents followed inconsistent decision paths, with an average consistency ratio was 1.48, and their responses were deemed too inconsistent for use. The valid decision paths, as well as the number of respondents that followed each are given in Table 6-3.

Table 6-3. Summary of Consistent Decision Paths

Path Number	Cost Compared to Energy Consumption	Condition Compared to Costs	Energy Consumption Compared to Condition	Number of Respondents
1	More Important →	More Important →	Less Important	8
2	More Important →	Equally Important →	Less Important	4
3	More Important →	Less Important →	More Important	1
4	More Important →	Less Important →	Equally Important	0
5	More Important →	Less Important →	Less Important	0
6	Equally Important →	More Important →	Less Important	1
7	Equally Important →	Equally Important →	Equally Important	1
8	Equally Important →	Less Important →	More Important	0
9	Less Important →	More Important →	More Important	1
10	Less Important →	More Important →	Less Important	1
11	Less Important →	More Important →	Equally Important	6
12	Less Important →	Equally Important →	More Important	0
13	Less Important →	Less Important →	More Important	0

By breaking the responses into different decision paths and comparing the weights for each respondent within each decision path, it was found that the weights for the respondents within each decision path were very similar. This result is expected, and the variability's are due to the degree of preferences. The average weights for each criteria for each path are shown in Figure 6-5.

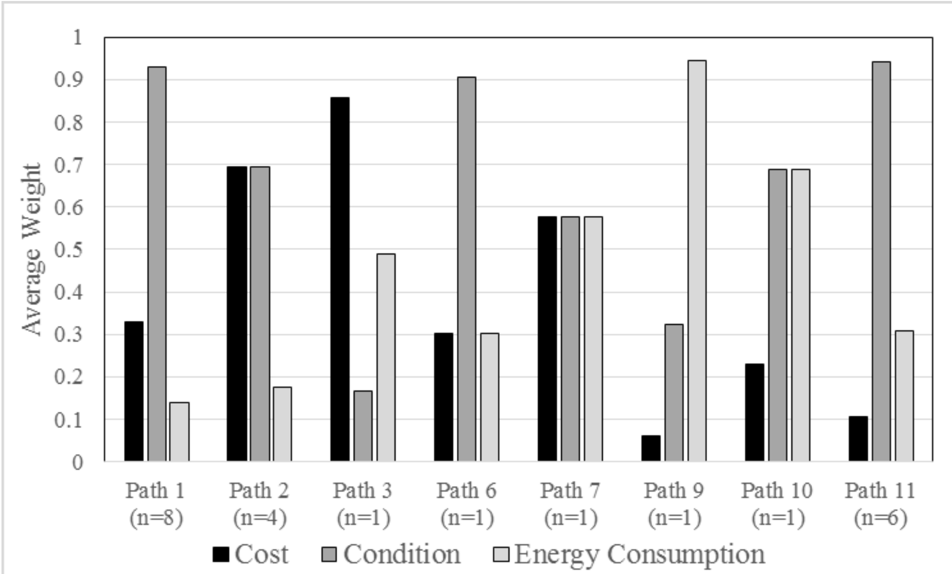


Figure 6-5. Average Weights for the Criteria for Respondents for Each Decision Path

6.6.2. Analyzing the Certainty Equivalents

In order to analyze the risk preferences of the respondents, utility functions were fit to the data provided in the responses. Given that little data was collected from each respondent and no assumptions could be made about increasing or decreasing levels of risk aversion (or risk proneness), we decided that polynomial utility functions in the form of $u(x) = ax^2 + bx + c$ would provide sufficient information about the risk preferences of the respondents. In order to measure a level of risk proneness or risk averseness between the respondents across the various criteria, a similar concept to the measurement of the risk premium (Keeney and Raiffa, 1993) was adopted. The measure was taken as $u(f(0.5x)) - 0.5$ for decreasing utility functions, and $0.5 - u(f(0.5x))$ for increasing utility functions. Where $u(f(0.5x))$ is the utility value of the utility function evaluated at the midpoint of the range of values over the data (e.g., the utility value for condition utility function evaluated at condition 85). Values less than zero indicate risk averseness, and values greater than zero indicate risk proneness. The results using the defined measure of risk are shown in Figure 6-6.

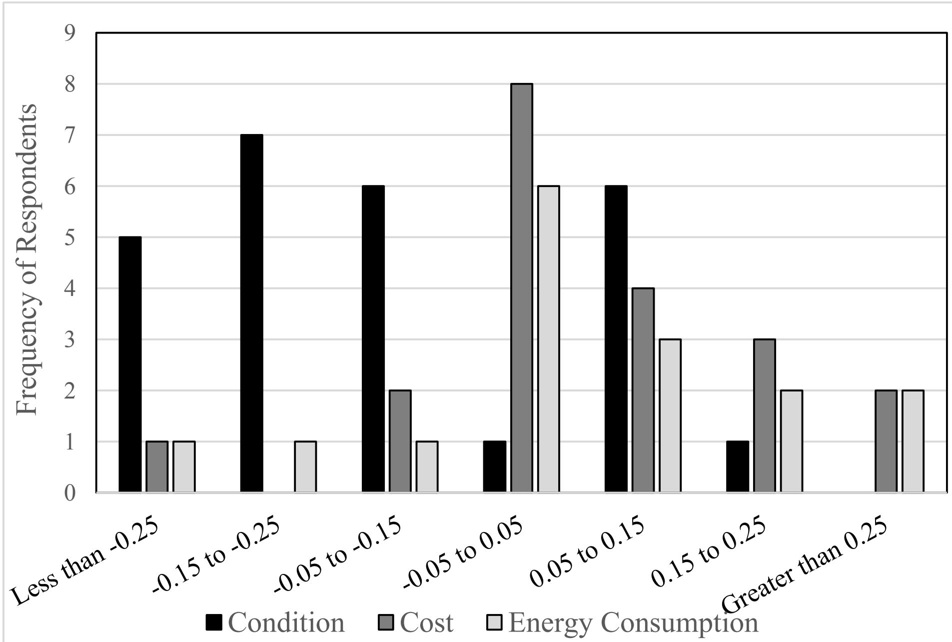


Figure 6-6. Measure of Risk Preference for Each Respondent across Each Criteria

Figure 6-6 demonstrates that the risk preferences of the respondents follow a similar trend to that as the weights. The respondents tended to be most risk averse to condition, and similarly risk averse for costs as energy consumption. One observation that was made is that no relationship was found between the weight assigned to a specific criteria and the risk preferences for the criteria for each respondent. In other words, if a respondent weighted a specific criterion more heavily than another criterion, they were equally as likely to be risk prone as they were to be risk averse towards the highest weighted criteria. Also, there was no relationship found between the measure of risk averseness and the confidence that each respondent indicated they had in their responses. Another notable result was that no statistically significant relationship was found between the respondents risk preferences for one criteria, and their risk preferences for the other criteria. For example, if a respondent was strongly risk averse towards condition, it did not impact their risk preferences towards costs, as is seen in Figure 6-7.

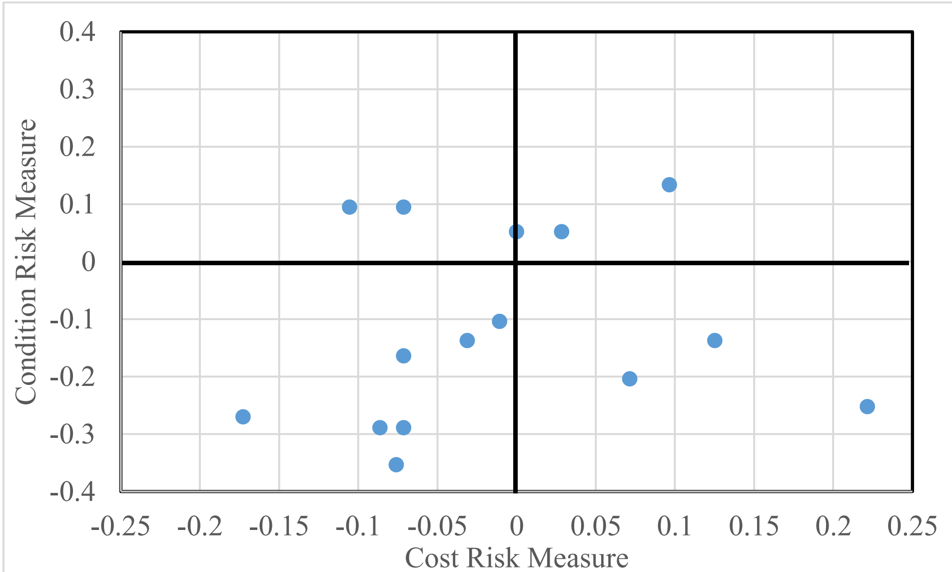


Figure 6-7. Condition Risk Measure vs. Cost Risk Measure

6.7. Applying Weights and Certainty Equivalents to Decision Problems

In order to evaluate the impact of the results of the survey on outcomes related to pavement management, the study presented in Bryce et al. (2014a) was evaluated using the weights and certainty equivalents found in the survey. First, the decision space that relates total maintenance costs, average five-year condition and total energy consumption is shown in Figure 6-8. Figure 6-8 demonstrate the tradeoff between costs (*y*-axis), average condition (*x*-axis) and the minimum achievable energy consumption (*z*-axis) for each cost and condition value. The responses from in the survey were then simulated over a larger population that statistically represented the respondents given the analysis presented in previous sections of this paper. The simulation used responses obtained from the survey from each question as prior information, and then a randomized set of stakeholders was generated that the larger group was representative of the actual respondents. Then, the larger simulated set of responses were used to evaluate several points within the decision space, and the results are shown in Figure 6-9 and Figure 6-10. Figure 6-9 presents the most desirable value for each point within the decision space among all of the decision makers. Figure 6-10 shows the results if the level of desirability of all of the decision maker's outcomes are averaged for each point in the decision space.

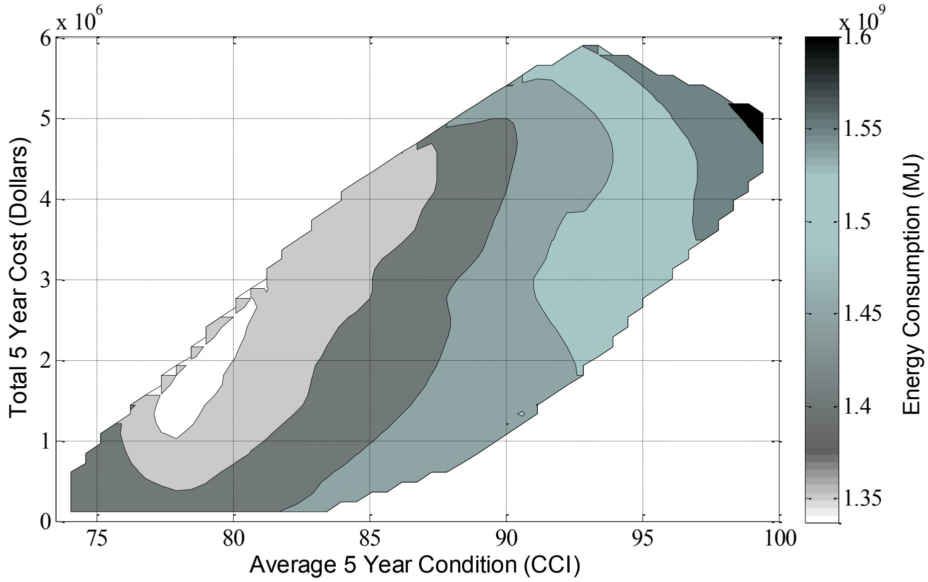


Figure 6-8. Tradeoff of Cost Condition and Energy Consumption as Presented in Bryce et al. (2014a)

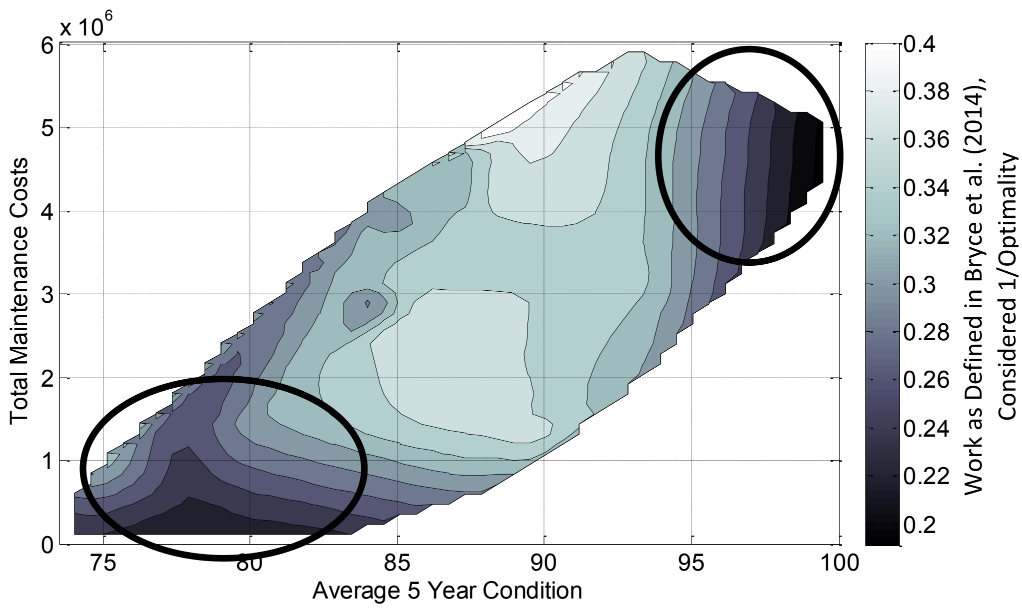


Figure 6-9. Outcomes Considered Optimal By Respondents, Where Lower Elevations Are Considered More Optimal

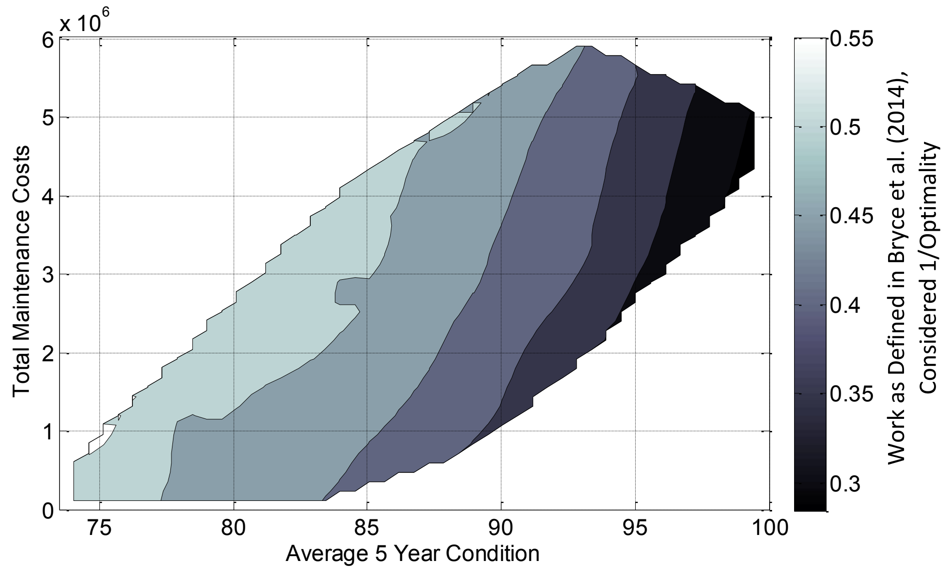


Figure 6-10. Average of Optimal Points Considered by All Decision Makers

The results shown in Figure 6-9 indicate that there are two areas of the decision space (denoted on the figure) that would be considered more desirable than the rest. This is important, because it indicates the most desirable outcomes fall within certain parts of the decision space, and several outcomes can be eliminated from discussion among this stakeholder group. However, Figure 6-10 shows that the overwhelming majority of this stakeholder group prefers outcomes that maximize condition above all else.

6.8. DISCUSSION

This paper presented the results of an anonymous survey designed to collect weights and certainty equivalents from a single group of stakeholders for sustainable infrastructure management. The certainty equivalents were used to develop utility functions for the group of respondents, which provide information about the respondents preferences and information about risk (Winterfeldt and Edwards, 2007). The methods for obtaining weights and certainty equivalents are generally performed in an interview setting (e.g., Ananda and Herath 2005) so that feedback can be given to the respondents about the implications and consistencies of their selections. The lack of feedback in the survey reported in this paper potentially led to a considerable amount of the inconsistencies seen in the answers (e.g., the case where the rankings and weightings of the criteria were reversed for respondents). Therefore, any future work on collecting certainty equivalents and weights at a large scale should be done using a platform which enables immediate feedback to the users about the implications of their responses.

Secondly, the results in this paper are representative of one stakeholder group that is familiar with pavement management, and this could explain the considerably high weights associated with condition. The condition of pavements is directly related to maintenance costs, and it is well known that the relationship is non-linear (i.e., a small drop in condition could lead to a relatively large increase in costs). Therefore, by placing such a high importance on condition, this stakeholder group may have considered that maintenance costs would decrease. By providing feedback (e.g., by presenting the stakeholders with

Figure 6-8 and Figure 6-10 prior to their completion of the survey), it would be important to see whether their preferences changed or stayed consistent.

