ASSESSING THE ENVIRONMENTAL IMPACTS OF WORK ZONES IN ARTERIAL IMPROVEMENT PROJECTS

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16. Abstract

Preservation treatments help in extending the remaining service lives of pavements, but at the same time, they may have substantial environmental impacts due to the acquisition of raw materials, transportation of the extracted materials, manufacturing of the final product, and the use of various equipment during the treatment process. Traditional and accelerated maintenance, repair and rehabilitation (MRR) techniques were identified for both flexible and rigid pavements. Environmental impacts of the commonly used MRR strategies were calculated. A life cycle assessment (LCA) approach was used, taking into account the life extension of the pavement for each type of strategy. The scope boundary included only the construction activities relevant to pavement MRR. LCA results showed that for flexible pavements, accelerated rehabilitation techniques like partial or full depth reclamation have less life cycle environmental impacts than traditional techniques like milling and overlay or total reconstruction. For rigid pavements, all the rehabilitation techniques are comparatively new. The environmental impacts were found to be similar for both traditional techniques like concrete full depth repair and accelerated techniques like precast concrete pavement systems. Minor treatment processes for both flexible and rigid pavements like fog seal, crack seal, concrete seal joints, diamond grinding, and concrete partial depth repair have minimum impacts with maximum benefits when the corresponding life extensions are compared. The results obtained can assist highway construction management professionals to select environmentally sustainable MRR solutions.

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Official
AFDR	Asphalt Full Depth Reclamation
AIEH	Athena Impact Estimator for Highways
APDR	Asphalt Partial Depth Reclamation
ASCE	American Society of Civil Engineers
CFC	Chlorofluorocarbon
ECC	Engineered Cementitious Composites
EIO-LCA	Economic Input Output Life Cycle Assessment
EPA	Environmental Protection Agency
FDR	Full Depth Repair
FHWA	Federal Highway Administration
GHG	Green House Gases
GWP	Global Warming Potential
HMA	Hot Mix Asphalt
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MRR	Maintenance, Repair, and Rehabilitation
NDOR	Nebraska Department of Roads
OMOT	Ontario Ministry of Transportation
PCC	Portland Cement Concrete
PVI	Pavement Vehicle Interaction
SP	Super Pave
USDOC	United States Department of Commerce
USDOT	United States Department of Transportation
UTC	University Transportation Center

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Executive Summary

The 2013 Report Card for America's Infrastructure published by the American Society of Civil Engineers (ASCE) reveals that 32% of the country's major arterial network is in "poor or mediocre condition," resulting in an increase of repair and operating cost by $67 billion per year or $324 per motorist. ASCE projected a required investment of $85 billion annually for improving the physical condition of the roads which means a considerable amount of maintenance, repair, and rehabilitation (MRR) activities are on their way. Although preservation treatments help in extending the remaining service lives of pavements, they may have substantial environmental impacts due to the acquisition and processing of raw materials, transportation of the materials between points of interest, manufacturing of the final product, and the use of various equipment during the treatment process. Any energy usage originating from non-renewable fuel sources like diesel, coal, natural gas, gasoline, liquid petroleum gas, and electricity is responsible for greenhouse gas (GHG) emissions, which mainly consist of carbon dioxide, methane, and nitrous oxide.

Accelerated construction techniques are known to have several advantages such as reducing delay and congestion, decreasing safety concerns, and in turn minimizing socio-economic impacts associated with work zones. But these techniques have several disadvantages as well, such as higher cost, durability issues, design complexity, increased uncertainty, and higher worker fatigue. This report intends to justify the use of accelerated construction from an environmental point of view. Traditional pavement MRR techniques (i.e. chip seal, crack seal, fog seal, scrub seal, slurry seal, thin cold mix overlay, thin hot mix overlay, crack and joint seal, full depth slab repair, mud jacking, partial/ full depth joint repair, dowel bar retrofit, diamond grinding and slab replacement) and accelerated MRR techniques (i.e. partial depth reclamation, full depth reclamation, and precast concrete pavement systems) were identified for flexible, and rigid pavements.

Environmental impacts of the most commonly used MRR techniques were calculated in terms of global warming potential (in kg CO_2 eq), acidification potential (in moles of H+ eq), eutrophication potential (in kg N eq), ozone depletion potential (in kg CFC-11 eq), and smog potential (in kg O_3 eq). Data were obtained from existing life cycle assessment (LCA) studies

and calculations were done using LCA software like the Athena Highway Impact Estimator, and GaBi. While some of the accelerated techniques show lesser environmental impacts than traditional MRR methods, some traditional pavement treatments have the least environmental impacts with maximum benefits. It was found that the type and amount of materials used for the treatments have the maximum influence on energy use and GHG emissions. Generally products with lower asphalt content and lesser heat requirements use considerably less energy than others. The results obtained can assist highway construction management professionals to select environmentally sustainable MRR solutions.

1. Introduction

The 2013 Report Card for America's Infrastructure published by the ASCE reveals that 32% of the country's major arterial network is in "poor or mediocre condition," resulting in an increase of repair and operating costs by $67 billion per year or $324 per motorist (ASCE, 2013). ASCE projected a required investment of $85 billion annually for improving the physical condition of the roads which means a considerable amount of maintenance, repair and rehabilitation (MRR) activities are on their way. Although preservation treatments help in extending the remaining service life of pavements, they may have substantial environmental impacts due to the acquisition and processing of raw materials, transportation of the materials between points of interest, manufacturing of the final product, and the use of various equipment during the treatment process (Cass & Mukherjee, 2011). Any energy usage originating from non-renewable fuel sources like diesel, coal, natural gas, gasoline, liquid petroleum gas, and electricity, is responsible for greenhouse gas (GHG) emissions, which mainly consist of carbon dioxide, methane, and nitrous oxide (Chehovits & Galehouse, 2010).

Lately, there is a widespread awareness of the possible damage that high levels of GHG can cause to the planet. The Kyoto Protocol adopted in Kyoto, Japan in 1997 formally documented these risks and established certain ground rules in an effort to bring GHG emissions down to 1990 levels (United Nations Framework Convention on Climate Change (UNFCCC), 2008). Although the United States signed the protocol, it did not push hard to ratify it. From 1990 to 2011, the total US GHG emissions have increased by 8.4% (USEPA, 2013). According to the data published by U.S. Department of Energy in 2008, the United States emitted 5.9 billion metric tons of CO_2, which is equivalent to 13% of the global CO_2 emissions, the second most in the world after China. The United States also emits approximately 1.1 billion metric tons of other GHG. These challenges have motivated State Departments of Transportation to investigate ways to reduce the GHG emissions caused by pavement MRR activities. As the nature of pavement MRR varies from project to project, it is difficult to generate a generalized process to estimate the environmental effects of the activities. Thus, it is necessary to collect performance and MRR data for different life cycle stages of the pavement to prepare construction inventories with accurate details on materials required and equipment used for the process (Cass & Mukherjee, 2011). Different construction alternatives should also be investigated, including accelerated construction techniques, which involve the use of various innovative materials (FHWA, 2011). Accelerated construction techniques are known to have several advantages such as reducing delay and congestion, decreasing safety concerns, and in turn minimizing socio-economic impacts associated with work zones. But these techniques may have many disadvantages as well, such as higher cost, durability issues, design complexity, increased uncertainty, and higher worker fatigue (Salem et al, 2014). This report intends to justify the use of accelerated construction from an environmental point of view.

2. Objective

This project serves to fulfill TranLIVE's Second Goal: "Develop modeling, simulation, and visualization tools that assess energy, environmental and emission impacts of transportation systems to support transportation decision making at the local, regional, and national levels." This project also fulfills TranLIVE's Strategy 2.3: "Define a process to evaluate the life cycle costs and benefits of alternative transportation policies, including environmental, social, and economic impacts." The objectives of this project are:

i. To assess the environmental impacts of construction activities involved with arterial maintenance, repair and, rehabilitation (MRR) projects and;
ii. To understand the environmental benefits (if any) of accelerated construction techniques over traditional MRR from a life cycle assessment (LCA) point of view.

More specifically, the study focuses on calculating the greenhouse gas emissions, energy usage, and resource usage during the construction activities involved with MRR of pavements of different functional types.

3. Tasks

The research methodology includes completion of the following activities:

Task 1. Literature Review:

A comprehensive review of available literature in the following areas:

1.1. Distresses for flexible and rigid pavements

1.2. MRR strategies for :

1.2.1. Asphalt Pavements: Chip Seal, Crack Seal, Micro-surfacing, Slurry Seal, Fog Seal, Thin Hot Mix Asphalt Overlay

1.2.2. Concrete Pavements: Diamond Grinding, Dowel Bar Retrofit, Full Depth Repair, Partial Depth Repair, Joint Sealing

1.3. Life Cycle Assessment (LCA)

1.3.1. Process-based LCA

1.3.2. Environmental Input Output LCA

1.3.3. Hybrid LCA

1.4. LCA for pavements

1.5. LCA Tools: BEES 3.0 , CMLCA 4.2, SimaPro, GaBi, GREET 1.7, PaLATE, Athena Impact Estimator for Highways

Task 2. Preparing the Life Cycle Assessment Model

2.1. Selection of LCA tools suitable for evaluating life cycle impacts of maintenance, repair, and rehabilitation activities (Athena Impact Estimator for Highways and GaBi)

2.2. Identifying data sources for the LCA process:

2.2.1. Raw materials extracted and used for different treatment and preservation activities

2.2.2. Transportation distances for extracted raw materials and equipment

2.2.3. Basic geometry and traffic volumes of different functional types of pavements

2.2.4. Rehabilitation schedule for pavements of different functional types

2.2.5. Determination of the functional unit for assessment

Task 3. Calculating the Environmental Impacts

3.1. Estimating the amount of resources used for each MRR process

3.2. Calculating the environmental impacts of each MRR activity in terms of Global Warming Potential (in kg CO_2 eq), Acidification Potential (moles of H^+ eq), Ozone Depletion Potential (kg O_3 eq)

3.3. Calculating the energy consumption from various sources such as hydropower, thermal power, diesel, feedstock, gasoline, heavy fuel oil, natural gas, liquid petroleum gas, and nuclear power

3.4. Analyzing and summarizing the overall impacts

Task 4. Preparation of Final Report

Preparation of a final report that will summarize all the research efforts and will assist State Departments of Transportation (DOTs) in making well-informed decisions with regards to different pavement preservation strategies from an environmental impacts perspective.

4. Literature Review

4.1 Pavement Distresses

Any condition of a pavement that reduces its serviceability or leads to a reduction of its serviceability is known as a pavement distress (NDOR, 2002). Serviceability refers to the level of safety and comfort that can be provided by the pavement to the users. Some of the commonly occurring distresses for flexible and rigid pavements are as follows:

4.1.1. Flexible Pavement Distresses

Alligator Cracking: This consists of a series of interconnected cracks on the asphalt layer and looks like the hide of an alligator. If not repaired in time, it may result in penetration of water into surface materials and subgrade, which may cause further damage to the pavement. These cracks often form along the wheel tracts and are also called fatigue cracks. Some of the possible causes of alligator cracking are deficient pavement structure, poor base support, inadequate base drainage, aging and traffic loading (NDOR, 2002).

Edge Cracking: This is similar to alligator cracking and occurs within 1- 2 feet of the edge. The crack adversely affects the wheel path condition and lets moisture into the subgrade soil and base materials. Sometimes longitudinal cracks are present which causes the widening of the concrete base course. Possible factors for causing edge cracking are traffic loading, environmental conditions, construction defects, low shoulder, and high shoulder holding water (NDOR, 2002).

Longitudinal Cracking: This type of crack runs parallel to the center line and is primarily caused by traffic loading, frost action, improper construction practices (also known as joint cracks), poor drainage, and reflection cracks (NDOR, 2002).

Random/ Block cracking: These divide the pavement into rough, approximately rectangular pieces and appear in regular intervals. Thermal stress and aging are the most probable causes for this type of cracking (NDOR, 2002).

Transverse Cracking: This type of crack occurs perpendicular to the centerline of the pavement and extends for three fourth of the width of the pavement. Possible causes may be thermal stress, swelling and shrinkage of the subgrade, reflection cracks, and settlement of trench and backfill (NDOR, 2002).

Raveling/Weathering: This is caused by the wearing away of pavement surfaces resulting in the loss of the asphalt binder and loosening of the aggregate particles. Some of the possible reasons are use of poor quality mixtures, hardening of asphalt due to aging, absence of the proper amount of asphalt, and defective construction (NDOR, 2002).

Distortion: Any distress involving densification, consolidation, swelling, heave, creep, or slipping of the surface or foundation is called distortion. Possible causes may include inadequate support or overloading, freeze and thaw cycles, bonding failure between base layer and surface layer, depression, and soft asphalt concrete or shoving (NDOR, 2002).

Rutting: Rutting is the surface depression caused by traffic loading on the wheel path because of poor moisture, insufficient support, and improper construction procedures (NDOR, 2002).

Excess Asphalt: This is also known as bleeding or flushing and happens when a thin film of asphalt results in a smooth, shiny, greasy and reflective surface around the wheel path. Possible reasons include defective mixtures, lower quality materials, improper construction practices, and use of excess asphalt (NDOR, 2002).

4.1.2. Rigid Pavement Distresses

Joint Distress: This refers to the deterioration of concrete joint sections located between two feet of either side of the joint. This may include breaking and chipping of the joints resulting in feathered edges. One of the major reasons for this kind of distress is the expansive internal pressure created due to alkali-aggregate reactivity between cement and aggregates, corrosion, and deterioration of dowel bars. The freeze and thaw cycle can also damage dowel bars considerably. Some other reasons of joint distress are misaligned dowel bars, loss of support due to voids, and pumping action and overloading (NDOR, 2002).

Faulting: This refers to uneven vertical displacement of slabs or any other structural member along a joint or a crack. Although faulting can be both longitudinal and transverse, it is more common for the transverse joints of portland cement concrete (PCC) pavements without dowels. This is also known as step deformation with an "upstream" slab at a higher level than a "downstream" slab. This can be caused by uneven roadbed support, thermal and moisture stresses, defective dowels, and structural deficiency of the pavement (NDOR, 2002).

Transverse Cracks: These cracks occur parallel to the centerline of the pavement and break the panel into two (Class I) or more pieces (Class II). These are caused mostly due to thermal contraction, long joint spacing, overloading, and subgrade deformation (i.e. swelling, shrinkage or settlement) (NDOR, 2002).

Pattern Cracking: These are severe interconnected cracks occurring anywhere in the slab but not extending to the entire depth of the panel. Material related distresses such as the alkali-aggregate reactivity, and shrinkage are the main reasons behind these cracks (NDOR, 2002).

Surface Distress: This is a result of scaling, spalling, and chipping of the concrete surface which considerably increases the roughness of the pavement and reduces the durability in the long run. Surface distress is generally measured in square feet per panel and excludes the distresses within two feet of a joint. Poor mix design, thermal and moisture stresses, corrosion in reinforcing steel, and insufficient concrete cover for reinforcement are mainly responsible for this kind of distress (NDOR, 2002).

Slab Cracking: This refers to any longitudinal or diagonal crack that runs through the full depth of the slab. Factors involved are overloading, long joint spacing, shallow or late joint sawing, pumping of the subgrade, curling or warping of the slab, and the presence of culvert or utility trenches (NDOR, 2002).

4.2 Pavement Maintenance, Repair, and Rehabilitation Strategies

The US arterial network constantly undergoes MRR activities. The definitions of maintenance, repair and rehabilitation of highway infrastructure are nuanced. Hudson et al (1997) defined maintenance as "the set of activities required to keep a component, system, infrastructure asset, or facility functioning as it was originally designed and constructed to function." Maintenance activities can be categorized into three types: preventive, corrective, and emergency. Preventive maintenance refers to a series of surface treatments intended to extend the functional life of the pavement by retarding the progressive failures of the pavements. Corrective maintenance is defined as a reactive action taken after the occurrence of deficiencies beyond acceptable levels (e.g. loss of friction, rutting, cracking, etc.). Emergency maintenance, as the name suggests, is required in case of unexpected failures due to accidents or severe weather conditions and is done in order to restore its safe functionality until more permanent repairs can be performed. Although all three maintenance types are required for pavements, the proper execution of preventive maintenance may reduce the need of corrective maintenance substantially (Johnson 2000). Fifteen distress types and their corresponding required maintenance activities are listed in Table 1.

Table 1: Distresses and Treatments

		Flexible Pavement									Rigid Pavement					
Manintenance by Category	Distress Type | Maintenance	Alligator Cracking	Edge Cracking	Longitudinal Cracking	Random/ Block Cracking	Transverse Cracking	Raveling/ Weathering	Distortion	Rutting	Excess Asphalt	Joint Distress	Faulting	Transverse Cracks	Pattern Cracking	Surface Distress	Slab Cracking
Flexible Pavements	Chip Seal/	x		x	x	x	x	x	x	x						
	Crack Seal/ Fill		x	x	x	x		x								
	Fog seal	x			x	x	x									
	Mill					x		x	x	x						
	Patching	x		x		x		x								
	Scrub Seal	x		x	x	x	x									
	Shoulder Maintenance		x													
	Slurry Seal	x			x	x	x									
	Thin Cold Mix Overlay	x	x		x		x	x	x	x						
	Thin Hot Mix Overlay	x			x		x	x	x	x	x	x	x	x	x	x
Rigid Pavements	Crack and Joint Seal/Fill										x		x			x
	Full Depth Slab Repair															x
	Mud Jacking											x				
	Partial/Full Depth										x		x		x	
	Slab replacement											x			x	

4.2.1. Flexible Pavement MRR

The descriptions of the maintenance, repair, and rehabilitation activities for flexible pavements are as follows:

Mill and overlay: The traditional and most cost effective repair method for flexible pavements has been mill and overlay (Jensen, Rea, & Syslo, 2008). This process can be used to remove surface distresses like rutting, cracking, and raveling by milling 25 – 100 mm from the existing pavement. The milled surface is then provided with a tack coat and a couple of layers of asphalt. One of the major issues with mill and overlay is its limitation in solving the problems originating from the subgrade or lower pavement layers which often moves upward through the new overlay in a few years (Jensen, Rea, & Syslo, 2008).

Total Reconstruction: This is also a traditional process often used when long term performance has higher priority than cost (Jensen, Rea, & Syslo, 2008). This is also effective in correcting the deficiencies in the sub-grade level. The process includes the removal of the existing pavement by milling to a depth of approximately 150 mm through the subgrade layer. The subgrade is stabilized and a new layer of asphalt is laid which ensures high quality and long-term performance (Jensen, Rea, & Syslo, 2008).

Fog Seal: This involves the application of a diluted emulsion without an aggregate cover and can only be used where the road surface is porous enough to absorb most of the emulsion applied. This can be performed on both high and low volume roads (Raza, 1995). Fog seal curing time depends on the weather and pavement surface conditions. But under ideal conditions, it is recommended to keep traffic off the road for two hours after application until a minimum coefficient of friction of 0.30 is obtained (State of California Department of Transportation, 2003). Traffic speed moderation may be needed for fresh seal coat. Pilot cars can be used to keep traffic speed below 24 miles per hour (FHWA, 2002).