Finally, it was commented within the survey by many of the respondents that the questions to determine certainty equivalents (e.g., Figure 6-2), as well as the many options associated with the AHP (Figure 6-1) were confusing. This lends support to the idea that feedback is a necessary component of determining certainty equivalents and weights. Furthermore, a Likert scale more familiar to the users, or another weighting technique may be better suited for a large scale survey, as opposed to using the AHP.

6.9. CONCLUSIONS

Sustainable infrastructure management is a multi-criteria problem that involves the input from many different stakeholders. Thus, sustainable decision making within infrastructure management requires tradeoffs to be made between the many objectives (Wu and Flintsch 2009; Gurganus and Gharaibeh 2012). This paper expanded on previous research that used utility theory (Li and Sinha 2004; Georgy et al. 2005; Zietsman et al. 2006), as well as the AHP (Smith and Tighe 2006; Stich et al. 2011), to measure the preferences of decision makers on a more broad scale. It was determined that a platform that provides real time feedback to respondents would be a more appropriate approach over the static platform used in this work. However, some insightful finding could be made from this work. For example, people who work within infrastructure management tend to be much more concerned with condition than costs and energy consumption. Secondly, energy consumption and costs were weighted similarly, but it is thought this could be due to inconsistencies in the responses given that the majority of respondents ranked costs second most important (although ranking does not preserve the scale of preferences, only the order). Finally, it was shown that several feasible solutions could be determined as non-preferable outcomes by including input from the many different respondents.

6.10. Chapter 6 Referecnces

Barrella, E. M., Amekudzi, A. A., and Meyer, M. D. (2013). Evaluating Sustainability Approaches of Transportation Agencies Through a Strengths, Weaknesses, Opportunities,and Threats Framework. *Transportation Research Record: Journal of the Transportation Research Board*, No 2357, 41-49.

Bryce, J., Flintsch, G., & Hall, R. (2014a). A Multi Criteria Decision Analysis Technique for Sustainable Infrastructure Management Business Practices. *Transport Research Part D, **In Review**.*

Bryce, J., Katicha, S., Flintsch, G., Sivaneswaran, N., & Santos, J. (2014b). Probablistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements . *93rd Annual Meeting of the Transportation Research Board of the National Academies.* Washington, D.C.

Chamorro, A., and Tighe, S. L. (2009). Development of a Management Framework for Rural Roads in Developing Countries. *Transportation Research Record of the National Academies No. 2093*, pp. 99-107.

Choo, Eng U., Schoner, Bertram, Wedley, William. (1999). Interpretation of criteria weights in multicriteria decision making. *Computers & Industrial Engineering, Volume 37, Issue 3.* pp. 527-541

Committee on Sustainability Linkages in the Federal Government. (2013). *Sustainability for the Nation: Resource Connection and Governance Linkages*. Washington, DC: National Research Council .

Davis, S., Caldeira, K., and Matthews, D. (2010). Future CO^2 Emissions and Climate Change from Existing Energy Infrastructure. *Science No. 329*, 1330-1333.

Dietz, T., and Stern, P. C. (2008). *Public Participation in Environmental Assessment and Decision Making*. Washington, DC: National Research Council.

ECMT. (2004). *European Conference of Ministers of Transportation: Assessment and Decision Making for Sustainable Transport*. Paris: OECD Publications Service.

FHWA. (2011). *Transportation Planning for Sustainability Guidebook*. Washington, DC: US Department of Transportation.

Gurganus, C., and Gharaibeh, N. (2012). Project Selection and Prioritization of Pavement Preservation. *Transportation Research Record of the National Academies No. 2292*, 36-44.

Handfield, R., Walton, S. V., Sroufe, R., and Melnyk, S. A. (2002). Applying environmental criteria to supplier assessment: A study in the application of the Analytical Hierarchy Process. *European Journal of Operational Research*, Vol. 141, pp. 70-87.

Holden, M. (2013). Sustainability indicator systems within urban governance: Usability analysis of sustainability indicator systems as boundary objects. *Ecological Indicators*, 32, 89-96.

Jansen, S. J. (2011). The Multi-attribute Utility Method. In S. J. Jansen, H. Coolen, and R. Goetgeluk, *The Measurement and Analysis of Housing Preference and Choice* (pp. 101-125). Dordrecht: Springer.

Li, Z., and Sinha, K. C. (2004). *Methodology for the Development of a Highway Asset Management System for Indiana: Publication FHWA/IN/JTRP-2003/21*. West Lafayette, Indiana: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University.

Mansfield, T. J., and Hartell, A. M. (2012). Institutionalizing Sustainability at the Level of State Departments of Transportation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2271, 9-18.

Robbins, M., Simonsen, B., Feldman, B. (2008). Citizens and Resource Allocation: Improving Decision

Making with Interactive Web-Based Citizen Participation. *Public Administration Review*, pp. 564-575.

Smith, J., and Tighe, S. (2006). The Analytical Hierarchy Process as a Tool for Infrastructure Management. *Transportation Research Record, Journal of the Transportation Research Board*, 1974.

Stich, B., Holland, J. H., Noberga, R. A., and O'Hara, C. G. (2011). Using multi-criteria decision making to highlight stakeholders' values in the corridor planning process. *The Journal of Transport and Land Use*, 4(3), 105-118.

US Energy Information Administration. (2014, February 25). *Frequently Asked Questions*. Retrieved from How Much Electricity Does an American Home Use?: www.eia.gov/tools/faqs

Winterfeldt, D. v., and Edwards, W. (2007). Defining a Decision Analytic Structure. In D. v. Winterfeldt, and W. Edwards (Eds.), *Advances in Decision Analysis* (pp. 81-103). New York: Cambridge University Press.

Wu, Z., and Flintsch, G. (2009). Pavement Preservation Optimization Considering Multiple Objectives and Budget Variability. *ASCE Journal of Transportation Engineering*, 135(5), 305-315.

Zietsman, J., Rilett, L., and Kim, S.-J. (2006). Transportation Corridor Decision Making with Muti Attribute Utility Theory. *International Journal of Management and Decision Making*, 7(2/3), 254-266.

Chapter 7.
Conclusions and Recommendations for Future Research

7.1. SUMMARY OF DISSERTATION

This dissertation had two main objectives, to (1) expand the boundaries of pavement LCA to include the use phase and assess the impact of this on pavement management decision making, and (2) develop a decision analysis methodology that assists engineers and planners when including environmental factors into asset management decision processes. The work started with a review of pavement lifecycle assessment, the current state of sustainable pavement management, and an analysis of two recently developed rolling resistance models. The two recently developed rolling resistance models produced similar results, and the conclusion that was drawn that small variations in vehicle speed (assuming freeway conditions) could have a significant impact on vehicle fuel consumption compared to pavement condition or surface properties. However, it is still debated whether the range of conditions of roads in the US is wide enough to impact driver speed. Therefore, in order to promote reduced energy consumption (and increased environmental sustainability), highway agencies should consider pavement roughness as an indicator of the environmental impacts of pavements.

Based on the review of typical pavement LCA practices, it was determined that the biggest shortcoming of many pavement LCA's is the exclusion of the use phase. However, the recently developed rolling resistance models provide some of the necessary information to allow the use phase to be included into a pavement LCA. Using this knowledge, a case study which included a comprehensive LCA was evaluated for a specific project conducted on an interstate in Virginia. The comprehensive case study demonstrated the considerable impact that the pavement use phase has on all environmental indicators, with the exception of abiotic resshowedource depletion. It was also discovered that expanding the boundaries of the typical pavement LCA to include pre-production sources results in approximately 10 to 20 percent of environmental impacts from the pavement network potentially originates from the power grid (e.g., the power supplied to manufacturing plants). Therefore, a national energy plan that reduces environmental impacts from energy production, will also extend to reducing the environmental impacts from the transportation sector. Furthermore, it was demonstrated how applying an inadequate treatment to a pavement segment in order to maintain it in adequate condition could result in considerably higher environmental impacts when compared to applying a treatment designed to address the causes of rapid pavement deterioration.

Another finding in the literature review was that there is a lack of tools for conducting a pavement LCA for a network of pavements. This is because LCA's are detailed processes defined by specific steps, whereas network level pavement management data is not as detailed as is required to conduct an LCA. To address this, a probabilistic approach to a network level environmental LCA using a typical Monte Carlo approach was presented. The many uncertainties in network-level pavement management decisions could be represented as probability distributions, and then combined to develop distributions of potential outcomes based on desired levels of certainty. Furthermore, it was shown how the non-dominated solution surface (considering three pavement management objectives) is expected to evolve with evolving preferences.

The network level pavement LCA revealed the tradeoff that must be addressed between the cost, condition and energy consumption of the pavement network. This tradeoff constitutes a multi-criteria decision analysis problem. Many tools exist to choose the best solution among a set of non-dominated solutions. However, the uniqueness of the pavement management problem is that many stakeholders must be able to communicate their preferences given that transportation infrastructure is a public asset. Therefore, a novel method for combining two commonly used decision analysis techniques into a decision approach for evaluating the feasible solution space was developed for the three objective variables. Presenting the desirability of the entire feasible solution space has the benefit of providing decision makers with a means of communication across many stakeholder groups. A nonlinear binary integer program was developed to develop the non-dominated surface of results for the costs of maintenance, average condition and the resulting energy consumption (used as an environmental indicator) of a pavement network. It was shown that reducing energy consumption may require deviating from the contour defining the minimum cost-benefit alternatives.

Finally, a method for capturing preferences for many people within a stakeholder group was presented in terms of a survey that was designed specifically for transportation professionals pertaining to the tradeoffs between maintenance costs, energy consumption and average condition. It was found that the overwhelming majority of transportation professionals weighted and ranked condition considerably greater than energy consumption and costs. The transportation professionals tended to be risk averse towards condition, while preferences towards the other two criteria were equally risk averse and risk prone. It was shown how evaluating the preferences of all responses could potentially identify a few areas of the solution space that are more optimal than the remaining solutions, meaning that a large portion of the solution space can be labeled as not preferred. One shortcoming of the approach used was that the respondents were not provided with real time feedback, making the implications of their responses less understandable as they took the survey. Thus, it is recommended that a dynamic platform that produces real time feedback to participants should be used to capture preferences for a large group of people.

7.2. FINDINGS

This research has led to the following findings:

- Recently developed models that relate vehicle rolling resistance to pavement properties can prove to be a valuable resource for transportation agencies, particularly when they are concerned with analyzing such factors as the impact of excessive roughness on fuel consumption or the potential value of smoothness to road users.
- A relatively small decrease in vehicle speed may negate the increased fuel consumption from the increased rolling resistance that accompanies poor pavement condition. However, the pavement conditions representative of US roads may not influence vehicle speeds (i.e., cars may not have to slow down due to poor pavement conditions).
- The models developed to measure rolling resistance as a function of pavement properties in Europe and the US produce similar results when compared using the same data.
- The results of LCA's at the network level includes a significant amount of uncertainties. In order to account for these uncertainties, LCA results can be analyzed similar to costs, in that uncertainties

can be quantified and combined to produce distributions of possible outcomes.

- The phase of a pavement lifecycle that produces the most significant environmental burden is the usage phase. Therefore, even small improvements in surface condition of the pavements may produce significant decreases in environmental burdens over the pavements life.
- It was found that, for the case study evaluated within this dissertation, increasing the structural capacity of a pavement can significantly reduce the environmental impact of the pavement by reducing the frequency of requires maintenance actions.
- The detailed case study found that pre-combustion energy represents approximately 17% of the primary energy consumed over the life cycle of the pavement system. Thus a shift in the national power grid towards more sustainable energy production could have a significant impact on the environmental burdens associated with pavement networks.
- A significant tradeoff exists between the various criteria considered in sustainable management. For example, reducing the energy consumption over a pavements life may include higher costs. Given that transportation infrastructure is a public asset, clear communication of the tradeoffs between economic and environmental impacts is essential. Therefore, in order to implement more sustainable practices in pavement management, a multi-criteria decision approach which elucidates the feasible solution space for each of the objective variables should be adopted.
- In order to implement a multi criteria approach in sustainable pavement management, stakeholder preferences need to be evaluated, thus allowing the tradeoffs between the several criteria among several stakeholders to be investigated. To do this, a tool must be created to help the stakeholders understand the problem, the tradeoffs and the implications of their preferences.

7.3. CONCLUSIONS

The shift towards sustainable infrastructure requires a shift in management practices for the agencies that fund and maintain the infrastructure. The first step in this shift is understanding the potential impact that the infrastructure has on the environment. Secondly, it has to be clearly demonstrated how decision making may be influenced if environmental impacts are included in the decision process. This dissertation represents a step in the direction towards more environmentally sound decision making by presenting both the impacts of infrastructure on the environment, as well as the change in decision alternatives when environmental decision making is included as a decision objective.

Based on the work presented in this dissertation, it can be concluded that adequate tools exist to include the use phase into a pavement LCA. Furthermore, the impact of not including the use phase into a pavement LCA can lead to decision making that has a minimal immediate environmental impact, but has a significantly higher long-term environmental impact. For example, a minimal mill and overlay will have a significantly smaller environmental impact than a reconstruction when only considering the materials and construction phases. However, the reconstruction may reduce the rate of deterioration of the pavement, which would reduce the rolling resistance, and ultimately reduce the environmental impact of the pavement.

Secondly, methods that address the tradeoff between economic and environmental impacts must have the ability to convey the tradeoff to the many stakeholders impacted by transportation infrastructure. These methods should act as an intermediary communication tool between different sets of stakeholders. This is critical because different stakeholders will have different preferences, which means they will see different outcomes as optimal. Given the significant costs of maintaining a pavement network, as well as the significant environmental impact pavement networks have, the preferences of all stakeholder groups should be used to inform the strategic level objectives for pavement management.

Finally, a paradigm shift is required for transportation infrastructure to become more sustainable. This shift means that transportation infrastructure cannot be seen as isolated system to be managed outside of its connection with society and the natural environment. Transportation infrastructure is the foundation that connects communities together, as well as connects society to the natural environment. Therefore, transportation infrastructure management should be informed by public policy initiatives (e.g., environmental protection) along with sound engineering principles.

7.4. SIGNIFICANCE AND IMPACT

This dissertation has presented a series of manuscripts designed to add to the body of knowledge related to pavement LCA's and decision analysis as it pertains to sustainable pavement management. Each manuscript represents a contribution to the field of infrastructure management. Furthermore, the information within each manuscript was disseminated through conferences and publications in order to increase the impact of their contents.

This dissertation contributes to the engineering field by providing engineers with additional techniques and models with which they can evaluate the environmental impact resulting from their pavement management decisions. Furthermore, the work within this dissertation can be used to inform engineering decisions, such as justifying the extra effort to thoroughly conduct a pavement LCA including the use phase. Also, it is expected that the data and models presented within this dissertation are directly applicable to modern engineering practice.

The results within this dissertation involve the impact of pavement management decisions on the natural environment, which has a broad impact on many fields of science and engineering. However, the main scientific contribution from this work is the development of a decision analysis technique that can be used as a communication tool to express preferences between many stakeholders. Previously, decision analysis focused on determining one optimal solution (or a small set of solutions), as opposed to analyzing the desirability of an entire solution space. However, decision analysis is prescriptive in nature, which means that personal preferences inform logical models in order to find a best solution. By presenting the desirability of an entire decision space, the impact of the preferences of many stakeholders can be compared, and the tradeoff made by each stakeholder when a final solution is reached can be clearly illustrated and understood.

7.5. RECOMMENDATIONS FOR FUTURE RESEARCH

- Energy consumption was used as the main environmental indicator throughout much of this dissertation. However, work should be conducted to determine how good of an indicator that energy consumption is when related to other pollutants (e.g., greenhouse gases) at the network level.
- This research focused mainly on the impact of pavement roughness on the environmental impacts, and not the impact that different types of pavement maintenance have on the texture of the surface. A recommendation to increase the understanding of the sustainability of maintenance actions is to evaluate the impact of particular pavement maintenance activities on the pavement surface texture.
- Following the previous recommendation, the evolution of pavement surface texture over time should be modeled to better understand the increase in vehicle fuel consumption as pavement age increases.
- The models for rolling resistance indicate that reducing pavement macrotexture can significantly reduce rolling resistance. However, macrotexture also impacts several other important pavement management concerns such as noise, friction and splash and spray. Therefore, research should be done to determine the influence macrotexture has on each of these concerns, and the tradeoff that occurs when each of these concerns are improved.
- Social indicators should be measured in terms of how pavement management decisions may impact their outcomes, and then combined into the multi criteria decision techniques. For example, environmental justice dictates that pollutants should not be disproportionally placed on one particular area or group of people. Another social indicator could be the amount and location of pavement work conducted in specific areas, given that this work has economic impacts such as providing jobs to specific areas. Thus measures to indicate the impact of projects on societies need to be developed.
- A tool that provides real time feedback to respondents should be developed in order to gather the value functions and weights of many stakeholders. The best method for developing such a tool should include research with engineers as well as social scientists and communications professionals.