Slurry Seal: This is a combination of fine aggregates, emulsion, water, mineral filler, and additives (optional). Slurry seal is suitable in cases of excessive oxidation and hardening of the existing surface. It is very commonly employed on city and county streets and sometimes on moderate and high-volume roads. The curing time ranges from 1 to 2 hours depending on the amount of binder used (Raza, 1995). Traffic speed should be limited to 25 mph while the seal is still fresh (FHWA, 2005) .

Micro-surfacing: This is a thin surface paving system prepared by mixing aggregates, polymer modified emulsion, water, mineral fillers, and field control additives. This treatment can be used for both flexible and rigid pavements in case of texturing/sealing and rut filling. Micro-surfacing can be done for both moderate and high volume roads. Traffic can be restored in one hour under favorable conditions (Raza, 1995). Traffic speed should be restricted to 25 mph over fresh micro-surfacing (FHWA, 2002).

Chip Seal: In this process, asphalt is applied followed by a cover of single or multiple layers of aggregate. Chip seal can range in thickness from 10 to 40 mm. Rapid setting asphalt emulsion is commonly used. This treatment is suitable for low to moderate volume roads. Traffic can be allowed after rolling with a restricted speed of 25 mph or less for two hours (Raza, 1995).

Thin Hot Mix Asphalt Overlays (HMA) or Resurfacing: HMA is a combination of aggregates and different asphalt cements. The application thickness can vary between 15 and 30 mm. This type of treatment can be used for all types of roads and works best for high volume roads where longer life and lower noise surfaces are expected. HMA application can be conducted with minimal impacts on traffic (Raza, 1995).

Crack Seal: Crack seal is done for working cracks, which are usually transverse and sometimes longitudinal or diagonal and meet the 3 mm movement criteria. This includes the treatment of cracks using specialized materials designed to adhere to the crack side walls in case of expansion and contraction (Smith & Romine, 1999). Rubber modified emulsions that can handle low-stress elongation especially at lower temperatures are suitable for this purpose.

Crack Filling: Crack filling involves treatment of non-working cracks using conventional filling materials to prevent water infiltration. Non-working cracks may be diagonal, longitudinal, or block cracks and are closely spaced with little tendency of movement i.e. less than 3 mm (Smith & Romine, 1999).

4.2.2. Accelerated Flexible Pavement Rehabilitation

Asphalt Partial Depth Reclamation: In this process, a part of the asphalt layer is "milled and windrowed by a milling unit, picked up from the roadway surface by a screening unit, screened, crushed if necessary, mixed with lime and/or emulsion and deposited back on the milled asphalt surface" by a milling machine (Jensen, Rea, & Syslo, 2008). The milled material is compacted after an hour of distribution. If the construction process starts during the day, traffic can be resumed in the evening of the same day. A wearing course is applied 7–28 days after the reclamation process. Partial depth reclamation is used at places where distresses are only limited to the upper asphalt layer and the subgrades are in stable condition. Moreover, the subgrade layer or the lower asphalt layer should be strong enough to resist the additional load of the recycling train during the reclamation process. The recycled materials can be stabilized by pulverizing and mixing with asphalt emulsions or with thin layers of soil and binders (Jensen, Rea, & Syslo, 2008).

Asphalt Full Depth Reclamation: This process involves the recycling and treatment of the whole section of the asphalt pavement and some part of the subgrade which can be used for the construction of a stable base course (FHWA, 2014). The base material is improved by adding asphalt emulsions and chemical agents like calcium chloride, portland cement, fly ash, and lime. The process starts with pulverizing the existing pavement, mixing additives, laying the treated material, compacting, and finishing up with a wearing course. Asphalt Full Depth Reclamation (AFDR) is generally performed on a depth of 100 to 300 mm. Additional materials are only added if the excavated materials are not sufficient for attaining the desired depth. The benefits of full depth reclamation include significant improvement in the pavement structure and uniformity without altering the pavement geometry, low production and engineering costs and elimination of waste and minimization of environmental impacts due to the use of recycled materials. AFDR can be used to eliminate all kinds of cracks, rutting, and maintenance patches featuring sprays and deep hot mix (FHWA, 2014).

4.2.3. Rigid Pavement MRR

The MRR activities for rigid pavements are as follows:

Full Depth Repair (FDR): This type of treatment is mostly used for transverse cracks, shattered slabs or corner breaks in concrete pavement contraction design (CPCD), and for punchouts and deep spalling in continuously reinforced concrete pavements. The process includes identifying the distressed areas, saw-cutting the perimeters, removing the concrete slab and damaged sub-base if needed, drilling holes for tie bars to provide longitudinal and transverse steel continuity, and then placing concrete (TxDOT, 2011).

Partial Depth Repair (PDR): TxDOT uses partial depth repair for only shallow spallings. Shallow spallings are considered to be four inches or less in depth and may also include horizontal delamination. The PDR procedure is similar to that of FDR, except parts of slabs are not fully replaced. Repair materials that have comparable strength and modulus of elasticity values to those of the existing concrete section and good bond strength are used (TxDOT, 2011).

Dowel Bar Retrofit (DBR): This technique is used in concrete pavement contraction design to restore the load transfer between adjacent slabs when the effectiveness of aggregate interlock decreases due to concrete shrinkage with time. The aggregate is further minimized during the cold weather due to the contraction of concrete. The DBR process includes cutting of slots for the dowel bars at the joint, removing of concrete from the slots, placing the dowel bars in the slots, filling with backfilling materials and often diamond grinding after curing (TxDOT, 2011).

Joint Repair: Joint repair is required for transverse construction joint failures in continuously reinforced concrete pavement (CRCP) and CPCD. This is often accompanied by FDR. Load transfer devices for CPCD include placement of dowels at the transverse joints and tie bars at longitudinal joints. For CRCP, joint repair is similar to the placement of tie bars as recommended in FDR (TxDOT, 2011).

Diamond Grinding (DG): This is a process of removing a thin layer of hardened PCC pavement surface using closely spaced diamond blades to remove bumps and produce saw-cut grooves. DG is used to fix surface defects such as roughness, increase surface friction for old concrete pavement surfaces, and reduce noise due to tire-pavement interaction. DG also helps in improving drainage and skid resistance by increasing the macro-texture of the surface. One of the major advantages is that it can be performed during off-peak hours with short lane closures without affecting the adjacent traffic. Other advantages include its cost effectiveness in comparison to an overlay; the lack of need for taper at entrances, exits, and side streets; and minimal effect on the overhead clearances underneath bridges (TxDOT, 2011).

4.2.4. Accelerated Rigid Pavement MRR

Precast Concrete Pavement Systems: Precast concrete slabs are fabricated off-site and transported to the project site. They are installed on prepared foundation and no field curing is required to achieve strength. They can be categorized into jointed systems and pre-stressed systems (FHWA, 2014). This process can be completed overnight, on weekends, and during off-peak hours and thus decreases the duration of road closure. Precast panels serve best for the rehabilitation of busy intersections and ramps with heavy traffic and helps in reducing congestion. A higher quality of standard and fabrication is possible as the panels are precast off-site, making the repairs last longer. Precasting allows for thinner slabs and thus is suitable for roadways under overpasses with limited clearance. Concrete panels can be post tensioned on site to increase the strength of the structure thus eliminating the need of prestressing and decreasing the probability of cracking in the slabs. There are some proprietary and nonproprietary precast slabs available such as Super-Slab, KWIK SLAB, and precast prestressed concrete pavement

(PPCP), which can be customized in terms of thickness, cross slope, and layout requirements and can be installed quickly with minimal training. For example, for Super-Slab a productivity rate of 1500 square feet per hour or 10 slab per hour can be achieved (FHWA, 2014).

Portland Cement Concrete Pavement with Admixture: Admixtures are added to the cementitious mix for many reasons such as accelerating or retarding the setting time, increasing workability, improving concrete strength, reducing the water-cement ratio, and improving frost and chemical resistance (Lee & McCullouch, 2009). Every admixture has drawbacks and more than one admixture is often used in a mix to compensate for each admixture's shortcomings. One of the frequently used accelerators is calcium chloride ($CaCl_2$), but it cannot be used for reinforced concrete as it increases the probability of corrosion for the metal bars. This can be counteracted by using other admixtures such a silica fumes. $CaCl_2$ may also increase the occurrence of shrinkage which can be neutralized by using sodium sulfate (Na_2SO_4). Some of the non-chloride accelerators often used to avoid the drawbacks of the $CaCl_2$ are Triethanolamine ($NC_2H_4OH_3$) and Calcium Nitrite [$Ca(NO_2)_2$]. Generally higher amounts of non-chloride admixtures are necessary to achieve the same effect as that of $CaCl_2$ (Lee & McCullouch, 2009).

Rapid Setting Concrete (RSC): RSC also known as epoxy cement resembles PCCP but does not contain any cementitious products (Lee & McCullouch, 2009). It is a mixture of epoxy and aggregates and can reach its full hardness and structural strength within a few hours, even in low temperatures (i.e. below 40^{o}F). RSC is quite resistant to oil, water, and other chemicals like acid. It can be applied in a thin overlay (i.e. about ½ - ¾ inch) or can be used as a patch filler. The commonly used epoxy based concrete are methyl methacrylate (MMA), high molecular weight methacrylate (HMWM), polyesters, and epoxy-urethanes. MMA is most frequently used because of its ease of use, although it is highly inflammable and has a strong odor. MMA can attain a structural strength of 8,000 psi in one hour at 70^{o}F. HMWM is similar in characteristics to MMA but is less flammable and has less odor. However, it is considerably more expensive than MMA. Polyesters are the least expensive among all and are, therefore, widely used. However, they are not as fast and strong as HMWM and MMA and can have shrinkage problems on settling. Epoxy-urethanes are mostly used for coating and waterproofing purposes and do not contribute considerably to the strength of the pavement structure (Lee & McCullouch, 2009).