Appendix A.
Code Used in Chapter 3: Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements

The following bulleted lists describes the flow (and consequently) the order of the files in this appendix.

- Main
  - Rdevel

    (Rdevel is a script to develop the 'R' matrix, which is a matrix with roads as rows, and years as columns. It is a binary matrix such that a value of 1 indicates work done on road (j) in year (i))

    - Combrds

      (Combrds is a function to develop multiple combinations of roads given certain constraints)

  - Costs (a function to assign costs to maintenance)
  - Energy (The function to assign energy values to the maintenance performed)
    - Preventive (Energy for PM)
    - Corrective (Energy for CM)
    - Restorative (Energy for RM)
    - Reconstruct (Energy for RC)
  - Condition (The function to determine the condition of the road)
  - RRener2 (The function to determine the energy from vehicles travelling on the pavement)

A.1 Main File

```
% This is the main input file
tic
load('ts.mat', 'ts'); %ts is a set of predefined maintenance actions
p3=[1 5 10 25 50 75 90 95 99]; %This is the set of probabilities to be
evaluated
for countAltMat=1:50000

    if countAltMat<10
        R=ts(1:5,:,countAltMat);
    else
        [R]=Rdevel(yrs,pci);
    end

    for ip=1:9
        p=p3(ip);
        hvf=[0  1   0.01728; 1  2   0.0144; 2   3   0.0117; 3   4
           0.01378;...
            4   5   0.0159; 5   6   0.01908; 6  7   0.0285; 7   8
           0.0392;...
            8   9   0.04704; 9  10  0.054; 10   11  0.05508; 11 12
```

```
   0.05712;...
    12  13  0.057; 13   14  0.06656; 14 15  0.06936; 15 16
   0.07738;...
    16  17  0.09114; 17 18  0.0602; 18  19  0.0517; 19  20
   0.04418;...
    20  21  0.03496; 21 22  0.03072; 22 23  0.02496; 23 24
   0.02162];

LookupTableCar=[5 128.05309267598; 10   66.76; 15 46.94; 20
               37.74; 25 33.00; 30 30.66;...
    35 29.84; 40 30.09; 45 31.19; 50 32.97; 55 35.35];
LookupTableTr=[5 221.620637912342; 10 137.9323999; 15
               112.9167756; 20 104.7499829;...
    25 104.6470697; 30 109.7694233; 35 118.9155463; 40
               131.516404;...
    45 147.3014505; 50 166.1660815; 55 188.2483439];

yrs=5; n=3000;
lngth=[1.8 2.2 1.1 2.4 2.1 1.6 1.3 1.9];
Traffic=[20000 37000 25000 12000 32000 41000 15000 30000];
truckpercentage=[0.23 0.25 0.21 0.27 0.25 0.19 0.22 0.24];
price=[0 0.14 1.41 3.56 10]; pci=[65 83 92 55 73 68 93 75];
thresholds=[90 80 65 50]; IRIa=[130 80 77 115 97 110 65 91];
%p=50; % p is the percentile (i.e., 50 gives the mean of the
data)
numberrds=1:length(pci);
xlsheet=1;
% PCI Increase for PM
PMbump=8; stdPMbumb=1;Rupdated=zeros(yrs,8);
Cond=zeros(yrs,8); Mon=zeros(yrs,8); NetEn=zeros(yrs,8);
MaintEn=zeros(yrs,8); Cond(1,:)=pci(1,:);

for i=1:yrs
    if i>1
        Cond(i,:)=condt2;
    end

    Condi=Cond(i,:);
    if sum(sum(R))>0
        [cost]=costs(price,thresholds,Condi);
        cost2=cost.*lngth;
        Mon(i,:)=cost2(1,:).*R(i,:);
        li=find(Mon(i,:)>0);
        [MaintEnP]=energy(Condi,thresholds,n,p);
        MaintEnP(1,:)=MaintEnP(1,:).*R(i,:);
        MaintEn(i,li)=MaintEnP(1,li);
    end

    % Revise R for rolling resistance
    Rfind(1,:)=R(i,:).*Cond(i,:);
    lR=find(Rfind(1,:)<thresholds(2) & Rfind(1,:)~=0);
```

```
            if ~isempty(lR)
                Rupdated(i,lR)=1;
                Cond(i,lR)=100; % Reset major rehab back to zero
            end

            % Add PCI to Preventive Maint
            lPM=find(Rfind(1,:)>=thresholds(2) &
Rfind(1,:)<=thresholds(1));
            PMrand=2*stdPMbumb*rand(1,1)-1+PMbump;
            if ~isempty(lPM)
                Cond(i,lPM)=Cond(i,lPM)+PMrand; % add a uniformaly
distributed amount to pavements that recieve PM
            end
            [condt2]=condition(Cond(i,:),n,p);
        end

        % Develop the Alternative Matrix countAltMat
        for k3=1:yrs
            LngthCondt(k3)=sum(Cond(k3,:).*lngth)/sum(lngth);
        end
        WtAveCond=mean(LngthCondt);
        TotCost=sum(sum(Mon));
        TotMaintEn=sum(sum(MaintEn));

        [EnergyConsum, Veh]=RRener2(n, IRIa, Traffic, lngth,
truckpercentage, p, Rupdated, yrs);
        TotRRener=sum(sum(EnergyConsum));

        TotEn=TotMaintEn+TotRRener;
        AltMat(countAltMat,1,ip)=TotCost;
        AltMat(countAltMat,2,ip)=WtAveCond;
        AltMat(countAltMat,3,ip)=TotEn;
        AltMat(countAltMat,4,ip)=TotMaintEn;
        AltMat(countAltMat,5,ip)=TotRRener;

        if ip==1
            Cdt1(:,:,countAltMat)=Cond;
            Mny1(:,:,countAltMat)=Mon;
        elseif ip==2
            Cdt5(:,:,countAltMat)=Cond;
            Mny5(:,:,countAltMat)=Mon;
        elseif ip==3
            Cdt10(:,:,countAltMat)=Cond;
            Mny10(:,:,countAltMat)=Mon;
        elseif ip==4
            Cdt25(:,:,countAltMat)=Cond;
            Mny25(:,:,countAltMat)=Mon;
        elseif ip==5
            Cdt50(:,:,countAltMat)=Cond;
            Mny50(:,:,countAltMat)=Mon;
        elseif ip==6
```

```
            Cdt75(:,:,countAltMat)=Cond;
            Mny75(:,:,countAltMat)=Mon;
        elseif ip==7
            Cdt90(:,:,countAltMat)=Cond;
            Mny90(:,:,countAltMat)=Mon;
        elseif ip==8
            Cdt95(:,:,countAltMat)=Cond;
            Mny95(:,:,countAltMat)=Mon;
        else
            Cdt99(:,:,countAltMat)=Cond;
            Mny99(:,:,countAltMat)=Mon;
        end
    end
end
toc
```

A.2 Rdevel File

```
function [R]=Rdevel(yrs,pci)
% yrs=20; pci=[65 83 92 55 73 68 93 75];
R=zeros(yrs,8);
rds=1:length(pci);
[s2]=combrds(rds);
randnum=round(length(s2)*rand(1,1));
if randnum==0
    randnum=1;
end
Malt=s2(randnum,:);
Malt=nonzeros(Malt);
for imalt=1:length(Malt)
    R(1,Malt(imalt))=1;
end

for iyrs=2:yrs
    tup=zeros(1,8);
    rds2=zeros(1,8);
    up=min(5,iyrs);

    fv=(iyrs-up+1); nv=(iyrs-1);

    for gup=fv:nv
        lgup= R(gup,:)>0;
        tup(lgup)=1;
    end
    rds2=find(tup==0);
    [s2]=combrds(rds2);

    if length(s2(:,1))>1
        randnum=round(length(s2)*rand(1,1));
        if randnum==0
            randnum=1;
```

```
        end
        Malt=s2(randnum,:);
        Malt=nonzeros(Malt);
        for imalt=1:length(Malt)
            R(iyrs,Malt(imalt))=1;
        end
    end
end
```

A.3 Combrds File

```
function [s2]=combrds(rds2)
% rds2=[2 3 4 5 6 7 8];
count5=1;

if ~isempty(rds2)
    for i=1:length(rds2)
        R2=combnk(rds2,i);
        count5=count5+size(R2,1);
    end
    s2=zeros(count5,length(rds2));
    count5=1;
    for i=1:length(rds2);
        R2=combnk(rds2,i);
        o1=size(R2,1);
        o2=size(R2,2);
        for h=1:o1
            for h2=1:o2
                s2(count5,h2)=R2(h,h2);
            end
            count5=count5+1;
        end
    end
else
    s2=zeros(1,8);
end
```

A.4 Costs File

```
function [cost]=costs(price,thresholds,Cond)

for u6=1:8
    if Cond(u6)>90
        cost(u6)=price(1);
    elseif Cond(u6)<=thresholds(1) && Cond(u6)>thresholds(2)
        cost(u6)=price(2);
    elseif Cond(u6)<=thresholds(2) && Cond(u6)>thresholds(3)
        cost(u6)=price(3);
    elseif Cond(u6)<=thresholds(3) && Cond(u6)>thresholds(4)
        cost(u6)=price(4);
    elseif Cond(u6)<=thresholds(4) && Cond(u6)>0
        cost(u6)=price(5);
    elseif Cond(u6)==0
        cost(u6)=0;
    end
end
```

A.5 Energy Function

```
function [MaintEnP]=energy(Cond,thresholds,n,p)
ener=zeros(n,8); MaintEnP=zeros(1,8);
for u7=1:8
    if Cond(u7)>thresholds(1)
        ener(:,u7)=0;
    elseif Cond(u7)<=thresholds(1) && Cond(u7)>thresholds(2)
        [PM]=Preventive(n);
        ener(:,u7)=PM(:,1);
    elseif Cond(u7)<=thresholds(2) && Cond(u7)>thresholds(3)
        [CM]=Corrective(n);
        ener(:,u7)=CM(:,1);
    elseif Cond(u7)<=thresholds(3) && Cond(u7)>thresholds(4)
        [RM]=Restorative(n);
        ener(:,u7)=RM(:,1);
    elseif Cond(u7)<=thresholds(4) && Cond(u7)>0
        [RC]=Reconstruct(n);
        ener(:,u7)=RC(:,1);
    elseif Cond(u7)==0
        ener(:,u7)=0;
    end
end
MaintEnP(1,:)=prctile(ener,p);
```

A.6 Preventive Function

```
%% Preventive Maintenance
% This code calculates a distribution of expected values for
preventive
% maintenance PER LANE-MILE OF TREATED ROAD

function[PM]=Preventive(n)

Pl=normrnd(2470,247,n,1); % Energy distibution for placing materials
Md=normrnd(200548,20055,n,1); % Energy distibution for mix design
Trans1=unifrnd(1,50,n,1); % Distribution of Hauling Distance -
Aggregate to Plant
Trans2=unifrnd(1,50,n,1); % Distribution of Hauling Distance - Plant
to Site
AggPlant=(normrnd(200,10,n,1)./35.3).*Trans1; % Calculates Energy to
Haul Aggregate to plant
PlantSite=(normrnd(200,10,n,1)./35.3).*Trans2; % Calculates Energy to
Haul from plant to site
PM=Pl+Md+AggPlant+PlantSite;
```

A.7 Corrective Function

```
%% Corrective Maintenance
% This code calculates a distribution of expected values for
corrective
% maintenance PER LANE-MILE OF TREATED ROAD

function[CM]=Corrective(n)

% First initialize the random vaiables
x=rand(n,1);  % Generate an array of random numbers
OL=normrnd(1.7,0.4,n,1); % Distribution of Mix Thicknesses
Mill=sqrt(x.*((OL-0.5.*OL).^2))+0.5.*OL; % Sample Triangular
distribution
Trans1=unifrnd(1,50,n,1); % Distribution of Hauling Distance -
Disposal
Trans2=unifrnd(1,50,n,1); % Distribution of Hauling Distance -
Aggregate to Plant
Trans3=unifrnd(1,50,n,1); % Distribution of Hauling Distance - Plant
to Site

% Calculate the energy for each process given the above variables
MillE=normrnd(4550.*Mill,450.*Mill); % Distribution of Milling Energy
based on milling depth
LdE=normrnd(1310.*Mill,130.*Mill); % Distribution of Loading Energy
based on milling depth
AggProd=normrnd(14770.*OL,1477.*OL); % Distribution of Aggregate
Production Energy
BitProd=normrnd(111500.*OL,11150.*OL); % Distribution of Bitumen
Production Energy
HMAProd=normrnd(130125.*OL,13012.*OL); % Distribution of HMA
Production Energy
Tack=normrnd(3260,326,n,1); % Distribution of energy for tack coat
Pave=normrnd(913.*OL,91.*OL); % Distribution of paving energy
Roll=normrnd(913.*OL,91.*OL); % Distribution of rolling energy
TransDisp=normrnd(409.*Mill,41.*Mill).*Trans1; % Distribution of
disposal transport energy
TransAgg=normrnd(343.*OL,34.*OL).*Trans2; % Distribution of aggregate
transport energy
TransHMA=normrnd(409.*OL,41.*OL).*Trans3; % Distribution of HMA
transport energy

CM=MillE+LdE+AggProd+BitProd+HMAProd+Tack+Pave+Roll+TransDisp+TransAgg
+TransHMA;
```

A.8 Restorative Function

```
%% Restorative Maintenance
% This code calculates a distribution of expected values for
restorative
% maintenance PER LANE-MILE OF TREATED ROAD
```

```
function[RM]=Restorative(n)

% First initialize the random vaiables
x=rand(n,1);  % Generate an array of random numbers
OL=normrnd(3.6,0.5,n,1); % Distribution of Mix Thicknesses
Mill=sqrt(x.*((OL-0.5.*OL).^2))+0.5.*OL; % Sample Triangular
distribution
Trans1=unifrnd(1,50,n,1); % Distribution of Hauling Distance -
Disposal
Trans2=unifrnd(1,50,n,1); % Distribution of Hauling Distance -
Aggregate to Plant
Trans3=unifrnd(1,50,n,1); % Distribution of Hauling Distance - Plant
to Site

% Calculate the energy for each process given the above variables
MillE=normrnd(4550.*Mill,450.*Mill); % Distribution of Milling Energy
based on milling depth
LdE=normrnd(1310.*Mill,130.*Mill); % Distribution of Loading Energy
based on milling depth
AggProd=normrnd(14770.*OL,1477.*OL); % Distribution of Aggregate
Production Energy
BitProd=normrnd(111500.*OL,11150.*OL); % Distribution of Bitumen
Production Energy
HMAProd=normrnd(130125.*OL,13012.*OL); % Distribution of HMA
Production Energy
Tack=normrnd(3260,326,n,1); % Distribution of energy for tack coat
Pave=normrnd(913.*OL,91.*OL); % Distribution of paving energy
Roll=normrnd(913.*OL,91.*OL); % Distribution of rolling energy
TransDisp=normrnd(409.*Mill,41.*Mill).*Trans1; % Distribution of
disposal transport energy
TransAgg=normrnd(343.*OL,34.*OL).*Trans2; % Distribution of aggregate
transport energy
TransHMA=normrnd(409.*OL,41.*OL).*Trans3; % Distribution of HMA
transport energy

RM=MillE+LdE+AggProd+BitProd+HMAProd+Tack+Pave+Roll+TransDisp+TransAgg
+TransHMA;
```

A.9 Reconstruct Function

```
%% Rehabilitation Reconstruction
% This code calculates a distribution of expected values for
Rehabilitation/Reconstruction
% maintenance PER LANE-MILE OF TREATED ROAD

function[RC]=Reconstruct(n);
% First initialize the random vaiables
x=rand(n,1);  % Generate an array of random numbers
OL=normrnd(9,1.5,n,1); % Distribution of Mix Thicknesses
Mill=sqrt(x.*((OL-0.5.*OL).^2))+0.5.*OL; % Sample Triangular
distribution
```

```
Trans1=unifrnd(1,50,n,1); % Distribution of Hauling Distance -
Disposal
Trans2=unifrnd(1,50,n,1); % Distribution of Hauling Distance -
Aggregate to Plant
Trans3=unifrnd(1,50,n,1); % Distribution of Hauling Distance - Plant
to Site
% Calculate the energy for each process given the above variables
MillE=normrnd(4550.*Mill,450.*Mill); % Distribution of Milling Energy
based on milling depth
LdE=normrnd(1310.*Mill,130.*Mill); % Distribution of Loading Energy
based on milling depth
AggProd=normrnd(14770.*OL,1477.*OL); % Distribution of Aggregate
Production Energy
BitProd=normrnd(111500.*OL,11150.*OL); % Distribution of Bitumen
Production Energy
HMAProd=normrnd(130125.*OL,13012.*OL); % Distribution of HMA
Production Energy
Tack=normrnd(3260,326,n,1); % Distribution of energy for tack coat
Pave=normrnd(913.*OL,91.*OL); % Distribution of paving energy
Roll=normrnd(913.*OL,91.*OL); % Distribution of rolling energy
TransDisp=normrnd(409.*Mill,41.*Mill).*Trans1; % Distribution of
disposal transport energy
TransAgg=normrnd(343.*OL,34.*OL).*Trans2; % Distribution of aggregate
transport energy
TransHMA=normrnd(409.*OL,41.*OL).*Trans3; % Distribution of HMA
transport energy
Comp=normrnd(7040,704,n,1); % Distribution of compaction energy
RC=MillE+LdE+AggProd+BitProd+HMAProd+Tack+Pave+Roll+TransDisp+TransAgg
+TransHMA+Comp;
```