Roller Compacted Concrete Pavement (RCCP): RCCP uses portland cement concrete with zero slump which can be placed using bituminous asphalt pavement equipment or common earthmoving equipment and compacted with a vibratory and rubber tire rollers (Lee & McCullouch, 2009). The composition of RCCP is 75-85% aggregate having a maximum size of 19 mm, 9-18% cement, and 4-7% water. RCCP is only suitable for low speed pavements (not for highways). It can handle harsh weather conditions and heavy traffic usage. It is also used sometimes in composite pavements as a base and then topped by a thin layer of asphalt. Some of the advantages of RCCP over PCCP are lower cost, shorter construction duration, and a comparable performance. RCC can be placed in a similar fashion as placement of asphalt even in operational traffic and thus eliminates the need for concrete formworks. RCCP does not need joints, can be laid continuously, and can attain a strength of 400 psi in a period of 24-48 hours (Lee & McCullouch, 2009).

4.3. Life Cycle Assessment

Life cycle assessment (LCA) is a methodology to evaluate the environmental impacts of a product over its life cycle, i.e. from material extraction to the end of life disposition (Santero, Masanet, & Horvath, 2010). The guidelines for performing LCA are provided by the International Organization for Standardization (ISO), which demonstrates how LCA can help i) to reduce the environmental impacts of the products throughout their life cycles, ii) industrial, government, and non-government organizations in making an informed decision on the process design and re-design of a product, iii) to identify parameters to evaluate environmental performance, and iv) to attain marketing benefits by implementing eco-labeling schemes (Santero, Masanet, & Horvath, 2010). Possible life cycle stages of a process and its typical inputs and outputs are presented in Figure 1.

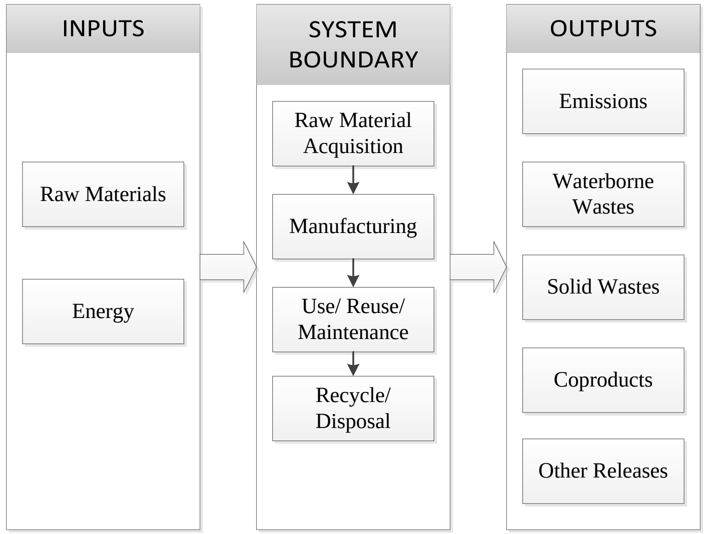

Figure 1: Life Cycle Stages (Hendrickson, Lave, & Matthews, 2006)

The environmental impacts addressed by LCA are: resource use, direct impacts on nature and landscape, air pollution, soil pollution, surface water, noise, electromagnetic radiation or fields, and ionizing radiation. LCA analysis consists of four stages: goal definition, life cycle inventory, life cycle impact assessment, and life cycle interpretation. These stages are graphically presented in Figure 2.

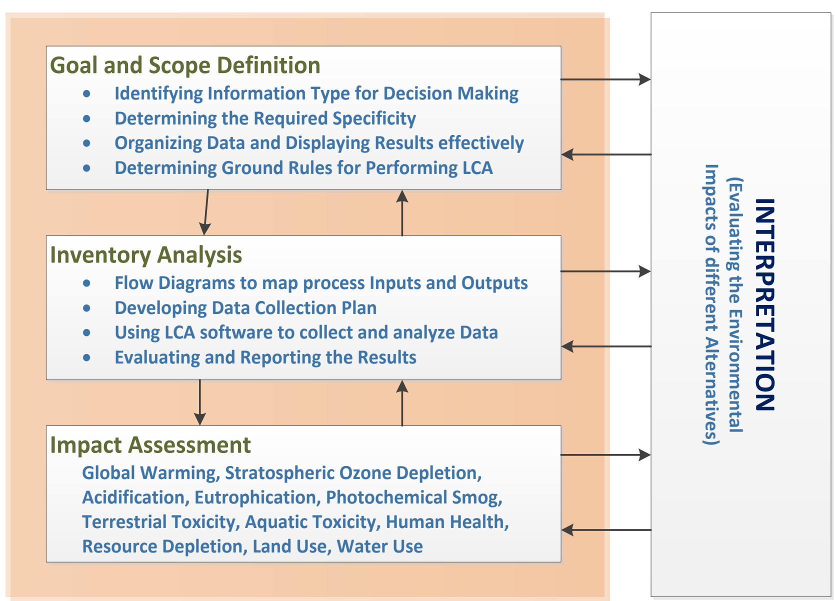

Figure 2: Life Cycle Assessment Framework (ISO, 2006)

4.3.1. Goal Definition

The first step is to clearly state goals and scope to understand, organize, and relate the results of LCA (ISO, 2006). To ensure efficient use of time and resources, a six-step process needs to be followed:

- **i)** ***Defining the goals of the project:*** The primary goal is choosing the product and service that has the least impact on the environment and human health. Depending on the type of the project, there may be secondary goals for performing LCA.
- **ii)** ***Determining the type of information needed by the decision makers:*** Identifying appropriate questions can help decision makers determine the types of information needed to answer the questions.
- **iii)** ***Determining the required specificity:*** Deciding the level of specificity is important for every study. Sometimes this level is obvious for the project under consideration, but in some cases it should be chosen from several options possible.
- **iv)** ***Determining how the data should be organized and the results displayed:*** A functional unit needs to be chosen for consistent comparisons between different products.
- **v)** ***Defining the scope of the study:*** It determines whether one or all of the four stages of a process life cycle should be included in the scope of the LCA.
- **vi)** ***Determining the ground rules for performing the work:*** This includes defining the logistical procedures for the project such as documenting assumptions, quality assurance procedures, and reporting requirements.

4.3.2. Life Cycle Inventory

Life cycle inventory identifies and quantifies resources, energy inputs and products, and waste emission outputs for the entire life cycle of a process (ISO, 2006). According to the EPA, there are four steps in a life cycle inventory:

- i) Developing a flow diagram to map the inputs and outputs of the process,
- ii) Developing a data collection plan,
- iii) Collecting data by using LCA software, and
- iv) Evaluating and reporting the results.

4.3.3. Life Cycle Impacts Assessment (LCIA)

LCIA determines the potential environmental and human health effects associated with a product's life cycle (ISO, 2006). LCIA consists of the following steps:

i) Selection and definition of relevant environmental impact categories
ii) Organizing and combining LCI results into impact categories
iii) Characterizing the impacts using science-based conversion factors.
iv) presents some commonly used life cycle impact categories with their examples
v) Normalization of impact indicator results which can be compared among the impact categories
vi) Grouping and sorting the indicators by their characteristics and ranking system
vii) Assigning weights to different impact categories based on their importance
viii) Evaluating and documenting LCIA results and verifying the accuracy of the results

Descriptions of some of the commonly used life cycle impact categories are presented below:

Global Warming Potential (in kg CO_2 eq): The global warming potential of a gas is measured by its ability to absorb energy over a period of 100 years compared to carbon dioxide (VanDunien & Deisl, 2006). Gases like carbon dioxide, methane, and CFCs absorb the sun's radiation (infrared radiation) that is reflected from the surface of the earth, and then they release it in every direction including towards the surface of the earth. The amount of GHG is increasing due to human activities, which is resulting in a warming effect on the earth's surface. The greenhouse potential of an emission is generally expressed in terms of CO_2 equivalent amount released to the atmosphere (VanDunien & Deisl, 2006).

Acidification potential (in moles of H+ eq): Acidification potential is defined as the "ability of certain substances to build and release H^+ ions" (VanDunien & Deisl, 2006). Gases like sulfur dioxide and nitrogen oxide dissolve with water particles in the atmosphere and form their respective acids like H_2SO_4 and HNO_3 respectively which reduces the pH-value of rainwater and fog from 5.6 to 4. This increases the acidity of the water and damages the ecosystem in many ways. Acidic water is harmful to trees and may cause major forest dieback. Acid rain may deplete the amount of nutrients in the soil and may increase the solubility of metals. It may also deteriorate built environment by reacting with metals and natural stones. The extent of acidification may vary regionally (VanDunien & Deisl, 2006).