A.10 Condition function

```
function [a b c d e f g h i j k l m n o p q]=condition(Cond, pmbmp);

load('cci.mat'); % first column is years, second is condition for VDOT
deterioration models
a1=find(cci(:,1)==1); a=cci(a1,2);
b1=find(cci(:,1)==2); b=cci(b1,2);
c1=find(cci(:,1)==3); c=cci(c1,2);
d=min(100,(b+pmbmp)); e=min(100,(c+pmbmp)); f=min(100,(c+(2*pmbmp)));

yg=interp1(cci(:,2),cci(:,1),Cond); yg=yg+1;
if yg<17.95
    g=interp1(cci(:,1),cci(:,2),yg);
else
    g=0;
end

yh=interp1(cci(:,2),cci(:,1),Cond); yh=yh+2;
if yh<17.95
```

```
    h=interp1(cci(:,1),cci(:,2),yh);
else
    h=0;
end

i=min(100,(h+pmbmp));

yj=interp1(cci(:,2),cci(:,1),Cond); yj=yj+3;
if yj<17.95
    j=interp1(cci(:,1),cci(:,2),yj);
else
    j=0;
end

k=min(100,(j+pmbmp)); l=min(100,(j+(2*pmbmp)));

ym=interp1(cci(:,2),cci(:,1),Cond); ym=ym+4;
if ym<17.95
    m=interp1(cci(:,1),cci(:,2),ym);
else
    m=0;
end

n=min(100,(m+pmbmp)); o=min(100,(m+(2*pmbmp)));
p=min(100,(m+(3*pmbmp)));

q=100;
```

A.11 RRener2 Function

```
function [EnergyConsum, Veh]=RRener2(n, IRIa, Traffic, ~,
truckpercentage, p, Rupdated, yrs)
Initial=70; % Initial Expected IRI after Maintenance Action
StdIRI=10;  % Standard Deviation for initial IRI
rate=5;  % Expected rate of increase of IRI (in/mile)
StdRT=0.5;  % Standard deviation on rate of increase of IRI
% n=10000;
FC=zeros(yrs,8); IRI=zeros(yrs,8);
for kr=1:8
    IRImeas=IRIa(kr);  % Enter Initial value of measured IRI

    AADT=Traffic(kr); %Enter the initial traffic count
```

```
    stdAADT=1000; %Enter the standard deviation for initial traffic
count
    GR=0.03;     % Enter the traffic Growth Rate
    StdGR=0.003;  % Enter the standard deviation for the traffic
groath rate
    PercTrucks=truckpercentage(kr);  % Percent Trucks (between 0 and
1)
    GasEn=132;  % MJ per gallon of gasoline
    DiesEn=146;  % MJ per gallon of Diesel

    % Determine the Traffic over the years
    Veh(:,1)=normrnd(AADT,stdAADT,n,1);
    if yrs>1
        for j=2:yrs
            growthrate=(normrnd(1+GR,StdGR,n,1).^(j-1))  ; %Need to
find additional vehicles as a function of growth
            Veh(:,j)=Veh(:,1).*growthrate;
        end
    end

    Cars=Veh.*(1-PercTrucks);
    Trucks=Veh.*(PercTrucks);


    Rupdated2=Rupdated(:,kr);

        % Develop the roughness and Fuel Consumption Numbers
    for urt=1:length(Rupdated2)

        if Rupdated2(urt)==1
            x=rand(n,1);
            a=(Initial-1.5*StdIRI);  b=(Initial+1.5*StdIRI);
c=Initial;
            x1=b-a;
            x2=(x1.*x)+a;  % Generate an array of random numbers
            IRImaint=zeros(n,1);

            for k=1:n
                if x2(k)<=Initial
                    IRImaint(k,1)=(((x(k)*((b-a)*(c-a))))^0.5)+a; %
Distribution of Initial IRI
                else
                    IRImaint(k,1)=b-(((1-x(k))*(b-a)*(b-c))^0.5); %
Distribution of Initial IRI
                end
            end

            % Calc Fuel
            FCcar1=((0.015196.*IRImaint+46.51140)./1000).*Cars(:,urt);
% Absolute Increase in Fuel Consumption per car per mile...
            %Defined over range of values using Chatti and Zaabar
```

```
(2012)

FCtruck1=((0.048678.*IRImaint+305.99202)./1000).*Trucks(:,urt);  % See
Above comment


FC(urt,kr)=((prctile(FCtruck1,p)*DiesEn)+(prctile(FCcar1,p).*GasEn))*3
65;
            IRI(urt,kr)=prctile(IRImaint,p);
        else
            if urt==1
                IRImaint=ones(n,1).*IRImeas;

FCcar1=((0.015196.*IRImaint+46.51140)./1000).*Cars(:,urt);  % Absolute
Increase in Fuel Consumption per car per mile...
                %Defined over range of values using Chatti and Zaabar
(2012)

FCtruck1=((0.048678.*IRImaint+305.99202)./1000).*Trucks(:,urt);  % See
Above comment
                IRI(urt,kr)=prctile(IRImaint,p);

FC(urt,kr)=((prctile(FCtruck1,p)*DiesEn)+(prctile(FCcar1,p).*GasEn))*3
65;
            else
                IRImaint=ones(n,1).*IRI((urt-1),kr);
                y=normrnd(rate,StdRT,n,1);
                IRImaint=IRImaint+y;

FCcar1=((0.015196.*IRImaint+46.51140)./1000).*Cars(:,urt);  % Absolute
Increase in Fuel Consumption per car per mile...
                %Defined over range of values using Chatti and Zaabar
(2012)

FCtruck1=((0.048678.*IRImaint+305.99202)./1000).*Trucks(:,urt);  % See
Above comment
                IRI(urt,kr)=prctile(IRImaint,p);

FC(urt,kr)=((prctile(FCtruck1,p)*DiesEn)+(prctile(FCcar1,p).*GasEn))*3
65;
            end
        end
    end

end
EnergyConsum=FC;
```

Appendix B.
Code Used in Chapter 5: A Multi-Criteria Decision Analysis Technique for Sustainable Infrastructure Management Business Practices

The code used in this chapter follows as:

- runalgo (This code runs the minimization algorithm using the MATLAB® genetic algorithm)
    - Main1 (main(x) is the code the genetic algorithm is trying to minimize. For the maximization case, x=-x)
        - maintenergy (determins the amount of energy in maintenance actions)
        - costcond (Determines the cost per condtion)
        - totalenergy ((The total energy = maintenance + rolling resistance)
        - rren (Rolling resistance energy)
        - rough (Function of roughness over time)
        - Traff (Function of traffic over time)
        - esals (esal's as a function of traffic)
        - condition (condition as a function of the work done and previous condition)

B.1 runalgo

```
tic
IntCon = 1:65;
lb=zeros(390,1);
ub=ones(390,1);
opts = gaoptimset('PlotFcns',@gaplotbestf);


 [x1,fval1] = ga(@Main1,390,[],[],[],[],...
    lb,ub,[],IntCon,opts);

 for i=1:length(x1)
    if x1(i)<=0.02
        x1(i)=0;
    elseif x1(i)>=0.98
        x1(i)=1;
    end
 end

 [a1 b1 c1]=Main(x1);
 minen=a1;
```

B.2 Main1

```
function [etot, TotCst, MeanCd]=Main1(Xin)
```

```
% This is set for a 5 year analysis
load('data.mat');
pci=data(:,1);
X=zeros(length(pci),5);
lpci=length(pci);
for iw=1:lpci
    X(iw,1)=Xin(iw);
    X(iw,2)=Xin(iw+lpci);
    X(iw,3)=Xin(iw+lpci+lpci);
    X(iw,4)=Xin(iw+lpci+lpci+lpci);
    X(iw,5)=Xin(iw+lpci+lpci+lpci+lpci);
end

iri=data(:,2);
lnght=data(:,3);
aadt=data(:,4);
PercTrucks=data(:,5);
load('cci.mat')
pmbmp=8; irigrowth=5; NewIRI=60;
thresholds=[90 80 65 45];
Costs=[7064 74073 186091 451657];
%X=ones(length(pci),5);
Y=zeros(length(pci),5); Cd=zeros(length(pci),6);
cst=zeros(length(pci),5);
GR=0.03; % Traffic Growth (0.03 is 3%)
yrs=5;

for i1=1:length(pci)
    % Calculate a through q
    % Ma is the maintenance energy

    Cond=pci(i1);
[Ma1, Mb1, Mc1, Md1, Me1, Mf1, Mg1, Mh1, Mi1, Mj1, Mk1, Ml1, Mm1, Mn1,
Mo1, Mp1, Mq1, Mr1, Ms1, Mt1, Mu1, Mv1, Mw1, Mx1, My1, Mz1, Maa1,
Mbb1, Mcc1, Mdd1, cdt]=maintenergy(Cond, pmbmp, thresholds, i1);
    rou=iri(i1); [A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q,
R, [DD]=rough(rou, irigrowth, NewIRI);
    Ma(i1,1)=Ma1; Mb(i1,1)=Mb1; Mc(i1,1)=Mc1; Md(i1,1)=Md1;
Me(i1,1)=Me1; Mf(i1,1)=Mf1;
    Mg(i1,1)=Mg1; Mh(i1,1)=Mh1; Mi(i1,1)=Mi1; Mj(i1,1)=Mj1;
Mk(i1,1)=Mk1;
    Ml(i1,1)=Ml1; Mm(i1,1)=Mm1; Mn(i1,1)=Mn1; Mo(i1,1)=Mo1;
Mp(i1,1)=Mp1; Mq(i1,1)=Mq1;
    Mr(i1,1)=Mr1; Ms(i1,1)=Ms1; Mt(i1,1)=Mt1; Mu(i1,1)=Mu1;
    Mv(i1,1)=Mv1; Mw(i1,1)=Mw1; Mx(i1,1)=Mx1; My(i1,1)=My1;
Mz(i1,1)=Mz1;
    Maa(i1,1)=Maa1; Mbb(i1,1)=Mbb1; Mcc(i1,1)=Mcc1; Mdd(i1,1)=Mdd1;

    a1=cdt(1); b1=cdt(2); c1=cdt(3); d1=cdt(4); e1=cdt(5); f1=cdt(6);
g1=cdt(7); h1=cdt(8); i1i=cdt(9); j1=cdt(10);
```

```
    k1=cdt(11); l1=cdt(12); m1=cdt(13); n1=cdt(14); o1=cdt(15);
p1=cdt(16); q1=cdt(17); r1=cdt(18); s1=cdt(19); t1=cdt(20);
    u1=cdt(21); v1=cdt(22); w1=cdt(23); x1=cdt(24); y1=cdt(25);
z1=cdt(26); aa1=cdt(27); bb1=cdt(28);
    cc1=cdt(29); dd1=cdt(30);

    a(i1,1)=a1; b(i1,1)=b1; c(i1,1)=c1; d(i1,1)=d1; e(i1,1)=e1;
f(i1,1)=f1;
    g(i1,1)=g1; h(i1,1)=h1; i(i1,1)=i1i; j(i1,1)=j1; k(i1,1)=k1;
    l(i1,1)=l1; m(i1,1)=m1; n(i1,1)=n1; o(i1,1)=o1; p(i1,1)=p1;
q(i1,1)=q1;
    r(i1,1)=r1; s(i1,1)=s1; t(i1,1)=t1; u(i1,1)=u1;
    v(i1,1)=v1; w(i1,1)=w1; x(i1,1)=x1; y(i1,1)=y1; z(i1,1)=z1;
    aa(i1,1)=aa1; bb(i1,1)=bb1; cc(i1,1)=cc1; dd(i1,1)=dd1;
    % Need Mv, Mw, Mx, My, Mz, Maa, Mbb, Mcc, Mdd


    % Use Traffic to calc the traffic for each road for 4 years
    Veh=aadt(i1);
    [Tr]=Traff(GR, Veh, PercTrucks(i1), yrs);
    %Tr(:,1) is cars and Tr(:,2) is trucks
    Lng=lnght(i1);
    %Need to find [R2a, R3a, R4a, R3b, R4b, R4c, R2g, R3h, R4j, R1q,
R2q,
    %R3q, R4q, and R1r]

    % Also R5m R5dd R5c R5b R5a R5q
    [R2a1, R3a1, R4a1, R3b1, R4b1, R4c1, R2g1, R3h1, R4j1, R1q1, R2q1,
R3q1, R4q1, R1r1, R5m1, R5dd1, R5c1, R5b1, R5a1, R5q1]=rren(A, B, C,
G, H, J, Q, R, M, DD, Tr, Lng);

    R5m(i1,1)=R5m1; R5dd(i1,1)=R5dd1; R5c(i1,1)=R5c1; R5b(i1,1)=R5b1;
R5a(i1,1)=R5a1; R5q(i1,1)=R5q1;

    R2a(i1,1)=R2a1; R3a(i1,1)=R3a1; R4a(i1,1)=R4a1;
    R3b(i1,1)=R3b1; R4b(i1,1)=R4b1; R4c(i1,1)=R4c1;
    R2g(i1,1)=R2g1; R3h(i1,1)=R3h1; R4j(i1,1)=R4j1;
    R1q(i1,1)=R1q1; R2q(i1,1)=R2q1; R3q(i1,1)=R3q1; R4q(i1,1)=R4q1;
    R1r(i1,1)=R1r1;
end

% Determine Condition Cd(:,1)=Intitial Condition (Condition in Year 1)
Cd(:,1)=pci(:,1);

for i2=1:length(pci)


    for pq=1:5
```

```
        if X(i2,pq)==1 && Cd(i2,pq)<=thresholds(1) &&
Cd(i2,pq)>thresholds(2)
            Y(i2,pq)=1;
            Cd(i2,(pq+1))=Cd(i2,pq)+pmbmp;
            cst(i2,pq)=Costs(1);

        elseif X(i2,pq)==1 && Cd(i2,pq)<=thresholds(2)
            Cd(i2,(pq+1))=100;

            if Cd(i2,pq)<=thresholds(2) && Cd(i2,pq)>thresholds(3)
                cst(i2,pq)=Costs(2);
            elseif Cd(i2,pq)<=thresholds(3) && Cd(i2,pq)>thresholds(4)
                cst(i2,pq)=Costs(3);
            elseif Cd(i2,pq)<=thresholds(4) && Cd(i2,pq)>0
                cst(i2,pq)=Costs(4);
            end

        elseif X(i2,pq)==1 && Cd(i2,pq)>thresholds(1)
            m1=interp1(cci(:,2),cci(:,1),Cd(i2,pq)); m1=m1+1;
            if m1<17.95
                Cd(i2,(pq+1))=interp1(cci(:,1),cci(:,2),m1);
            else
                Cd(i2,(pq+1))=0;
            end
            clear m1
        elseif X(i2,pq)==0
            m1=interp1(cci(:,2),cci(:,1),Cd(i2,pq)); m1=m1+1;
            if m1<17.95
                Cd(i2,(pq+1))=interp1(cci(:,1),cci(:,2),m1);
            else
                Cd(i2,(pq+1))=0;
            end
            clear m1
        end


    end

end

[etot]=totalenergy(X, Y,  Ma, Mb, Mc, Md, Me, Mf, Mg, Mh, Mi, Mj, Mk,
Ml, Mm, Mn, Mo, Mp, Mq, Mr, Ms, Mt, Mu, R5m, R5dd, R5c, R5b, R5a, R5q,
R2a, R3a, R4a, R3b, R4b, R4c, R2g, R3h, R4j, R1q, R2q, R3q, R4q, R1r,
Mv, Mw, Mx, My, Mz, Maa, Mbb, Mcc, Mdd);
cdt2=[a b c d e f g h i j k l m n o p q r s t u v w x y z aa bb cc
dd];
[cdtfinal]=meancdt(X, Y, cdt2, pci, pmbmp);
TotCst=sum(sum(cst)); MeanCd=cdtfinal;
```

B.3 Maintenergy

```
function [Ma Mb Mc Md Me Mf Mg Mh Mi Mj Mk Ml Mm Mn Mo Mp Mq Mr Ms Mt
Mu, Mv, Mw, Mx, My, Mz, Maa, Mbb, Mcc, Mdd, cdt]=maintenergy(Cond,
pmbmp,thresholds, i1)
%Cond=67; thresholds=[90 80 65 50]; pmbmp=8;

load('cci.mat')
load('PM.mat')
load('CM.mat')
load('RM.mat')
load('RC.mat')
a1=find(cci(:,1)==1); a=cci(a1,2); b1=find(cci(:,1)==2); b=cci(b1,2);
c1=find(cci(:,1)==3); c=cci(c1,2); d=min(100,b+pmbmp);
e=min(100,c+pmbmp);
f=min(100,c+2*pmbmp);

g1=interp1(cci(:,2),cci(:,1),Cond); g1=g1+1;
if g1<17.95
    g=interp1(cci(:,1),cci(:,2),g1);
else
    g=0;
end

u=min(100,g+pmbmp);

h1=interp1(cci(:,2),cci(:,1),Cond); h1=h1+2;
if h1<17.95
    h=interp1(cci(:,1),cci(:,2),h1);
else
    h=0;
end

i=min(100,h+pmbmp);
t=min(100,h+2*pmbmp);

j1=interp1(cci(:,2),cci(:,1),Cond); j1=j1+3;
if j1<17.95
    j=interp1(cci(:,1),cci(:,2),j1);
else
    j=0;
end

k=min(100,j+pmbmp);
l=min(100,j+2*pmbmp);

m1=interp1(cci(:,2),cci(:,1),Cond); m1=m1+4;
if m1<17.95
    m=interp1(cci(:,1),cci(:,2),m1);
else
    m=0;
end
```

```
n=min(100,m+pmbmp);
o=min(100,m+2*pmbmp);
p=min(100,m+3*pmbmp);

q=100;
r=Cond;
s=min(Cond+pmbmp,100);

v1=interp1(cci(:,2),cci(:,1),Cond); v1=v1+5;
if v1<17.95
    v=interp1(cci(:,1),cci(:,2),v1);
else
    v=0;
end

w=min(100,v+1*pmbmp);
x=min(100,v+2*pmbmp);
y=min(100,v+3*pmbmp);
z=min(100,v+4*pmbmp);

%c1=find(cci(:,1)==3); c=cci(c1,2); d=min(100,b+pmbmp);

aa1=find(cci(:,1)==4); aa2=cci(aa1,2); aa=min(100,aa2+pmbmp);
bb=min(100,aa2+2*pmbmp);
cc=min(100,aa2+3*pmbmp); dd=aa2;

cdt=[a b c d e f g h i j k l m n o p q r s t u v w x y z aa bb cc dd];
for ul=1:length(cdt)
    cdt1=cdt(ul);
    if cdt1>thresholds(1)
        ener(ul)=0;
    elseif cdt1<=thresholds(1) && cdt1>thresholds(2)
        ener(ul)=PM;
    elseif cdt1<=thresholds(2) && cdt1>thresholds(3)
        ener(ul)=CM;
    elseif cdt1<=thresholds(3) && cdt1>thresholds(4)
        ener(ul)=RM;
    elseif cdt1<=thresholds(4) && cdt1>0
        ener(ul)=RC;
    elseif cdt1==0
        ener(ul)=0;
    end
end

Ma=ener(1); Mb=ener(2); Mc=ener(3); Md=ener(4); Me=ener(5);
Mf=ener(6);
Mg=ener(7); Mh=ener(8); Mi=ener(9); Mj=ener(10); Mk=ener(11);

Ml=ener(12); Mm=ener(13); Mn=ener(14); Mo=ener(15); Mp=ener(16);
Mq=ener(17);
```

```
Mr=ener(18); Ms=ener(19); Mt=ener(20); Mu=ener(21);
Mv=ener(22); Mw=ener(23); Mx=ener(24); My=ener(25); Mz=ener(26);
Maa=ener(27); Mbb=ener(28); Mcc=ener(29); Mdd=ener(30);
```

B.4 Costcond

```
function [cost, condition]=costcond(Xin)
data=xlsread('t1.xlsx','Sheet1','b2:b11');
pci=data(:,1);
Cd=zeros(length(pci),6);
Cd(:,1)=pci(:,1);
thresholds=[90 80 65 50];
Costs=[100 500 1000 3000];
Y=zeros(length(pci),5); cst=zeros(length(pci),5);
load('cci.mat')
pmbmp=8;
lpci=length(pci);
X=zeros(length(pci),5);
for iw=1:lpci
    X(iw,1)=Xin(iw);
    X(iw,2)=Xin(iw+lpci);
    X(iw,3)=Xin(iw+lpci+lpci);
    X(iw,4)=Xin(iw+lpci+lpci+lpci);
    X(iw,5)=Xin(iw+lpci+lpci+lpci+lpci);
end

for pq=1:5


    if X(i2,pq)==1 && Cd(i2,pq)<=thresholds(1) &&
Cd(i2,pq)>thresholds(2)
        Y(i2,pq)=1;
        Cd(i2,(pq+1))=Cd(i2,pq)+pmbmp;
        cst(i2,pq)=Costs(1);

    elseif X(i2,pq)==1 && Cd(i2,pq)<=thresholds(2)
        Cd(i2,(pq+1))=100;

        if Cd(i2,pq)<=thresholds(2) && Cd(i2,pq)>thresholds(3)
            cst(i2,pq)=Costs(2);
        elseif Cd(i2,pq)<=thresholds(3) && Cd(i2,pq)>thresholds(4)
            cst(i2,pq)=Costs(3);
        elseif Cd(i2,pq)<=thresholds(4) && Cd(i2,pq)>0
            cst(i2,pq)=Costs(4);
        end

    elseif X(i2,pq)==1 && Cd(i2,pq)>thresholds(1)
        m1=interp1(cci(:,2),cci(:,1),Cd(i2,pq)); m1=m1+1;
        if m1<17.95
            Cd(i2,(pq+1))=interp1(cci(:,1),cci(:,2),m1);
        else
```

```
            Cd(i2,(pq+1))=0;
        end
        clear m1
    elseif X(i2,pq)==0
        m1=interp1(cci(:,2),cci(:,1),Cd(i2,pq)); m1=m1+1;
        if m1<17.95
            Cd(i2,(pq+1))=interp1(cci(:,1),cci(:,2),m1);
        else
            Cd(i2,(pq+1))=0;
        end
        clear m1
    end


end


cost=sum(sum(cst)); condition=mean(mean(Cd));
```