Eutrophication Potential (in kg N eq): Eutrophication involves the increase of concentration of nutrients at a particular location and is caused by various elements such as air pollutants, wastewater, and fertilizers (VanDunien & Deisl, 2006). This causes excessive algae growth that prevents sunlight from reaching the lower levels of the water body. This hinders the photosynthesis process and reduces the level of oxygen in the water. This leads to an anaerobic condition and eventually causes the death of the fish. Due to the lack of oxygen, dead fish and algae undergo anaerobic decomposition, which produces gases like hydrogen sulfide and methane, which are again harmful for the ecosystem. Eutrophicated soils reduce immunity of the plants and make them vulnerable to pests. Excess nutrition levels may increase the amount of nitrogen in the soil and may leach into the groundwater as nitrate. Although a small amount of nitrate is harmless for humans, the reaction product nitrite is quite toxic (VanDunien & Deisl, 2006).

Ozone Depletion Potential (in kg CFC-11 eq): Gases like chlorofluorocarbons (CFCs) and nitrogen oxides (NOx) have a depleting effect on the ozone layer (VanDunien & Deisl, 2006). Ozone is a disassociated product of oxygen produced in the atmosphere due to the exposure of short-wave UV-light. The ozone layer in the stratosphere is 15–50 km high and absorbs the short wave UV radiation while only letting the longer wavelengths pass through. This is critical for life on earth as humans, animals, and plants are sensitive to UV-B and UV-A radiation. UV radiation also causes warming of the Earth's surface, changes or decreases in crop harvest due to the disruption of photosynthesis, increases risks of skin cancer and eye disease for humans, and decreases sea planktons, which affects the whole ecosystem adversely. The ozone depletion potential is the measure of the ability of different ozone related substances to destroy the ozone layer and is measured in the amount equivalent of CFC 11. The long term, global and irreversible effects are taken into account during the calculation process (VanDunien & Deisl, 2006).

Smog Potential (in kg O_3 eq): Although ozone is useful in the stratosphere, it is considered a harmful gas at the ground level (VanDunien & Deisl, 2006). Ozone is created as a result of photochemical reaction in the presence of the sun's radiation, nitrogen oxides, and hydrocarbons in the troposphere. It is also termed as summer smog which in higher concentration is toxic to human beings and may damage vegetation. Hydrocarbon emissions are caused by the incomplete combustion of fossil fuels and produces high concentrations of ozone at places with high temperatures, less humidity, and static air conditions. As ozone is reduced to NO_2, CO_2 and O_2 by NO and CO, the concentration is generally low near the source of hydrocarbon emissions; but it occurs at places with clean air such as forests or the country side. The smog potential is calculated in amounts of ozone equivalent. The smog potential depends greatly on the local weather and other regional characteristics (VanDunien & Deisl, 2006).

Table 2: Commonly Used Life Cycle Impact Categories (Scientific Application International Corporation (SAIC), 2006)

Impact Category	Scale	Example of LCA Data
Global Warming	Global	Carbon Dioxide, Nitrogen Dioxide, Methane, Chlorofluorocarbons, Hydro Chlorofluorocarbons, and Methyl Bromide
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons, Hydro Chlorofluorocarbons, Halons, Methyl Bromide
Acidification	Regional Local	Sulfur Oxides, Nitrogen Oxides, Hydrochloric Acid, Hydrofluoric Acid, and Ammonia
Eutrophication	Local	Phosphate, Nitrogen dioxide, Nitrogen oxide, Nitrates, and Ammonia
Photochemical Smog	Local	Non-methane Hydrocarbon (NMHC)
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish
Human Health	Global Regional Local	Total releases to air, water, and soil
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications
Water Use	Global Regional Local	Water used or consumed

4.3.4. Life Cycle Interpretation (LCI)

LCI is the final phase of the LCA process where the results obtained from the LCI and LCIA are identified, quantified, checked, and evaluated. According to the International Organization for Standardization (2006), the objective of this phase is to analyze results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of the LCA. It is necessary to report the results of the life cycle interpretation in a transparent manner, and to provide a readily understandable, complete, and consistent presentation of the results of a LCA study in accordance with the goal and scope of the study (ISO, 2006). The steps included in this phase are:

i) Identification of significant issues
ii) Evaluation of completeness, sensitivity, and consistency of data; and
iii) Conclusions and recommendations

4.4. LCA Models

Life cycle assessment can be conducted using three types of models: i) Process-based LCA, ii) Economic input-output model, and iii) Hybrid models.

4.4.1. Process Based LCA

The USEPA and Society of Environmental Toxicology and Chemistry (SETAC) have played important roles in standardizing LCA in the United States. ISO 14041 lists the steps required for processing a system such as defining the goal, conducting the life cycle inventory, assessing the life cycle impact, and performing the interpretation (ISO, 2006). The method divides each system into individual process flows and attempts to quantify their impacts on the environment. The process method systematically computes the known environmental inputs and outputs by utilizing a process flow diagram. The data collection process includes gathering information from the architect, engineer, prime contractors, and owner. Data sources are construction drawings, technical specifications, approved submittals, bid tabulation, and schedules. The advantage of the process-based method is that it can calculate the materials and energy balances of each facility in great detail.

4.4.2. Input-Output Model (EIO-LCA)

The input–output method considers the direct effects of resources and related emissions to the environment and all indirect effects involved in the supply chain. The Department of Commerce in collaboration with Carnegie Mellon University integrated the economic input and output table with resources extracted and environmental discharges to prepare a 480 x 480 matrix which forms the body of the EIO-LCA tool. The tool can be accessed at http://www.eiolca.net. The data used in the EIO-LCA tool are derived from public datasets and assembled for different sectors. The tool considers a very large boundary and covers the entire economy and most of the materials and energy inputs. EIO-LCA reports the effects of a project on energy, global warming potential, resource conservation and hazardous wastes, toxic releases inventory (TRI), and toxic air releases. The four basic steps for EIO-LCA are as follows:

i) Estimating output changes to final demand by sector
ii) Assessing direct and indirect economic changes with the input-output model
iii) Assessing environmental discharges as a result of sector output changes
iv) Adding all the sector discharges to find the overall discharge

The advantages and disadvantages of Process LCA over EIO-LCA are listed in Table 3

Table 3: Advantages and Disadvantages of Process LCA and EIO-LCA Modeling Approaches (Hendrickson, Lave, & Matthews, 2006)

	Process Model	EIO-LCA
Advantages	• Detailed process-specified analysis • Specific product comparisons • Process improvements, weak point analyses • Future product development assessments	• Economy-wide, comprehensive assessments (all direct and indirect environmental effects included) • System LCA: industries, products, services, national economy • Sensitivity analyses, scenario planning • Publicly available data, reproducible results • Future product development assessments • Information on every commodity in the economy
Disadvantages	• Subjective system boundary-setting • Time intensive and costly • Difficulty in new process design • Use of proprietary data • Inability to be replicated if confidential data are used • Uncertainty in data	• Some product assessments contain aggregate data • Difficulty in process assessments • Difficulty in linking dollar values to physical units • Economic and environmental data may reflect past practices • Imports treated as US products • Difficulty to apply to an open economy (with substantial non-comparable imports)

4.4.3. Hybrid Models

The Hybrid LCA models combine the benefits of both process and input-output methods. EIO-LCA simplifies the modeling procedure, while process models improve the quality of analysis. Some examples of Hybrid LCA are: tiered, I-O based hybrid, integrated, and augmented process based (Hendrickson et al. 2006). The Hybrid LCA can be applied more easily than the I-O method or the process method alone. The advantages of Hybrid LCA are as follows:

i) Ability to perform more than one analysis in parallel for comparison purposes
ii) Using the detailed answers from process analysis to get more detailed answers from the EIO-LCA model

iii) Using the comprehensive scope of EIO-LCA to overcome the boundary limitation of process analysis

iv) Using process analysis to collect data which can be used to modify coefficients or disaggregate a sector

4.5. Life Cycle Assessment for Pavements

About 80% of materials in the United States are used for construction, and a large fraction of these materials is used for road construction (Horvath & Hendrickson, 1998). According to the Energy Information Administration (2002), asphalt production is the second most energy-intensive manufacturing industry in the United States. Asphalt needs to be constantly heated before use to maintain its fluidity which is energy intensive and thus produces a considerable amount of emissions. Cement production is ranked seventh among the most energy-intensive manufacturing industry. Due to the use of these energy intensive materials, large amounts of greenhouse gases are emitted during maintenance, repair, and rehabilitation of highways. Loijos (2011) in his study on LCA of rigid and flexible pavements presented the life cycle phases for each type as presented in Figure 3 and Figure 4.