B.5 Totalenergy

```
function [etot]=totalenergy(X, Y,  Ma, Mb, Mc, Md, Me, Mf, Mg, Mh, Mi,
Mj, Mk, Ml, Mm, Mn, Mo, Mp, Mq, Mr, Ms, Mt, Mu, R5m, R5dd, R5c, R5b,
R5a, R5q, R2a, R3a, R4a, R3b, R4b, R4c, R2g, R3h, R4j, R1q, R2q, R3q,
R4q, R1r, Mv, Mw, Mx, My, Mz, Maa, Mbb, Mcc, Mdd)


e1(:,1)=(X(:,1).*(Mr(:,1)+((1-
Y(:,1)).*R1q(:,1))+(Y(:,1).*R1r(:,1))))+((1-X(:,1)).*R1r(:,1));

e2(:,1)=(X(:,2).*X(:,1).*(Y(:,1).*Ms(:,1)+(1-
Y(:,2)).*R2q(:,1)+Y(:,2).*(1-
Y(:,1)).*R2a(:,1)+Y(:,2).*Y(:,1).*R2g(:,1)))+...
    ((1-X(:,1)).*X(:,2).*(Mg(:,1)+(1-
Y(:,2)).*R2q(:,1)+Y(:,2).*R2g(:,1)))+...
    ((1-X(:,2)).*X(:,1).*((1-Y(:,1)).*R2a(:,1)+Y(:,1).*R2g(:,1)))+...
    ((1-X(:,2)).*(1-X(:,1)).*R2g(:,1));

e3(:,1)=(X(:,3).*X(:,2).*X(:,1).*((1-Y(:,2)).*(1-
Y(:,3)).*Y(:,1).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,1)).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*Y(:,2).*Md(:,1)+(1-
Y(:,2)).*(1-
Y(:,1)).*Y(:,3).*Ma(:,1)+Y(:,2).*Y(:,3).*Y(:,1).*Mt(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*Md(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Ma(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*Ma(:,1)+...
    (1-Y(:,2)).*(1-Y(:,3)).*Y(:,1).*R3q(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*(1-Y(:,1)).*R3q(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,2).*R3q(:,1)+(1-Y(:,2)).*(1-
```

```
Y(:,1)).*Y(:,3).*R3a(:,1)+Y(:,2).*Y(:,3).*Y(:,1).*R3h(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*R3b(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*R3a(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*R3q(:,1)))+...
    (X(:,3).*(1-X(:,2)).*X(:,1).*((1-Y(:,3)).*Y(:,1).*Ma(:,1)+(1-
Y(:,3)).*(1-Y(:,1)).*Mb(:,1)+(1-
Y(:,1)).*Y(:,3).*Mb(:,1)+Y(:,3).*Y(:,1).*Mi(:,1)+(1-
Y(:,3)).*Y(:,1).*R3q(:,1)+(1-Y(:,3)).*(1-Y(:,1)).*R3q(:,1)+(1-
Y(:,1)).*Y(:,3).*R3b(:,1)+Y(:,3).*Y(:,1).*R3h(:,1)))+...
    (X(:,3).*(1-X(:,1)).*X(:,2).*((1-Y(:,2)).*(1-Y(:,3)).*Ma(:,1)+(1-
Y(:,3)).*Y(:,2).*Mu(:,1)+(1-
Y(:,2)).*Y(:,3).*Ma(:,1)+Y(:,2).*Y(:,3).*Mi(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*R3q(:,1)+(1-Y(:,3)).*Y(:,2).*R3q(:,1)+(1-
Y(:,2)).*Y(:,3).*R3a(:,1)+Y(:,2).*Y(:,3).*R3h(:,1)))+...
    (X(:,2).*(1-X(:,3)).*X(:,1).*((1-Y(:,2)).*Y(:,1).*R3a(:,1)+(1-
Y(:,1)).*Y(:,2).*R3b(:,1)+(1-Y(:,2)).*(1-
Y(:,1)).*R3a(:,1)+Y(:,2).*Y(:,1).*R3h(:,1)))+...
    (X(:,3).*(1-X(:,2)).*(1-X(:,1)).*((1-
Y(:,3)).*Mh(:,1)+Y(:,3).*Mh(:,1)+(1-
Y(:,3)).*R3q(:,1)+Y(:,3).*R3h(:,1)))+...
    (X(:,1).*(1-X(:,2)).*(1-X(:,3)).*((1-
Y(:,1)).*R3b(:,1)+Y(:,1).*R3h(:,1)))+...
    (X(:,2).*(1-X(:,1)).*(1-X(:,3)).*((1-
Y(:,2)).*R3a(:,1)+Y(:,2).*R3h(:,1)))+((1-X(:,2)).*(1-X(:,1)).*(1-
X(:,3)).*(R3h(:,1)));

e4(:,1)=(X(:,1).*X(:,2).*X(:,3).*X(:,4).*((1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,3)).*(1-Y(:,4)).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*R4q(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,4).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,4).*R4a(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*Y(:,3).*(1-
Y(:,4)).*Md(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*Y(:,3).*(1-
Y(:,4)).*R4q(:,1)+...
    (1-Y(:,1)).*Y(:,2).*(1-Y(:,3)).*(1-Y(:,4)).*Ma(:,1)+(1-
Y(:,1)).*Y(:,2).*(1-Y(:,3)).*(1-Y(:,4)).*R4q(:,1)+Y(:,1).*(1-
Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*Ma(:,1)+Y(:,1).*(1-Y(:,2)).*(1-
Y(:,3)).*(1-Y(:,4)).*R4q(:,1)+Y(:,1).*Y(:,2).*(1-Y(:,3)).*(1-
Y(:,4)).*Ma(:,1)+Y(:,1).*Y(:,2).*(1-Y(:,3)).*(1-Y(:,4)).*R4q(:,1)+...
    Y(:,1).*(1-Y(:,2)).*Y(:,3).*(1-Y(:,4)).*Md(:,1)+Y(:,1).*(1-
Y(:,2)).*Y(:,3).*(1-Y(:,4)).*R4q(:,1)+Y(:,1).*(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,4).*Ma(:,1)+Y(:,1).*(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,4).*R4a(:,1)+(1-Y(:,1)).*Y(:,2).*Y(:,3).*(1-
Y(:,4)).*Mf(:,1)+(1-Y(:,1)).*Y(:,2).*Y(:,3).*(1-Y(:,4)).*R4q(:,1)+(1-
Y(:,1)).*Y(:,2).*(1-Y(:,3)).*Y(:,4).*Ma(:,1)+...
    (1-Y(:,1)).*Y(:,2).*(1-Y(:,3)).*Y(:,4).*R4a(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,3).*Y(:,4).*Md(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,3).*Y(:,4).*R4b(:,1)+Y(:,1).*Y(:,2).*Y(:,3).*(1-
Y(:,4)).*Mp(:,1)+Y(:,1).*Y(:,2).*Y(:,3).*(1-
Y(:,4)).*R4q(:,1)+Y(:,1).*Y(:,2).*(1-
Y(:,3)).*Y(:,4).*Ma(:,1)+Y(:,1).*Y(:,2).*(1-
Y(:,3)).*Y(:,4).*R4a(:,1)+...
```

```
    Y(:,1).*(1-Y(:,2)).*Y(:,3).*Y(:,4).*Md(:,1)+Y(:,1).*(1-
Y(:,2)).*Y(:,3).*Y(:,4).*R4b(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*Y(:,4).*Mf(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*Y(:,4).*R4c(:,1)+Y(:,1).*Y(:,2).*Y(:,3).*Y(:,
4).*Mp(:,1)+Y(:,1).*Y(:,2).*Y(:,3).*Y(:,4).*R4j(:,1)))+...
    ((1-X(:,1)).*X(:,2).*X(:,3).*X(:,4).*((1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*R4q(:,1)+(1-
Y(:,2)).*(1-Y(:,3)).*Y(:,4).*Ma(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,4).*R4a(:,1)+(1-Y(:,2)).*Y(:,3).*(1-Y(:,4)).*Md(:,1)+(1-
Y(:,2)).*Y(:,3).*(1-Y(:,4)).*R4q(:,1)+...
    Y(:,2).*(1-Y(:,3)).*(1-Y(:,4)).*Ma(:,1)+Y(:,2).*(1-Y(:,3)).*(1-
Y(:,4)).*R4q(:,1)+Y(:,2).*Y(:,3).*(1-
Y(:,4)).*Mo(:,1)+Y(:,2).*Y(:,3).*(1-Y(:,4)).*R4q(:,1)+Y(:,2).*(1-
Y(:,3)).*Y(:,4).*Ma(:,1)+Y(:,2).*(1-Y(:,3)).*Y(:,4).*R4a(:,1)+(1-
Y(:,2)).*Y(:,3).*Y(:,4).*Md(:,1)+(1-
Y(:,2)).*Y(:,3).*Y(:,4).*R4b(:,1)+...

Y(:,2).*Y(:,3).*Y(:,4).*Mo(:,1)+Y(:,2).*Y(:,3).*Y(:,4).*R4j(:,1)))+...
    (X(:,1).*(1-X(:,2)).*X(:,3).*X(:,4).*((1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,4)).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-Y(:,4)).*R4q(:,1)+(1-
Y(:,1)).*(1-Y(:,3)).*Y(:,4).*Ma(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,4).*R4a(:,1)+(1-Y(:,1)).*Y(:,3).*(1-Y(:,4)).*Me(:,1)+(1-
Y(:,1)).*Y(:,3).*(1-Y(:,4)).*R4q(:,1)+Y(:,1).*(1-Y(:,3)).*(1-
Y(:,4)).*Ma(:,1)+Y(:,1).*(1-Y(:,3)).*(1-Y(:,4)).*R4q(:,1)+...
    Y(:,1).*Y(:,3).*(1-Y(:,4)).*Mo(:,1)+Y(:,1).*Y(:,3).*(1-
Y(:,4)).*R4q(:,1)+Y(:,1).*(1-Y(:,3)).*Y(:,4).*Ma(:,1)+Y(:,1).*(1-
Y(:,3)).*Y(:,4).*R4a(:,1)+(1-Y(:,1)).*Y(:,3).*Y(:,4).*Me(:,1)+(1-
Y(:,1)).*Y(:,3).*Y(:,4).*R4c(:,1)+Y(:,1).*Y(:,3).*Y(:,4).*Mo(:,1)+Y(:,
1).*Y(:,3).*Y(:,4).*R4j(:,1)))+...
    (X(:,1).*X(:,2).*(1-X(:,3)).*X(:,4).*((1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,4)).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,4)).*R4q(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*Y(:,4).*Ma(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,4).*R4a(:,1)+(1-Y(:,1)).*Y(:,2).*(1-Y(:,4)).*Me(:,1)+(1-
Y(:,1)).*Y(:,2).*(1-Y(:,4)).*R4q(:,1)+Y(:,1).*(1-Y(:,2)).*(1-
Y(:,4)).*Ma(:,1)+Y(:,1).*(1-Y(:,2)).*(1-Y(:,4)).*R4q(:,1)+...
    Y(:,1).*Y(:,2).*(1-Y(:,4)).*Mo(:,1)+Y(:,1).*Y(:,2).*(1-
Y(:,4)).*R4q(:,1)+Y(:,1).*(1-Y(:,2)).*Y(:,4).*Mb(:,1)+Y(:,1).*(1-
Y(:,2)).*Y(:,4).*R4a(:,1)+(1-Y(:,1)).*Y(:,2).*Y(:,4).*Me(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,4).*R4c(:,1)+Y(:,1).*Y(:,2).*Y(:,4).*Mo(:,1)+Y(:,
1).*Y(:,2).*Y(:,4).*R4j(:,1)))+...
    (X(:,1).*X(:,2).*X(:,3).*(1-X(:,4)).*((1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,3)).*R4a(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*Y(:,3).*R4b(:,1)+(1-
Y(:,1)).*Y(:,2).*(1-Y(:,3)).*R4a(:,1)+Y(:,1).*(1-Y(:,2)).*(1-
Y(:,3)).*R4a(:,1)+Y(:,1).*Y(:,2).*(1-Y(:,3)).*R4a(:,1)+Y(:,1).*(1-
Y(:,2)).*Y(:,3).*R4b(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*R4c(:,1)+Y(:,1).*Y(:,2).*Y(:,3).*R4j(:,1)))+.
..
    ((1-X(:,1)).*(1-X(:,2)).*X(:,3).*X(:,4).*((1-Y(:,3)).*(1-
Y(:,4)).*Ma(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*R4q(:,1)+(1-
Y(:,3)).*Y(:,4).*Ma(:,1)+(1-Y(:,3)).*Y(:,4).*R4a(:,1)+Y(:,3).*(1-
Y(:,4)).*Mn(:,1)+Y(:,3).*(1-
Y(:,4)).*R4q(:,1)+Y(:,3).*Y(:,4).*Mn(:,1)+Y(:,3).*Y(:,4).*R4j(:,1)))+.
```

```
..
    ((1-X(:,1)).*X(:,2).*(1-X(:,3)).*X(:,4).*((1-Y(:,2)).*(1-
Y(:,4)).*Mb(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*R4q(:,1)+(1-
Y(:,2)).*Y(:,4).*Mb(:,1)+(1-Y(:,2)).*Y(:,4).*R4b(:,1)+Y(:,2).*(1-
Y(:,4)).*Mn(:,1)+Y(:,2).*(1-
Y(:,4)).*R4q(:,1)+Y(:,2).*Y(:,4).*Mn(:,1)+Y(:,2).*Y(:,4).*R4j(:,1)))+.
..
    ((1*X(:,1)).*X(:,2).*X(:,3).*(1-X(:,4)).*((1-Y(:,2)).*(1-
Y(:,3)).*R4a(:,1)+(1-Y(:,2)).*Y(:,3).*R4c(:,1)+Y(:,2).*(1-
Y(:,3)).*R4a(:,1)+Y(:,2).*Y(:,3).*R4j(:,1)))+...
    (X(:,1).*(1-X(:,2)).*(1-X(:,3)).*X(:,4).*((1-Y(:,1)).*(1-
Y(:,4)).*Mc(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*R4q(:,1)+(1-
Y(:,1)).*Y(:,4).*Mc(:,1)+(1-Y(:,1)).*Y(:,4).*R4c(:,1)+Y(:,1).*(1-
Y(:,4)).*Mn(:,1)+Y(:,1).*(1-
Y(:,4)).*R4q(:,1)+Y(:,1).*Y(:,4).*Mn(:,1)+Y(:,1).*Y(:,4).*R4j(:,1)))+.
..
    (X(:,1).*(1-X(:,2)).*X(:,3).*(1-X(:,4)).*((1-Y(:,1)).*(1-
Y(:,3)).*R4a(:,1)+(1-Y(:,1)).*Y(:,3).*R4c(:,1)+Y(:,1).*(1-
Y(:,3)).*R4a(:,1)+Y(:,1).*Y(:,3).*R4j(:,1)))+...
    (X(:,1).*X(:,2).*(1-X(:,3)).*(1-X(:,4)).*((1-Y(:,1)).*(1-
Y(:,2)).*R4b(:,1)+(1-Y(:,1)).*Y(:,2).*R4c(:,1)+Y(:,1).*(1-
Y(:,2)).*R4b(:,1)+Y(:,1).*Y(:,2).*R4j(:,1)))+...
    ((1-X(:,1)).*(1-X(:,2)).*(1-X(:,3)).*X(:,4).*((1-
Y(:,4)).*Mm(:,1)+(1-
Y(:,4)).*R4q(:,1)+Y(:,4).*Mm(:,1)+Y(:,4).*R4j(:,1)))+...
    ((1-X(:,1)).*X(:,2).*(1-X(:,3)).*(1-X(:,4)).*((1-
Y(:,2)).*R4b(:,1)+Y(:,2).*R4j(:,1)))+(X(:,1).*(1-X(:,2)).*(1-
X(:,3)).*(1-X(:,4)).*((1-Y(:,1)).*R4c(:,1)+Y(:,1).*R4j(:,1)))+...
    ((1-X(:,1)).*(1-X(:,2)).*X(:,3).*(1-X(:,4)).*((1-
Y(:,3)).*R4a(:,1)+Y(:,3).*R4j(:,1)))+...
    ((1-X(:,1)).*(1-X(:,2)).*(1-X(:,3)).*(1-X(:,4)).*(R4j(:,1)));

e5(:,1)=(X(:,1).*X(:,2).*X(:,3).*X(:,4).*X(:,5).*((Y(:,1).*Y(:,2).*Y(:
,3).*Y(:,4).*Y(:,5).*Mz(:,1)+Y(:,1).*Y(:,2).*Y(:,3).*Y(:,4).*Y(:,5).*R
5m(:,1)+(1-Y(:,1)).*Y(:,2).*Y(:,3).*Y(:,4).*Y(:,5).*Mcc(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*Y(:,4).*Y(:,5).*R5dd(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Y(:,4).*Y(:,5).*Mf(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Y(:,4).*Y(:,5).*R5c(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*Y(:,4).*Y(:,5).*Md(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*Y(:,4).*Y(:,5).*R5b(:,1)+...
    (1-Y(:,4)).*Y(:,2).*Y(:,3).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,3).*Y(:,1).*Y(:,5).*R5a(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*Y(:,4).*Y(:,3).*Mz(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*Y(:,4).*Y(:,3).*R5q(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,3).*Y(:,4).*Y(:,5).*Mf(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,3).*Y(:,4).*Y(:,5).*R5c(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,2).*Y(:,4).*Y(:,5).*Md(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,2).*Y(:,4).*Y(:,5).*R5b(:,1)+...
    (1-Y(:,1)).*(1-Y(:,4)).*Y(:,3).*Y(:,2).*Y(:,5).*Ma(:,1)+(1-
Y(:,1)).*(1-Y(:,4)).*Y(:,3).*Y(:,2).*Y(:,5).*R5a(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,3).*Y(:,4).*Y(:,2).*Mcc(:,1)+(1-Y(:,1)).*(1-
```

```
Y(:,5)).*Y(:,3).*Y(:,4).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,1).*Y(:,4).*Y(:,5).*Md(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,1).*Y(:,4).*Y(:,5).*R5b(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,3).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,3).*Y(:,1).*Y(:,5).*R5a(:,1)+...
    (1-Y(:,2)).*(1-Y(:,5)).*Y(:,3).*Y(:,4).*Y(:,1).*Mf(:,1)+(1-
Y(:,2)).*(1-Y(:,5)).*Y(:,3).*Y(:,4).*Y(:,1).*R5q(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,1).*Y(:,2).*Y(:,5).*Ma(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,1).*Y(:,2).*Y(:,5).*R5a(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*Y(:,4).*Y(:,2).*Md(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*Y(:,4).*Y(:,2).*R5q(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*Y(:,1).*Y(:,2).*Ma(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*Y(:,1).*Y(:,2).*R5q(:,1)+...
    (1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*Y(:,4).*Y(:,5).*Md(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*Y(:,4).*Y(:,5).*R5b(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,4)).*Y(:,3).*Y(:,5).*Ma(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,4)).*Y(:,3).*Y(:,5).*R5a(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,5)).*Y(:,4).*Y(:,3).*Mf(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,5)).*Y(:,4).*Y(:,3).*R5q(:,1)+(1-
Y(:,1)).*(1-Y(:,3)).*(1-Y(:,4)).*Y(:,2).*Y(:,5).*Ma(:,1)+(1-
Y(:,1)).*(1-Y(:,3)).*(1-Y(:,4)).*Y(:,2).*Y(:,5).*R5a(:,1)+...
    (1-Y(:,1)).*(1-Y(:,3)).*(1-Y(:,5)).*Y(:,2).*Y(:,4).*Md(:,1)+(1-
Y(:,1)).*(1-Y(:,3)).*(1-Y(:,5)).*Y(:,2).*Y(:,4).*R5q(:,1)+(1-
Y(:,1)).*(1-Y(:,4)).*(1-Y(:,5)).*Y(:,2).*Y(:,3).*Ma(:,1)+(1-
Y(:,1)).*(1-Y(:,4)).*(1-Y(:,5)).*Y(:,2).*Y(:,3).*R5q(:,1)+(1-
Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-
Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*Y(:,1).*Y(:,5).*R5a(:,1)+(1-
Y(:,2)).*(1-Y(:,3)).*(1-Y(:,5)).*Y(:,1).*Y(:,4).*Md(:,1)+(1-
Y(:,2)).*(1-Y(:,3)).*(1-Y(:,5)).*Y(:,1).*Y(:,4).*R5q(:,1)+...
    (1-Y(:,2)).*(1-Y(:,4)).*(1-Y(:,5)).*Y(:,1).*Y(:,3).*Ma(:,1)+(1-
Y(:,2)).*(1-Y(:,4)).*(1-Y(:,5)).*Y(:,1).*Y(:,3).*R5q(:,1)+(1-
Y(:,3)).*(1-Y(:,4)).*(1-Y(:,5)).*Y(:,1).*Y(:,2).*Ma(:,1)+(1-
Y(:,3)).*(1-Y(:,4)).*(1-Y(:,5)).*Y(:,1).*Y(:,2).*R5q(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*Y(:,5).*Ma(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*Y(:,5).*R5a(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,5)).*Y(:,4).*Md(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,5)).*Y(:,4).*R5q(:,1)+...
    (1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,2).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*(1-Y(:,5)).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*(1-Y(:,5)).*R5q(:,1))))+...
((1-
X(:,1)).*X(:,2).*X(:,3).*X(:,4).*X(:,5).*(Y(:,2).*Y(:,3).*Y(:,4).*Y(:,
5).*My(:,1)+Y(:,2).*Y(:,3).*Y(:,4).*Y(:,5).*R5m(:,1)+(1-
Y(:,2)).*Y(:,3).*Y(:,4).*Y(:,5).*Ml(:,1)+(1-
Y(:,2)).*Y(:,3).*Y(:,4).*Y(:,5).*R5c(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,4).*Y(:,5).*Md(:,1)+(1-
```

```
Y(:,3)).*Y(:,2).*Y(:,4).*Y(:,5).*R5b(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,3).*Y(:,5).*Ma(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,3).*Y(:,5).*R5a(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,4).*Y(:,3).*Mv(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,4).*Y(:,3).*R5q(:,1)+...
    (1-Y(:,2)).*(1-Y(:,3)).*Y(:,4).*Y(:,5).*Md(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,4).*Y(:,5).*R5b(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,3).*Y(:,5).*Ma(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,3).*Y(:,5).*R5a(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,3).*Y(:,4).*Ml(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,3).*Y(:,4).*R5q(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,2).*Y(:,5).*Ma(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,2).*Y(:,5).*R5a(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,4).*Y(:,2).*Md(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,4).*Y(:,2).*R5q(:,1)+...
    (1-Y(:,4)).*(1-Y(:,5)).*Y(:,3).*Y(:,2).*Ma(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,5).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,5).*R5a(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,4).*Md(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,4).*R5q(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*R5q(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,2).*Ma(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,2).*R5q(:,1)+...
    (1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-Y(:,5)).*Ma(:,1)+(1-
Y(:,2)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-
X(:,2)).*X(:,1).*X(:,3).*X(:,4).*X(:,5).*(Y(:,1).*Y(:,3).*Y(:,4).*Y(:,
5).*My(:,1)+Y(:,1).*Y(:,3).*Y(:,4).*Y(:,5).*R5m(:,1)+(1-
Y(:,1)).*Y(:,3).*Y(:,4).*Y(:,5).*Mbb(:,1)+(1-
Y(:,1)).*Y(:,3).*Y(:,4).*Y(:,5).*R5dd(:,1)+(1-
Y(:,3)).*Y(:,1).*Y(:,4).*Y(:,5).*Md(:,1)+(1-
Y(:,3)).*Y(:,1).*Y(:,4).*Y(:,5).*R5b(:,1)+(1-
Y(:,4)).*Y(:,3).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-
Y(:,4)).*Y(:,3).*Y(:,1).*Y(:,5).*R5a(:,1)+(1-
Y(:,5)).*Y(:,1).*Y(:,4).*Y(:,3).*My(:,1)+(1-
Y(:,5)).*Y(:,1).*Y(:,4).*Y(:,3).*R5q(:,1)+...
    (1-Y(:,1)).*(1-Y(:,3)).*Y(:,4).*Y(:,5).*Md(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,4).*Y(:,5).*R5b(:,1)+(1-Y(:,1)).*(1-
Y(:,4)).*Y(:,3).*Y(:,5).*Ma(:,1)+(1-Y(:,1)).*(1-
Y(:,4)).*Y(:,3).*Y(:,5).*R5a(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,3).*Y(:,4).*Mbb(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,3).*Y(:,4).*R5q(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,1).*Y(:,5).*R5a(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*Y(:,4).*Md(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*Y(:,4).*R5q(:,1)+...
    (1-Y(:,4)).*(1-Y(:,5)).*Y(:,3).*Y(:,1).*Ma(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*Y(:,1).*R5q(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*Ma(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
```

```
Y(:,4)).*Y(:,5).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,5).*R5a(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,4).*Md(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,4).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*R5q(:,1)+...
    (1-Y(:,1)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-Y(:,5)).*Ma(:,1)+(1-
Y(:,1)).*(1-Y(:,3)).*(1-Y(:,4)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-
X(:,3)).*X(:,2).*X(:,1).*X(:,4).*X(:,5).*(Y(:,1).*Y(:,2).*Y(:,4).*Y(:,
5).*My(:,1)+Y(:,1).*Y(:,2).*Y(:,4).*Y(:,5).*R5m(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,4).*Y(:,5).*Mbb(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,4).*Y(:,5).*R5dd(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Y(:,4).*Y(:,5).*Mf(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Y(:,4).*Y(:,5)+(1-
Y(:,4)).*Y(:,2).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,1).*Y(:,5).*R5a(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*Y(:,4).*My(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*Y(:,4).*R5q(:,1)+...
    (1-Y(:,1)).*(1-Y(:,2)).*Y(:,4).*Y(:,5).*Me(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,4).*Y(:,5).*R5c(:,1)+(1-Y(:,1)).*(1-
Y(:,4)).*Y(:,2).*Y(:,5).*Ma(:,1)+(1-Y(:,1)).*(1-
Y(:,4)).*Y(:,2).*Y(:,5).*R5a(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,4).*Y(:,2).*Mbb(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,4).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,1).*Y(:,5).*R5a(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,4).*Y(:,1).*Me(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,4).*Y(:,1).*R5q(:,1)+...
    (1-Y(:,4)).*(1-Y(:,5)).*Y(:,1).*Y(:,2).*Ma(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*Y(:,2).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,5).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,5).*R5a(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,4).*Me(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,4).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,2).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*R5q(:,1)+...
    (1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,4)).*(1-Y(:,5)).*Ma(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,4)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-
X(:,4)).*X(:,2).*X(:,3).*X(:,1).*X(:,5).*(Y(:,1).*Y(:,2).*Y(:,3).*Y(:,
5).*My(:,1)+Y(:,1).*Y(:,2).*Y(:,3).*Y(:,5).*R5m(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*Y(:,5).*Mbb(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*Y(:,5).*R5dd(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Y(:,5).*Mf(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Y(:,5).*R5c(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*Y(:,5).*Mb(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*Y(:,5).*R5b(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*Y(:,3).*My(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*Y(:,3).*R5q(:,1)+...
```

```
    (1-Y(:,1)).*(1-Y(:,2)).*Y(:,3).*Y(:,5).*Me(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,3).*Y(:,5).*R5c(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,2).*Y(:,5).*Mb(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,2).*Y(:,5).*R5b(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,3).*Y(:,2).*Mbb(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,3).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,1).*Y(:,5).*Mb(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,1).*Y(:,5).*R5b(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,3).*Y(:,1).*Me(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,3).*Y(:,1).*R5q(:,1)+...
    (1-Y(:,3)).*(1-Y(:,5)).*Y(:,1).*Y(:,2).*Mb(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*Y(:,2).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,5).*Mb(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,5).*R5b(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,3).*Me(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,3).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,2).*Mb(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*Mb(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*R5q(:,1)+...
    (1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,5)).*Mb(:,1)+(1-
Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-
X(:,5)).*X(:,2).*X(:,3).*X(:,4).*X(:,1).*(Y(:,1).*Y(:,2).*Y(:,3).*Y(:,
4).*R5m(:,1)+ (1-Y(:,1)).*Y(:,2).*Y(:,3).*Y(:,4).*R5dd(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*Y(:,4).*R5c(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*Y(:,4).*R5b(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,3).*Y(:,1).*R5a(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,3).*Y(:,4).*R5c(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,2).*Y(:,4).*R5b(:,1)+(1-Y(:,1)).*(1-
Y(:,4)).*Y(:,3).*Y(:,2).*R5a(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,1).*Y(:,4).*R5b(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,3).*Y(:,1).*R5a(:,1)+...
    (1-Y(:,3)).*(1-Y(:,4)).*Y(:,1).*Y(:,2).*R5a(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*(1-Y(:,3)).*Y(:,4).*R5b(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,3).*R5a(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,2).*R5a(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,1).*R5a(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,4)).*R5a(:,1)))+...
((1-X(:,1)).*(1-
X(:,2)).*X(:,3).*X(:,4).*X(:,5).*(Y(:,3).*Y(:,4).*Y(:,5).*Mx(:,1)+Y(:,
3).*Y(:,4).*Y(:,5).*R5m(:,1)+(1-Y(:,3)).*Y(:,4).*Y(:,5).*Md(:,1)+(1-
Y(:,3)).*Y(:,4).*Y(:,5).*R5b(:,1)+(1-
Y(:,4)).*Y(:,3).*Y(:,5).*Ma(:,1)+(1-
Y(:,4)).*Y(:,3).*Y(:,5).*R5a(:,1)+(1-
Y(:,5)).*Y(:,4).*Y(:,3).*Mx(:,1)+(1-
Y(:,5)).*Y(:,4).*Y(:,3).*R5q(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,5).*Ma(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*Y(:,5).*R5a(:,1)+(1-
Y(:,3)).*(1-Y(:,5)).*Y(:,4).*Md(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,4).*R5q(:,1)+...
    (1-Y(:,4)).*(1-Y(:,5)).*Y(:,3).*Ma(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,3).*R5q(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*(1-
```

```
Y(:,5)).*Ma(:,1)+(1-Y(:,3)).*(1-Y(:,4)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-X(:,1)).*(1-
X(:,3)).*X(:,2).*X(:,4).*X(:,5).*(Y(:,2).*Y(:,4).*Y(:,5).*Mx(:,1)+Y(:,
2).*Y(:,4).*Y(:,5).*R5m(:,1)+(1-Y(:,2)).*Y(:,4).*Y(:,5).*Me(:,1)+(1-
Y(:,2)).*Y(:,4).*Y(:,5).*R5c(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,5).*Ma(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,5).*R5a(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,4).*Mx(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,4).*R5q(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,5).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*Y(:,5).*R5a(:,1)+(1-
Y(:,2)).*(1-Y(:,5)).*Y(:,4).*Me(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,4).*R5q(:,1)+...
    (1-Y(:,4)).*(1-Y(:,5)).*Y(:,2).*Ma(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*(1-
Y(:,5)).*Ma(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-X(:,1)).*(1-
X(:,4)).*X(:,3).*X(:,2).*X(:,5).*(Y(:,2).*Y(:,3).*Y(:,5).*Mx(:,1)+Y(:,
2).*Y(:,3).*Y(:,5).*R5m(:,1)+(1-Y(:,2)).*Y(:,3).*Y(:,5).*Me(:,1)+(1-
Y(:,2)).*Y(:,3).*Y(:,5).*R5c(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,5).*Mb(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,5).*R5b(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,3).*Mx(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,3).*R5q(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,5).*Mb(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*Y(:,5).*R5b(:,1)+(1-
Y(:,2)).*(1-Y(:,5)).*Y(:,3).*Me(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,3).*R5q(:,1)+...
    (1-Y(:,3)).*(1-Y(:,5)).*Y(:,2).*Mb(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,2).*R5q(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-
Y(:,5)).*Mb(:,1)+(1-Y(:,2)).*(1-Y(:,3)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-X(:,1)).*(1-
X(:,5)).*X(:,3).*X(:,4).*X(:,2).*(Y(:,2).*Y(:,3).*Y(:,4).*R5m(:,1)+(1-
Y(:,2)).*Y(:,3).*Y(:,4).*R5c(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,4).*R5b(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,3).*R5a(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*Y(:,4).*R5b(:,1)+(1-Y(:,2)).*(1-Y(:,4)).*Y(:,3).*R5a(:,1)+...
    (1-Y(:,3)).*(1-Y(:,4)).*Y(:,2).*R5a(:,1)+(1-Y(:,2)).*(1-
Y(:,3)).*(1-Y(:,4)).*R5a(:,1)))+...
((1-X(:,2)).*(1-
X(:,3)).*X(:,1).*X(:,4).*X(:,5).*(Y(:,1).*Y(:,4).*Y(:,5).*Mx(:,1)+Y(:,
1).*Y(:,4).*Y(:,5).*R5m(:,1)+(1-Y(:,1)).*Y(:,4).*Y(:,5).*Maa(:,1)+(1-
Y(:,1)).*Y(:,4).*Y(:,5).*R5dd(:,1)+(1-
Y(:,4)).*Y(:,1).*Y(:,5).*Ma(:,1)+(1-
Y(:,4)).*Y(:,1).*Y(:,5).*R5a(:,1)+(1-
Y(:,5)).*Y(:,4).*Y(:,1).*Mx(:,1)+(1-
Y(:,5)).*Y(:,4).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-
Y(:,4)).*Y(:,5).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*Y(:,5).*R5a(:,1)+(1-
Y(:,1)).*(1-Y(:,5)).*Y(:,4).*Maa(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,4).*R5q(:,1)+...
    (1-Y(:,4)).*(1-Y(:,5)).*Y(:,1).*Ma(:,1)+(1-Y(:,4)).*(1-
Y(:,5)).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*(1-
Y(:,5)).*Ma(:,1)+(1-Y(:,1)).*(1-Y(:,4)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-X(:,2)).*(1-
```

```
X(:,4)).*X(:,3).*X(:,1).*X(:,5).*(Y(:,1).*Y(:,3).*Y(:,5).*Mx(:,1)+Y(:,
1).*Y(:,3).*Y(:,5).*R5m(:,1)+(1-Y(:,1)).*Y(:,3).*Y(:,5).*Maa(:,1)+(1-
Y(:,1)).*Y(:,3).*Y(:,5).*R5dd(:,1)+(1-
Y(:,3)).*Y(:,1).*Y(:,5).*Md(:,1)+(1-
Y(:,3)).*Y(:,1).*Y(:,5).*R5b(:,1)+(1-
Y(:,5)).*Y(:,3).*Y(:,1).*Mx(:,1)+(1-
Y(:,5)).*Y(:,3).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,5).*Mb(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*Y(:,5).*R5b(:,1)+(1-
Y(:,1)).*(1-Y(:,5)).*Y(:,3).*Maa(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,3).*R5q(:,1)+...
    (1-Y(:,3)).*(1-Y(:,5)).*Y(:,1).*Mb(:,1)+(1-Y(:,3)).*(1-
Y(:,5)).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,5)).*Mb(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-X(:,2)).*(1-
X(:,5)).*X(:,3).*X(:,4).*X(:,1).*(Y(:,1).*Y(:,3).*Y(:,4).*R5m(:,1)+(1-
Y(:,1)).*Y(:,3).*Y(:,4).*R5dd(:,1)+(1-
Y(:,3)).*Y(:,1).*Y(:,4).*R5b(:,1)+(1-
Y(:,4)).*Y(:,3).*Y(:,1).*R5a(:,1)+(1-Y(:,1)).*(1-
Y(:,3)).*Y(:,4).*R5b(:,1)+...
    (1-Y(:,1)).*(1-Y(:,4)).*Y(:,3).*R5a(:,1)+(1-Y(:,3)).*(1-
Y(:,4)).*Y(:,1).*R5a(:,1)+(1-Y(:,1)).*(1-Y(:,3)).*(1-
Y(:,4)).*R5a(:,1)))+...
((1-X(:,3)).*(1-
X(:,4)).*X(:,1).*X(:,2).*X(:,5).*(Y(:,1).*Y(:,2).*Y(:,5).*Mx(:,1)+Y(:,
1).*Y(:,2).*Y(:,5).*R5m(:,1)+(1-Y(:,1)).*Y(:,2).*Y(:,5).*Maa(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,5).*R5dd(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,5).*Mc(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,5).*R5c(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*Mx(:,1)+(1-
Y(:,5)).*Y(:,2).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,5).*Mc(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*Y(:,5).*R5c(:,1)+(1-
Y(:,1)).*(1-Y(:,5)).*Y(:,2).*Maa(:,1)+(1-Y(:,1)).*(1-
Y(:,5)).*Y(:,2).*R5q(:,1)+...
    (1-Y(:,2)).*(1-Y(:,5)).*Y(:,1).*Mc(:,1)+(1-Y(:,2)).*(1-
Y(:,5)).*Y(:,1).*R5q(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,5)).*Mc(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-Y(:,5)).*R5q(:,1)))+...
((1-X(:,3)).*(1-
X(:,5)).*X(:,1).*X(:,4).*X(:,2).*(Y(:,1).*Y(:,2).*Y(:,4).*R5m(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,4).*R5dd(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,4).*R5c(:,1)+(1-
Y(:,4)).*Y(:,2).*Y(:,1).*R5a(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,4).*R5c(:,1)+...
    (1-Y(:,1)).*(1-Y(:,4)).*Y(:,2).*R5a(:,1)+(1-Y(:,2)).*(1-
Y(:,4)).*Y(:,1).*R5a(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,4)).*R5a(:,1)))+...
((1-X(:,4)).*(1-
X(:,5)).*X(:,3).*X(:,1).*X(:,2).*(Y(:,1).*Y(:,2).*Y(:,3).*R5m(:,1)+(1-
Y(:,1)).*Y(:,2).*Y(:,3).*R5dd(:,1)+(1-
Y(:,2)).*Y(:,1).*Y(:,3).*R5c(:,1)+(1-
Y(:,3)).*Y(:,2).*Y(:,1).*R5b(:,1)+(1-Y(:,1)).*(1-
Y(:,2)).*Y(:,3).*R5c(:,1)+...
    (1-Y(:,1)).*(1-Y(:,3)).*Y(:,2).*R5b(:,1)+(1-Y(:,2)).*(1-
```

```
Y(:,3)).*Y(:,1).*R5b(:,1)+(1-Y(:,1)).*(1-Y(:,2)).*(1-
Y(:,3)).*R5b(:,1)))+...
((1-X(:,1)).*(1-X(:,2)).*(1-X(:,3)).*X(:,4).*X(:,5).*((1-Y(:,4)).*(1-
Y(:,5)).*Ma(:,1)+(1-Y(:,4)).*(1-Y(:,5)).*R5q(:,1)+(1-
Y(:,4)).*Y(:,5).*Ma(:,1)+(1-Y(:,4)).*Y(:,5).*R5a(:,1)+Y(:,4).*(1-
Y(:,5)).*Mw(:,1)+Y(:,4).*(1-
Y(:,5)).*R5q(:,1)+Y(:,4).*Y(:,5).*Mw(:,1)+Y(:,4).*Y(:,5).*R5m(:,1)))+.
..
((1-X(:,1)).*(1-X(:,2)).*(1-X(:,4)).*X(:,3).*X(:,5).*((1-Y(:,3)).*(1-
Y(:,5)).*Mb(:,1)+(1-Y(:,3)).*(1-Y(:,5)).*R5q(:,1)+(1-
Y(:,3)).*Y(:,5).*Mb(:,1)+(1-Y(:,3)).*Y(:,5).*R5b(:,1)+Y(:,3).*(1-
Y(:,5)).*Mw(:,1)+Y(:,3).*(1-
Y(:,5)).*R5q(:,1)+Y(:,3).*Y(:,5).*Mw(:,1)+Y(:,3).*Y(:,5).*R5m(:,1)))+.
..
((1-X(:,1)).*(1-X(:,2)).*(1-X(:,5)).*X(:,4).*X(:,3).*((1-Y(:,4)).*(1-
Y(:,3)).*R5b(:,1)+(1-Y(:,4)).*Y(:,3).*R5a(:,1)+Y(:,4).*(1-
Y(:,3)).*R5c(:,1)+Y(:,4).*Y(:,3).*R5m(:,1)))+...
((1-X(:,1)).*(1-X(:,3)).*(1-X(:,4)).*X(:,2).*X(:,5).*((1-Y(:,2)).*(1-
Y(:,5)).*Mc(:,1)+(1-Y(:,2)).*(1-Y(:,5)).*R5q(:,1)+(1-
Y(:,2)).*Y(:,5).*Mc(:,1)+(1-Y(:,2)).*Y(:,5).*R5c(:,1)+Y(:,2).*(1-
Y(:,5)).*Mw(:,1)+Y(:,2).*(1-
Y(:,5)).*R5q(:,1)+Y(:,2).*Y(:,5).*Mw(:,1)+Y(:,2).*Y(:,5).*R5m(:,1)))+.
..
((1-X(:,1)).*(1-X(:,3)).*(1-X(:,5)).*X(:,2).*X(:,4).*((1-Y(:,2)).*(1-
Y(:,4)).*R5a(:,1)+(1-Y(:,2)).*Y(:,4).*R5c(:,1)+Y(:,2).*(1-
Y(:,4)).*R5a(:,1)+Y(:,2).*Y(:,4).*R5m(:,1)))+...
((1-X(:,1)).*(1-X(:,4)).*(1-X(:,5)).*X(:,2).*X(:,3).*((1-Y(:,2)).*(1-
Y(:,3)).*R5b(:,1)+(1-Y(:,2)).*Y(:,3).*R5c(:,1)+Y(:,2).*(1-
Y(:,3)).*R5b(:,1)+Y(:,2).*Y(:,3).*R5m(:,1)))+...
((1-X(:,2)).*(1-X(:,3)).*(1-X(:,4)).*X(:,1).*X(:,5).*((1-Y(:,1)).*(1-
Y(:,5)).*Mdd(:,1)+ (1-Y(:,1)).*(1-Y(:,5)).*R5q(:,1)+(1-
Y(:,1)).*Y(:,5).*Mdd(:,1)+(1-Y(:,1)).*Y(:,5).*R5dd(:,1)+Y(:,1).*(1-
Y(:,5)).*Mw(:,1)+Y(:,1).*(1-
Y(:,5)).*R5q(:,1)+Y(:,1).*Y(:,5).*Mw(:,1)+Y(:,1).*Y(:,5).*R5m(:,1)))+.
..
((1-X(:,2)).*(1-X(:,3)).*(1-X(:,5)).*X(:,1).*X(:,4).*((1-Y(:,1)).*(1-
Y(:,4)).*R5a(:,1)+(1-Y(:,1)).*Y(:,4).*R5dd(:,1)+Y(:,1).*(1-
Y(:,4)).*R5a(:,1)+Y(:,1).*Y(:,4).*R5m(:,1)))+...
((1-X(:,2)).*(1-X(:,4)).*(1-X(:,5)).*X(:,1).*X(:,3).*((1-Y(:,1)).*(1-
Y(:,3)).*R5b(:,1)+(1-Y(:,1)).*Y(:,3).*R5dd(:,1)+Y(:,1).*(1-
Y(:,3)).*R5b(:,1)+Y(:,1).*Y(:,3).*R5m(:,1)))+...
((1-X(:,3)).*(1-X(:,4)).*(1-X(:,5)).*X(:,1).*X(:,2).*((1-Y(:,1)).*(1-
Y(:,2)).*R5c(:,1)+(1-Y(:,1)).*Y(:,2).*R5dd(:,1)+Y(:,1).*(1-
Y(:,2)).*R5c(:,1)+Y(:,1).*Y(:,2).*R5m(:,1)))+...
((1-X(:,1)).*(1-X(:,2)).*(1-X(:,3)).*(1-X(:,4)).*X(:,5).*((1-
Y(:,5)).*Mv(:,1)+(1-
Y(:,5)).*R5q(:,1)+Y(:,5).*Mv(:,1)+Y(:,5).*R5m(:,1)))+...
((1-X(:,1)).*(1-X(:,2)).*(1-X(:,3)).*(1-X(:,5)).*X(:,4).*((1-
Y(:,4)).*R5a(:,1)+Y(:,4).*R5m(:,1)))+...
((1-X(:,1)).*(1-X(:,2)).*(1-X(:,4)).*(1-X(:,5)).*X(:,3).*((1-
Y(:,3)).*R5b(:,1)+Y(:,3).*R5m(:,1)))+...
((1-X(:,1)).*(1-X(:,3)).*(1-X(:,4)).*(1-X(:,5)).*X(:,2).*((1-
```

```
Y(:,2)).*R5c(:,1)+Y(:,2).*R5m(:,1)))+...
((1-X(:,2)).*(1-X(:,3)).*(1-X(:,4)).*(1-X(:,5)).*X(:,1).*((1-
Y(:,1)).*R5dd(:,1)+Y(:,1).*R5m(:,1)))+...
((1-X(:,1)).*(1-X(:,2)).*(1-X(:,3)).*(1-X(:,4)).*(1-
X(:,5)).*(R5m(:,1)));

etot=sum(sum(e1+e2+e3+e4+e5));
```

B.6 rren

```
function [R2a, R3a, R4a, R3b, R4b, R4c, R2g, R3h, R4j, R1q, R2q, R3q,
R4q, R1r, R5m, R5dd, R5c, R5b, R5a, R5q]=rren(A, B, C, G, H, J, Q, R,
M, DD, Tr, Lng)

GasEn=132;  % MJ per gallon of gasoline
DiesEn=146;  % MJ per gallon of Diesel

%Tr(:,1) is cars and Tr(:,2) is trucks

% Calc Fuel Consumption from Rolling Resistance
R2a1=((0.015196*A+46.51140)/1000)*Tr(2,1);  % Absolute Increase in
Fuel Consumption per mile...
%Defined over range of values using Chatti and Zaabar (2012)
R2a2=((0.048678*A+305.99202)/1000)*Tr(2,2);  % See Above comment
R2a=(R2a1+R2a2)*365*Lng;

R3a1=((0.015196*A+46.51140)/1000)*Tr(3,1);
R3a2=((0.048678*A+305.99202)/1000)*Tr(3,2);
R3a=(R3a1+R3a2)*365*Lng;

R4a1=((0.015196*A+46.51140)/1000)*Tr(4,1);
R4a2=((0.048678*A+305.99202)/1000)*Tr(4,2);
R4a=(R4a1+R4a2)*365*Lng;

R3b1=((0.015196*B+46.51140)/1000)*Tr(3,1);
R3b2=((0.048678*B+305.99202)/1000)*Tr(3,2);
R3b=(R3b1+R3b2)*365*Lng;

R4b1=((0.015196*B+46.51140)/1000)*Tr(4,1);
R4b2=((0.048678*B+305.99202)/1000)*Tr(4,2);
R4b=(R4b1+R4b2)*365*Lng;

R4c1=((0.015196*C+46.51140)/1000)*Tr(4,1);
R4c2=((0.048678*C+305.99202)/1000)*Tr(4,2);
R4c=(R4c1+R4c2)*365*Lng;

R2g1=((0.015196*G+46.51140)/1000)*Tr(2,1);
R2g2=((0.048678*G+305.99202)/1000)*Tr(2,2);
R2g=(R2g1+R2g2)*365*Lng;
```

```
R3h1=((0.015196*H+46.51140)/1000)*Tr(3,1);
R3h2=((0.048678*H+305.99202)/1000)*Tr(3,2);
R3h=(R3h1+R3h2)*365*Lng;

R4j1=((0.015196*J+46.51140)/1000)*Tr(4,1);
R4j2=((0.048678*J+305.99202)/1000)*Tr(4,2);
R4j=(R4j1+R4j2)*365*Lng;

R1q1=((0.015196*Q+46.51140)/1000)*Tr(1,1);
R1q2=((0.048678*Q+305.99202)/1000)*Tr(1,2);
R1q=(R1q1+R1q2)*365*Lng;

R2q1=((0.015196*Q+46.51140)/1000)*Tr(2,1);
R2q2=((0.048678*Q+305.99202)/1000)*Tr(2,2);
R2q=(R2q1+R2q2)*365*Lng;

R3q1=((0.015196*Q+46.51140)/1000)*Tr(3,1);
R3q2=((0.048678*Q+305.99202)/1000)*Tr(3,2);
R3q=(R3q1+R3q2)*365*Lng;

R4q1=((0.015196*Q+46.51140)/1000)*Tr(4,1);
R4q2=((0.048678*Q+305.99202)/1000)*Tr(4,2);
R4q=(R4q1+R4q2)*365*Lng;

R1r1=((0.015196*R+46.51140)/1000)*Tr(1,1);
R1r2=((0.048678*R+305.99202)/1000)*Tr(1,2);
R1r=(R1r1+R1r2)*365*Lng;

R5m1=((0.015196*M+46.51140)/1000)*Tr(5,1);
R5m2=((0.048678*M+305.99202)/1000)*Tr(5,2);
R5m=(R5m1+R5m2)*365*Lng;

R5dd1=((0.015196*DD+46.51140)/1000)*Tr(5,1);
R5dd2=((0.048678*DD+305.99202)/1000)*Tr(5,2);
R5dd=(R5dd1+R5dd2)*365*Lng;

R5c1=((0.015196*C+46.51140)/1000)*Tr(5,1);
R5c2=((0.048678*C+305.99202)/1000)*Tr(5,2);
R5c=(R5c1+R5c2)*365*Lng;

R5b1=((0.015196*B+46.51140)/1000)*Tr(5,1);
R5b2=((0.048678*B+305.99202)/1000)*Tr(5,2);
R5b=(R5b1+R5b2)*365*Lng;

R5a1=((0.015196*A+46.51140)/1000)*Tr(5,1);
R5a2=((0.048678*A+305.99202)/1000)*Tr(5,2);
R5a=(R5a1+R5a2)*365*Lng;

R5q1=((0.015196*Q+46.51140)/1000)*Tr(5,1);
```

```
R5q2=((0.048678*Q+305.99202)/1000)*Tr(5,2);
R5q=(R5q1+R5q2)*365*Lng;
```