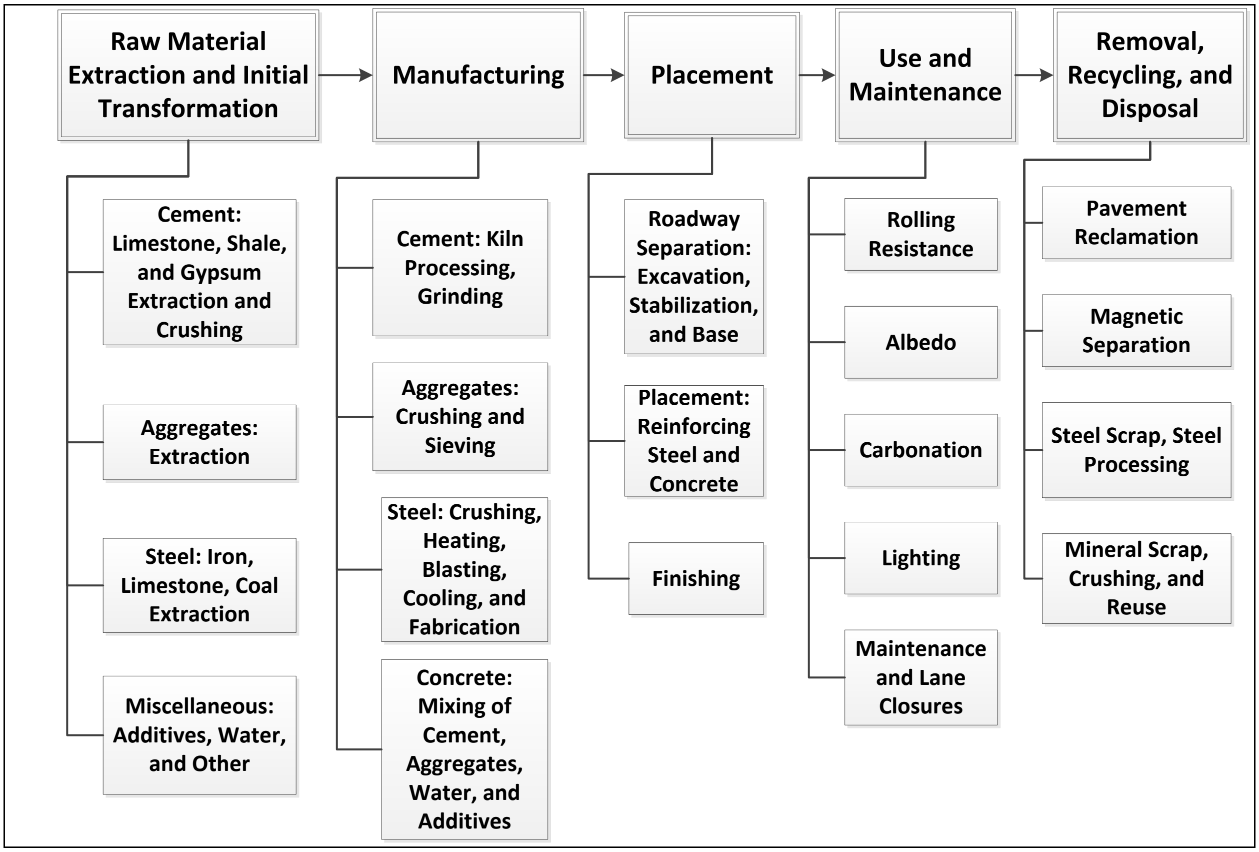

Figure 3: Life Cycle Phases and Components for Rigid Pavements (Loijos, 2011)

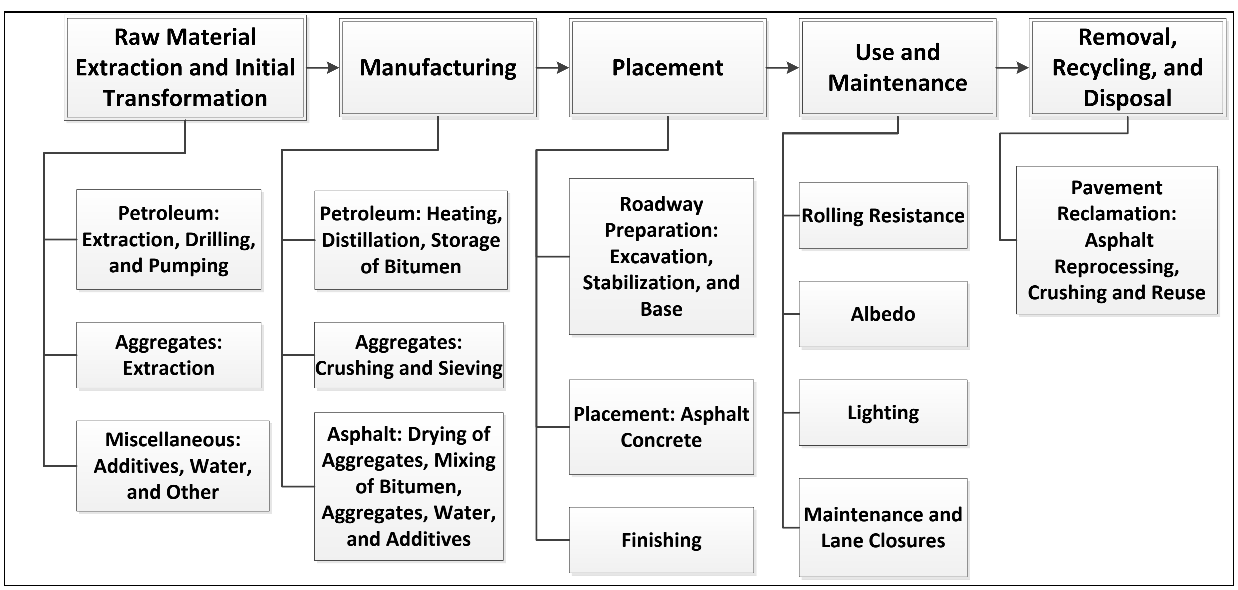

Figure 4: Life Cycle Phases and Components for Flexible Pavements (Loijos, 2011)

Cass and Mukherjee (2010) calculated the greenhouse gas effects of hot mix asphalt reconstruction projects and concrete rehabilitation and reconstruction projects in the State of Michigan. The Michigan DOT organizes its inventory data using the “Field Manager” tool. That data was used by the authors to calculate the environmental impacts using EIO-LCA and e-Calc (GHG Emission Calculator). The results indicate that emissions related to the concrete rehabilitation projects are significantly more than emissions of the HMA reconstruction projects (Cass & Mukherjee, 2011).

The life cycle impacts of overlay systems, engineered cementitious composites (ECC), and hot mixed asphalt (HMA) were studied by Keoleian et al. (2005). The LCA model prepared had six modules to calculate the impacts for different components involved: i) Material used (using SimaPro), ii) Construction Equipment (using NONROAD emission model), iii) Distribution, iv) Traffic Congestion, v) Usage (using MOBILE 6.2 Emission Model, KyUCP Traffic Flow Model, Fuel Economy Model, and the Roughness Model), and vi) End of Life (Keoleian, et al., 2005). The environmental impact categories studied in this paper are energy and material resources consumption, air and water pollutant emissions, solid waste generation, and global warming potential. The elements investigated were GHG emissions, carbon monoxide, volatile organic compound (VOC), PM2.5, NOx, SOx, ammonia, biological oxygen demand (BOD), dissolved matter, and phosphates. From an environmental point of view, the ECC system consumes less energy and uses fewer nonrenewable resources, resulting in fewer emissions and pollutants. ECC also excels from a social perspective by reducing user delay due to traffic congestion (Keoleian, et al., 2005).

Zapata and Gambatese (2005) presented their study on the energy consumption of continuously reinforced concrete pavements (CRCP) and asphalt pavements. LCA was performed using both the process-based and EIO-LCA models. The process model used is called the Society of Environmental Toxicology and Chemistry – Environmental Protection Agency (SETAC-EPA) technique. Widely used in the US and many European countries, this model divides the system into individual processes that can be analyzed independently, and the results can be summarized in a flow chart. The study was conducted on a one kilometer section of a typical two-lane highway with a high volume of traffic. The environmental impacts were calculated throughout various life cycle phases of the pavement. The study shows that cement production requires more energy than that of bitumen and also PCC pavements require more energy for extraction of raw materials, manufacturing, and placing of course pavement materials. In asphalt pavement construction, the majority of energy is consumed during asphalt mixing and the drying of aggregates. The authors recommended the use of byproducts such as fly ash as a substitute for cement and limestone in concrete mixtures. Some of the advantages of using fly ash in concrete are: less CO_2 emissions, less energy consumption, fewer landfills, better workability, less water requirement, lower permeability, higher durability, better crack resistance, and higher ultimate strength of concrete (Zapata & Gambatese, 2005).

A life cycle optimization (LCO) model was prepared by Kendal et al. (2008) to determine the optimal preservation (maintenance and rehabilitation) strategy for pavement overlay systems and to minimize the total life cycle energy consumption and emissions. Three pavement overlay systems i.e. concrete, ECC, and HMA were analyzed in this study using an integrated LCA-LCCA model, a pavement deterioration model, and a LCO model. The integrated LCCA-LCA model can calculate agency cost, user cost, and environmental cost depending on the life cycle impacts of the pavement. The LCO model captures construction events, traffic congestion, and roughness effects dynamically and calculates the energy consumption, costs, and GHG emissions for various levels of pavement performance. Overall, results show that the optimal preservation strategies will reduce total life cycle energy consumption by 5-30%, GHG emissions by 4-40%, and cost by 0.4-12% for all the overlay systems (Kendall, Keoleian, & Helfand, 2008).

4.6. Life Cycle Assessment Tools

In recent years, in parallel to the advancements in the computer technology, a number of software tools were developed to perform life cycle assessment. A brief review of some of the LCA tools available is presented below:

4.6.1. BEES 3.0 (Building for Environmental and Economic Sustainability)

Developed by the National Institute of Standards and Technology Building and Fire Research Laboratory, BEES 3.0 can be used for LCA, LCI, LCIA and LCC. This tool uses the ISA 14040 LCA approach and can measure the environmental performance of building products and balance the environmental and economic performance of building products. It analyzes all life stages of a product, such as raw material acquisition, manufacturing, transportation, installation, use, and recycling and waste management. The software has its own database and it comes with data files containing rolled-up LCIs for over 230 building products and parking lot paving. Some of the environmental and economic performance measures used in this software include global warming acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, smog, ecological toxicity, ozone depletion, and human health. More information about the software can be found at http://www.bfrl.nist.gov/oae/software/bees.html.

4.6.2. Chain Management by Life Cycle Assessment (CMLCA 4.2)

CMLCA was created by the Center of Environmental Sciences at Leiden University. In addition to calculating all the components of LCA, the software also calculates social LCA, life cycle sustainability assessment (LCSA), environmental input-output analysis (EIOA), and eco-efficiency analysis (E/E). CMLCA 4.2 supports full hybrid inventories. The software is free and does not need to be installed on a computer. The necessary database needs to be downloaded to carry out the specific required analysis. More information about the software can be found at http://www.leidenuniv.nl/interfac/cml/ssp/software/cmlca/index.html.

4.6.3. SimaPro (System for Integrated Environmental Assessment of Products)

SimaPro was developed by Pre Consultants B.V. and can be used for life cycle management (LCM). Some additional features of this tool besides performing LCA is life cycle work environment (LCWE), product stewardship, supply chain management, design for environment and design for reliability (DfE, DfR), life cycle engineering (LCE), and substance/material flow analysis (SFA/MFA). This software allows users to make hybrid data models that combine input-output with traditional processes and can measure environmental impacts such as carbon footprint, product design and eco-design, and environmental product declaration. SimaPro uses its own database and a library with eleven impact assessment methods and includes several inventory databases with thousands of processes. More information about the software can be found at http://www.pre-sustainability.com/simapro.

4.6.4. GaBi (Ganzliche Bilanzierung)

GaBi was developed by PE International and the University of Stuttgart. This software can be used for LCA, LCI, LCWE, product stewardship, supply chain management, LCIA, LCSA, LCC, DfE, DfR, and SFA/MFA. The GaBi database has a large number of datasets and consists of about 1000 processes. This software is used widely by industries to reduce resource costs, develop more sustainable processes, increase product preference, improve regulatory compliance, increase brand value, and create more sustainable products. More information about the software can be found at http://www.gabi-software.com/.

4.6.5. GREET 1.7 (Greenhouse Gases, Regulated Emission, and Energy use in Transportation)

GREET was developed by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). The software can measure GHG, regulated emissions, and energy use in transportation. By using the life cycle model, GREET evaluates various vehicle and fuel combinations on full fuel cycle from wells to wheel/vehicle–cycle basis. It also includes more than 85 fuel production pathways and more than 70 vehicle/fuel technology options for evaluation. The output files are well-to-pump energy use and emissions and well to wheels energy and emissions. More information about the software can be found at http://www.transportation.anl.gov/software/GREET/index.html.

4.6.6. PaLATE (Pavement Life Cycle Assessment Tool for Environmental and Economic Effects)

PaLATE is an Excel-based tool used for studying the environmental and economic effects of pavements and roads. The software was developed by the University of California, Berkeley. Inputs required by the program are roadway design, initial construction, maintenance, equipment use, and costs. The outputs include life cycle environmental effects due to energy consumption, gas emissions, and leachate information. More information about the software can be found at http://www.ce.berkeley.edu/~horvath/palate.html.

5. Methodology

5.1. Scope

The study analyzes the life cycle inventory of embodied primary energy and GHG emissions of maintenance, repair, and rehabilitation activities of flexible and rigid pavements. The GHG emissions were combined and calculated in terms of CO_2 equivalence, which is the characteristic measure for global warming potential. The scope boundary includes only the processes that are relevant to pavement MRR and does not take into consideration the broader effects such as traffic impacts. The road system boundaries include material use and construction process for granular sub-base, base, shoulder, and finished surfaces for both road and shoulder. It does not take into consideration right-of-way clearing, sub-grade construction, lane dividing painting, barrier construction, right-of-way restoration, and other activities not directly related to the pavement itself.

5.2. Functional Units

A functional unit is necessary to conduct consistent comparisons between different process analyses and results. All the parameters were analyzed over one center kilometer of the respective functional road types. The results were also annualized for one square meter of the pavement for some comparisons. The functional definition and traffic capacity of each type is adopted from the Federal Highway Administration's Highway Statistics 2008 and 2010 and is presented in Table 4 (FHWA, 2010). The highway design parameters considered for calculating the material quantities were at par with the American Association of State Highway and Transportation Official (AASHTO 1993). The mechanistic-empirical design methods prepared by the Portland Cement Association were also used.

Table 4: Basic Design and Traffic Capacity by Functional Type (FHWA, 2010)

Functional Type		Interstate	Freeway	Principal Arterial	Minor Arterial	Collector	Local
Functional Definition	AADT (Vehicles/ Day)	78187	52908	19133	9405	4194	961
	AADTT (Trucks/Day)	6303	2152	785	389	169	39
	Total Lanes	6	4	4	2	2	2
	Lane Width	3.7	3.7	3.7	3.7	3.4	2.7

5.3. Rehabilitation Schedule

Maintenance and rehabilitation schedules such as intervals for certain types of MRR, life expectancy, construction process, and materials used for the treatment processes used are necessary to estimate the life cycle impacts of the MRR activities throughout the design life of a pavement. Schedules are specifically important for rehabilitation activities as they involve more materials, equipment, and energy intensive activities. It is difficult to find schedules for small maintenance and repair activities like chip seal, slurry seal, fog seals, concrete seal joints, etc. because they are highly dependent on location, weather conditions, and the local DOT. Moreover, the materials and energy required for these activities are also much smaller than those required for rehabilitation activities. The materials used and the life expectancy of minor maintenance activities are presented in Table 5.

Table 5: Life Expectancy of Minor Treatment Types (Chehovits & Galehouse, 2010)

Treatment Type	Materials used	Expected Life Span (Year/s)
Chip Seal	Emulsion (2 L/m2), Aggregate (21 kg/m2)	5 – 10
	Emulsion (1.6 L/m2), Aggregate (15 kg/m2)	5 – 10
Micro-surfacing	12% Emulsion (13 kg/m2)	3 - 5
	14% Emulsion (8.7 kg.m2)	2 - 4
Crack Seal	0.37m/m2	1-3
Fog Seal	0.23 l/m2, 50/50 diluted emulsion	1
	0.46 l/m2, 50/50 diluted emulsion	1
	0.69 l/m2, 50/50 diluted emulsion	1

Rehabilitation schedule varies for different DOTs. Sample rehabilitation schedules used by the Ontario Ministry of Transportation (OMOT) in Canada were used for the analysis and are presented in Table 6 and Table 7. OMOT uses AASHTO 1993 design guidelines for their pavement design as followed by most of the state DOTs in the USA. Thus, the analysis results can also provide USDOT officials with valuable information with regards to the environmental impacts of MRR activities for different functional and structural types of pavements.

Table 6: Flexible Pavements Rehabilitation Schedule (Athena Sustainable Material Institute, 2013)

Functional Type	Activity Type	Years after Initial Const.	Expected Life Span (Years)	Materials	Thicknes s
Local, Collector and Minor Arterial	Partial Depth Reclamation	10	5	Reclaimed Pavement (Super Pave (SP)12.5)[1], Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Route and Seal	10	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Milling and overlay	20	15	Milling and Overlay with Super Pave 12.5	40 mm
	Route and Seal	25	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	30	5	Reclaimed Pavement (SP12.5), Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Full Depth Reclamation	35	13	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	80 mm
	Milling and overlay	35	13	Milling and Overlay with Super Pave 12.5	40 mm
	Rout and Seal	40	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	43	5	Reclaimed Pavement, Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Milling and overlay	48	12	Milling and Overlay with Super Pave 12.5	40 mm
Principal Arterial	Partial Depth Reclamation	10	5	Reclaimed Pavement, Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Route and Seal	10	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	15	5	Reclaimed Pavement, Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Milling and overlay	20	15	Milling and Overlay with Super Pave 12.5 FC1	40 mm
	Route and Seal	25	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	30	5	Reclaimed Pavement, Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Full Depth Reclamation	35	13	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	80 mm
	Milling and overlay	35	13	Milling and Overlay with Super Pave 12.5 FC1	40 mm
	Route and Seal	40	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm

[1] Detailed information about Super Pave can be found in Super Pave Mixture Design Guide (FHWA, 2001)

Functional Type	Activity Type	Years after Initial Const.	Expected Life Span (Years)	Materials	Thickness
	Partial Depth Reclamation	43	5	Reclaimed Pavement (12.5FC1), Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Resurfacing	48	12	Resurfaced with SP19, Emulsified Asphalt Tack Coat (1 mm)	50 mm
	Milling and overlay	48	12	Milling and Overlay with Super Pave 12.5 FC1	90 mm
Freeway	Rout and Seal	5	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	10	5	Reclaimed Pavement (12.5FC1), Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Rout and Seal	10	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Milling and Overlay	20	15	Milling and Overlay with Super Pave 12.5 FC1	40 mm
	Rout and Seal	25	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Rout and Seal	28	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	30	5	Reclaimed Pavement (12.5FC1), Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Resurfacing	35	13	Resurfacing with SP19, Emulsified Asphalt Tack Coat (1 mm)	50 mm
	Milling and overlay	35	13	Milling and Overlay with Super Pave 12.5 FC1	90mm
	Rout and Seal	40	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	45	5	Reclaimed Pavement (12.5FC1), Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Full Depth Reclamation	48	12	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	100 mm
	Milling and overlay	48	5	Milling and Overlay with Super Pave 12.5 FC1	40 mm
Interstate	Partial Depth Reclamation	8	5	Reclaimed Pavement (12.5FC1), Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Rout and Seal	8	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	13	5	Reclaimed Pavement (12.5FC1), Emulsified Asphalt Tack Coat (1 mm)	40 mm