B.7 rough

```
function [A B C D E F G H I J K L M N O P Q R DD]=rough(rou,irigrowth,
NewIRI)
A=NewIRI+1.5*irigrowth; B=NewIRI+2.5*irigrowth;
C=NewIRI+3.5*irigrowth; D=B; E=C; F=C;
G=rou+1.5*irigrowth; H=rou+2.5*irigrowth; I=H; J=rou+3.5*irigrowth;
K=J; L=J;
M=rou+4.5*irigrowth; N=M; O=M; P=M; Q=NewIRI; R=rou;
DD=NewIRI+4.5*irigrowth;
```

B.8 Traff

```
function [Tr]=Traff(GR, Veh, PercTrucks, yrs)

%GR=0.03; Veh=[19000]; PercTrucks=0.2; yrs=4;
growthrate(1)=1;

for j=2:yrs
    growthrate(j)=(1+GR).^(j-1)  ; %Need to find additional vehicles
as a function of growth
end

Vehicles=growthrate.*Veh;

Cars=Vehicles.*(1-PercTrucks);
Trucks=Vehicles.*(PercTrucks);

Tr=[Cars; Trucks]';
```

B.9 esals

```
function [esal]=esals(

growthrate(1)=1;
for j=2:yrs
    growthrate(j)=(1+GR).^(j-1)  ; %Need to find additional vehicles
as a function of growth
    Veh(:,j)=Veh(:,1).*growthrate;
end
```

B.10 condition

```
function [Ma Mb Mc Md Me Mf Mg Mh Mi Mj Mk Ml Mm Mn Mo Mp
Mq]=condition(Cond, pmbmp,thresholds)
load('cci.mat')
load('PM.mat')
load('CM.mat')
load('RM.mat')
load('RC.mat')
a1=find(cci(:,1)==1); a=cci(a1,2); b1=find(cci(:,1)==2); b=cci(b1,2);
c1=find(cci(:,1)==3); c=cci(c1,2); d=min(100,b+pmbmp);
e=min(100,c+pmbmp);
f=min(100,c+2*pmbmp);

g1=interp1(cci(:,2),cci(:,1),Cond); g1=g1+1;
if g1<17.95
    g=interp1(cci(:,1),cci(:,2),g1);
else
    g=0;
end

h1=interp1(cci(:,2),cci(:,1),Cond); h1=h1+2;
if h1<17.95
    h=interp1(cci(:,1),cci(:,2),h1);
else
    h=0;
end

i=min(100,h+pmbmp);

j1=interp1(cci(:,2),cci(:,1),Cond); j1=j1+3;
if j1<17.95
    j=interp1(cci(:,1),cci(:,2),j1);
else
    j=0;
end

k=min(100,j+pmbmp);
l=min(100,j+2*pmbmp);

m1=interp1(cci(:,2),cci(:,1),Cond); m1=m1+4;
if m1<17.95
    m=interp1(cci(:,1),cci(:,2),m1);
else
    m=0;
end

n=min(100,m+pmbmp);
o=min(100,m+2*pmbmp);
p=min(100,m+3*pmbmp);

q=100;
```

```
cdt=[a b c d e f g h i j k l m n o p q];
for ul=1:length(cdt)
    cdt1=cdt(ul);
    if cdt1>thresholds(1)
        ener(ul)=0;
    elseif cdt1<=thresholds(1) && cdt1>thresholds(2)
        ener(ul)=PM;
    elseif cdt1<=thresholds(2) && cdt1>thresholds(3)
        ener(ul)=CM;
    elseif cdt1<=thresholds(3) && cdt1>thresholds(4)
        ener(ul)=RM;
    elseif cdt1<=thresholds(4) && cdt1>0
        ener(ul)=RC;
    elseif cdt1==0
        ener(ul)=0;
    end
end

Ma=ener(1); Mb=ener(2); Mc=ener(3); Md=ener(4); Me=ener(5);
Mf=ener(6);
Mg=ener(7); Mh=ener(8);

Mi=ener(9); Mj=ener(10); Mk=ener(11); Ml=ener(12); Mm=ener(13);
Mn=ener(14);
Mo=ener(15); Mp=ener(16); Mq=ener(17);
```

Appendix C.

Approval For from the Virginia Tech Institutional Review Board for the Data Gathered and Presented in Chapter 6

VirginiaTech

Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120, Virginia Tech
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE: March 10, 2014

TO: Gerardo W Flintsch, James Matthew Bryce

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires April 25, 2018)

PROTOCOL TITLE: Applying Pavement Life Cycle Assessment Result to Enhance Sustainable Pavement Management Decision Making

IRB NUMBER: **14-303**

Effective March 10, 2014, the Virginia Tech Institution Review Board (IRB) Administrator, Carmen T Papenfuss, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As:	**Exempt, under 45 CFR 46.110 category(ies) 2**
Protocol Approval Date:	**March 10, 2014**
Protocol Expiration Date:	**N/A**
Continuing Review Due Date*:	**N/A**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

Appendix D.
Survey Sent to Transportation Professionals

VirginiaTech
Invent the Future

Default Question Block

This survey is designed to gauge how you value maintenance and construction costs relative to infrastructure condition and environmental impacts. The condition used in this survey is a 0 to 100 scale (with 100 being perfect). The indicator for environmental impacts is total energy consumption from maintenance/construction and the vehicles traveling along the infrastructure. The energy consumption values relate to emissions, cumulative energy demand, and other environmental indicators. Please answer the following 9 questions based on your preferences and knowledge.

Participation in this survey is voluntary and your responses are greatly appreciated. By continuing in the survey and responding to any of the questions, you consent to allow your responses to be used for research purposes.

Question 1

Please select the number of years of experience you have in working with pavements, pavement management, or infrastructure asset management.

- ○ 0 to 2 years
- ○ 2 to 5 years
- ○ 5 to 10 years
- ○ 10 to 15 years
- ○ Greater than 15 years

Question 2

Please rank the following in order of importance to you, with 1 being most important and 3 being least important. You may choose two or all items to be equally important.

- ☐ Costs of maintenance
- ☐ Condition of the network
- ☐ Energy Consumption (related to environmental impacts)

Question 3

Please compare your preferences about the costs of maintenance related to condition and energy consumption (used to determine global climate change impacts).

Choose the option that best fills in the blank for the corresponding statement

	Extremely less important	Very Strongly less important	Strongly less important	Moderately less important	As Important	Moderately More Important	Strongly more important	Very Strongly more important	Extremely more important
I consider costs (blank) related to energy consumption.	○	○	○	○	○	○	○	○	○
I consider condition (blank) related to costs.	○	○	○	○	○	○	○	○	○
I consider energy consumption (blank) related to condition	○	○	○	○	○	○	○	○	○

Question 4

You have three pavement projects with initial conditions of 70, 80 and 90. You can choose to perform maintenance on any of them for the same cost and the same environmental impact, and 10 points will be added to the condition. Rate the relative importance of performing maintenance on each, with the most important being 100. For example, if a is twice as important as b, then a=100 and b=50. If you are indifferent between a and b, a=b=100.

☐ Bringing Pavements from Condition 70 to Condition 80

☐ Bringing Pavements from Condition 80 to Condition 90

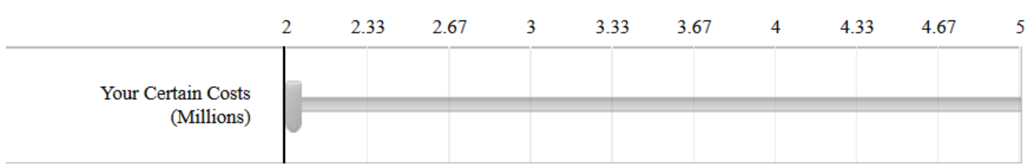
☐ Bringing Pavements from Condition 90 to Condition 100

Question 5

You can choose to have a contractor perform work on a pavement network. The contractor states that, given the uncertainties in the pavement condition, the costs of maintenance are uncertain. The contractor simplifies it such that two outcomes are equally probably: 50% it costs 2 million dollars, and 50% it costs 5 million dollars.

On the other hand, you know the pavement network much better, and therefore can manage it to where your costs are practically 100% known for the same condition and energy consumption. At which cost would you be inclined to choose the contractor over managing it your self. Think of your value as follows: if your costs increase by any amount then you choose the contractor, if your costs decrease by any amount then you choose to manage it yourself.

Once you choose the contractor, you must pay their final amount. Otherwise, if you choose your costs, you understand that there is a possibility that the contractor could have performed the work for less costs.



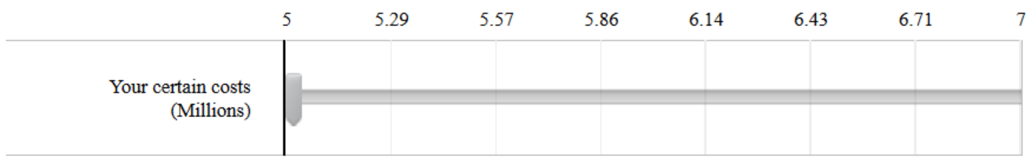
Question 6

This is similar to the previous question, with slightly higher costs.

You can choose to have a contractor perform work on a pavement network. The contractor states that, given the uncertainties in the pavement condition, the costs of maintenance are uncertain. The contractor simplifies it such that two outcomes are equally probably: 50% it costs 5 million dollars, and 50% it costs 7 million dollars.

On the other hand, you know the pavement network much better, and therefore can manage it to where your costs are practically 100% known for the same condition and energy consumption. At which cost would you be inclined to choose the contractor over managing it your self. Think of your value as follows: if your costs increase by any amount then you choose the contractor, if your costs decrease by any amount then you choose to manage it yourself.

Once you choose the contractor, you must pay their final amount. Otherwise, if you choose your costs, you understand that there is a possibility that the contractor could have performed the work for less costs.



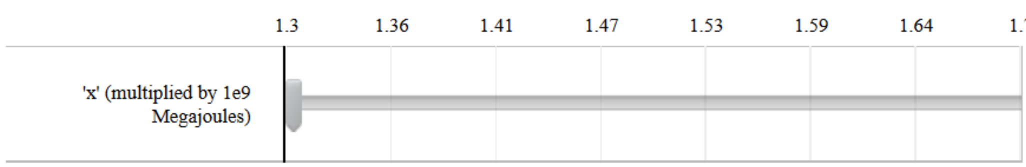
Question 7

The agency you manage has decided to track energy consumption from maintenance and from vehicles using the network using updated models. In order to do this, you form two design teams to propose maintenance plans given a specified condition and cost constraint.

Design team 1 proposes an innovative (but uncertain) plan that meets cost and condition constraints. The uncertainty is simplified as follows: a 50 percent probability an energy consumption value of 1.3e9 Megajoules (equivalent energy to power ~34,000 average American homes), or a 50 percent probability of 1.7e9 Megajoules (equivalent energy to power ~43,000 average American homes).

Design team 2 meets the same cost and condition, but delivers a certain value 'x' (assume ~100 percent certainty) for a value of energy consumption.

What value of 'x' would make you indifferent to choosing either design team. In this case, increasing 'x' would make you tend to choose design team 1, whereas decreasing 'x' would make you tend towards design team 2.



Question 8

Please indicate below your confidence level in understanding the previous four questions (0 indicates least confidence, 10 indicates full confidence). In other words, were the questions clear, and were your choices fully informed given the question structure.

	0	1	2	3	4	5	6	7	8	9	10
Confidence											

Final Page

Please address any additional comments or concerns in the text box below.

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James Bryce <jamesbrycece@gmail.com>

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