Functional Type	Activity Type	Years after Initial Const.	Expected Life Span (Years)	Materials	Thickness
	Rout and Seal	13	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Full Depth Reclamation	18	14	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	120 mm
	Milling and Overlay	18	14	Milling and Overlay with Super Pave 12.5 FC1	50mm
	Rout and Seal	23	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	28	5	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	50 mm
	Rout and Seal	28	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Full Depth Reclamation	32	13	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	50 mm
	Milling and Overlay	32	13	Milling and Overlay with Super Pave 12.5 FC1	90 mm
	Rout and Seal	37	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm
	Partial Depth Reclamation	40	5	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	40 mm
	Full Depth Reclamation	45	12	Reclaimed Pavement (SP19), Emulsified Asphalt Tack Coat (1 mm)	120 mm
	Milling and Overlay	45	12	Milling and Overlay with Super Pave 12.5 FC1	50 mm
	Rout and Seal	48	5	Rubberized Asphalt Sealant (for cracks 0.019 mm wide)	19 mm

Table 7: Rigid Pavement Rehabilitation Schedule (Athena Sustainable Material Institute, 2013)

Functional Type	Activity Type	Years after Initial Const.	Expected Life Span	Materials	Thickness
Local, Collector	Seal Joint	12	13	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	25	15	Replacing PCC	180 mm
	Partial Depth Repair	25	15	Replacing PCC	60 mm
	Seal Joint	25	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	
	Full Depth Repair	40	15	Replacing PCC	180 mm
	Partial Depth Repair	40	15	Replacing PCC	60 mm
	Seal Joint	40	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
Minor Arterial	Seal Joint	12	13	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	25	15	Replacing PCC	190 mm
	Partial Depth Repair	25	15	Replacing PCC	63 mm
	Seal Joint	25	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	40	15	Replacing PCC	190 mm
	Partial Depth Repair	40	15	Replacing PCC	63 mm
	Seal Joint	40	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
Principal Arterial	Seal Joint	12	13	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	25	15	Replacing PCC	200 mm
	Partial Depth Repair	25	15	Replacing PCC	67 mm
	Seal Joint	25	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	40	15	Replacing PCC	200 mm
	Partial Depth Repair	40	15	Replacing PCC	67 mm
	Seal Joint	40	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm

Functional Type	Activity Type	Years after Initial Const.	Expected Life Span	Materials	Thickness
Freeway	Partial Depth Repair	12	13	Replacing PCC	67 mm
	Seal Joint	12	13	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	25	15	Replacing PCC	200 mm
	Partial Depth Repair	25	15	Replacing PCC	67 mm
	Seal Joint	25	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	40	15	Replacing PCC	200 mm
	Partial Depth Repair	40	15	Replacing PCC	67 mm
	Seal Joint	40	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
Interstate	Partial Depth Repair	12	13	Replacing PCC	67 mm
	Seal Joint	12	13	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Full Depth Repair	25	15	Replacing PCC	200 mm
	Partial Depth Repair	25	15	Replacing PCC	67 mm
	Seal Joint	25	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Diamond Grinding	25	15	Concrete Texturization	5 mm
	Full Depth Repair	40	15	Replacing PCC	200 mm
	Partial Depth Repair	40	15	Replacing PCC	67 mm
	Seal Joint	40	15	Rubberized Asphalt Sealant (for cracks width 0.0115 mm)	23.5 mm
	Diamond Grinding	40	15	Concrete Texturization	5 mm

5.4. LCA Modeling

Most of the analysis was performed on Athena's Impact Estimator for Highways. The Athena Institute has prepared a comprehensive life cycle inventory which assists construction professionals in comparing design alternatives from an environmental point of view right from the preplanning stage of a project. It provides the decision makers with robust cradle-to-grave information about the impacts of building materials, products, transportation, and construction and demolition processes and is helpful for agencies that do not have in-house LCA experts. The Athena Impact Estimator for Highways (AIEH) is based on the LCA methodology standards specified by the International Organization of Standards (ISO) 14040 and 14044 series. The data used by Athena's tools comes from the US Life Cycle Inventory Database and Athena's own database, which required more than $2 million to be developed, verified, and updated.

The inventory documents the flow of energy and raw materials from nature to consumers and the resulting emissions to air, water, and land. Although this tool was initially prepared for freeways and major arterials, it can be used to analyze any type of roadway. AIEH has a database of fifty existing highway designs to choose from and also allows users to customize according to their needs. It also has the capability to model pavement vehicle interaction (PVI) by analyzing the effect of pavement roughness and deflection on predicted traffic fuel consumption. Although AIEH was built for nine locations in Canada, it can be customized to match the inventory characteristics of cities in the USA. Inputs can be provided on types of base, sub-base, and surface pavements using a simple graphic user interface. The software then runs the parameters through a wide array of databases of materials, energy, equipment, and transportation prepared by Athena. Material data comprises of national and industrial averages for the life cycle processes such as extraction, processing, and manufacturing of each material.

The footprint results are generated to present the environmental impacts in terms of global warming potential, acidification potential, ozone depletion potential, smog potential, and eutrophication potential as suggested by the US Environmental Protection Agency Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (US EPA TRACI). Other results include fossil fuel consumption and bill of materials required for the roadway design. AIEH calculates pre-combustion energy required to extract, refine, and deliver each material and the corresponding emissions to water, air, and land throughout the life cycle of the material. It also takes into account recycled content if any but ignores the demolition and disposal phase as most highways have a long service life.

The data screen requires the entry of a few general data items such as project name, location, roadway lifespan, etc. The default lifespan of the roadway is considered to be 50 years in the software but can be changed from 30–100 years depending on specific projects. The functional unit chosen by the software is gross roadway paved surface area. All the results are based on the surface area provided and the roadway assembly design. AIEH provides a list of heavy equipment that are most commonly used for pavement MRR. A default set of equipment are also selected for each activity. Users can customize the list if needed. Average transportation distances of materials in Canada are used by default by the software. These distances were adjusted using the United States national averages. The values were obtained from the Bureau of Transportation Statistics and the U.S. Census Bureau and are presented in Table 8. The mixes used for concrete and asphalt can also be modified if necessary. The roadway design dialogue box is used to record roadway cross sections and geometry is used to estimate the quantity of materials required. There are several designs already programmed in the software depending on the functional type (such as collector road, minor arterial and major arterial) and the pavement type (i.e. flexible, rigid, or composite). The global warming potential (GWP) and energy usage for prefabricated pavement systems were obtained from GaBi.

Table 8: Average Distance of Commodities in United States (USDOT and USDOC, 2010)

Material Type	Average Kilometers Per Ton	Tons (Thousands)	Ton-Kilometers (Millions)
Air-Cooled Blast-Furnace Slag - Crushed	117.3	885,363	103,871
Air-Cooled Blast-Furnace Slag - Not Crushed	117.3	885,363	103,871
Aluminum	950.2	38,789	36,859
Asphamin	950.2	38,789	36,859
Bitumen	244.7	329,862	80,728
Coarse Aggregate Crushed Stone	117.3	2,039,457	103,871
Coarse Aggregate Natural	117.3	2,039,457	103,871
Cold Rolled Sheet	950.2	185,342	36,859
Crumb Rubber (Rubber)	950.2	79,626	36,859

Material Type	Average Kilometers Per Ton	Tons (Thousands)	Ton-Kilometers (Millions)
Ethylene Vinyl Acetate	244.7	105,152	80,728
Fine Aggregate Crushed Stone	116.6	1,636,064	237,762
Fine Aggregate Natural	116.6	460,085	237,762
Fly Ash	524.1	885,363	97,143
Granulated Blast-Furnace Slag	1039.8	885,363	82,794
Granulated Nickel Slag	789.2	885,363	82,991
Granulated Steel Slag	145.3	885,363	237,762
Ground Granulated Blast-Furnace Slag	143.8	885,363	66,170
Hollow Structural Steel	117.3	103,111	103,871
Hot Rolled Sheet	117.3	185,342	103,871
Hydrated Lime	117.3	204,141	103,871
Lime	117.3	16,563	103,871
Low Density Polyethylene	117.3	82,469	103,871
Mineral Filler Crushed Stone	530.3	885,363	54,683
Mineral Filler Natural	524.1	885,363	97,143
Nails	197.0	58,733	40,217
Portland Cement	99.7	204,141	1,651
Portland Lime Cement	798.3	204,141	65,839
RAP Aggregate	117.3	885,363	103,871
RCM Aggregate	117.3	885,363	103,871
Rebar, Rod, Light Sections	641.7	103,111	37,689
Reinforcing Dowel Black Steel	197.0	103,111	40,217
Reinforcing Dowel Epoxy Coated Steel	197.0	103,111	40,217
Reinforcing Dowel Galvanized Steel	117.3	103,111	103,871
Reinforcing Dowel Stainless Steel	117.3	103,111	103,871
Rubberized Asphalt Sealant	530.3	24,297	54,683
Screws Nuts & Bolts	530.3	58,733	54,683
Silica Fume	530.3	885,363	54,683
Silicone Sealant	530.3	204,141	54,683
Steel Tubing	530.3	58,733	54,683
Styrene Butadiene Rubber	811.0	24,297	19,705
Water	641.7	0	37,689

5.5. Resource Usage

As mentioned earlier, the rehabilitation processes are resource intensive. Materials required for manufacturing the commonly used products for asphalt pavement rehabilitations are coarse aggregate, water, coal, natural gas, crude oil, and crude oil as feedstock. The same for concrete rehabilitation are lime stone, clay and shale, iron ore, sand, gypsum, coarse aggregate, water, coal, natural gas, crude oil, and crude oil as a feedstock. The amount of resources were calculated using AIEH software. A visual representation of the resources used for each type of MRR is provided in Figure 5 through Figure 16. Exact amounts of total resources used for materials extraction, equipment, and transportation used are presented in Appendix I.

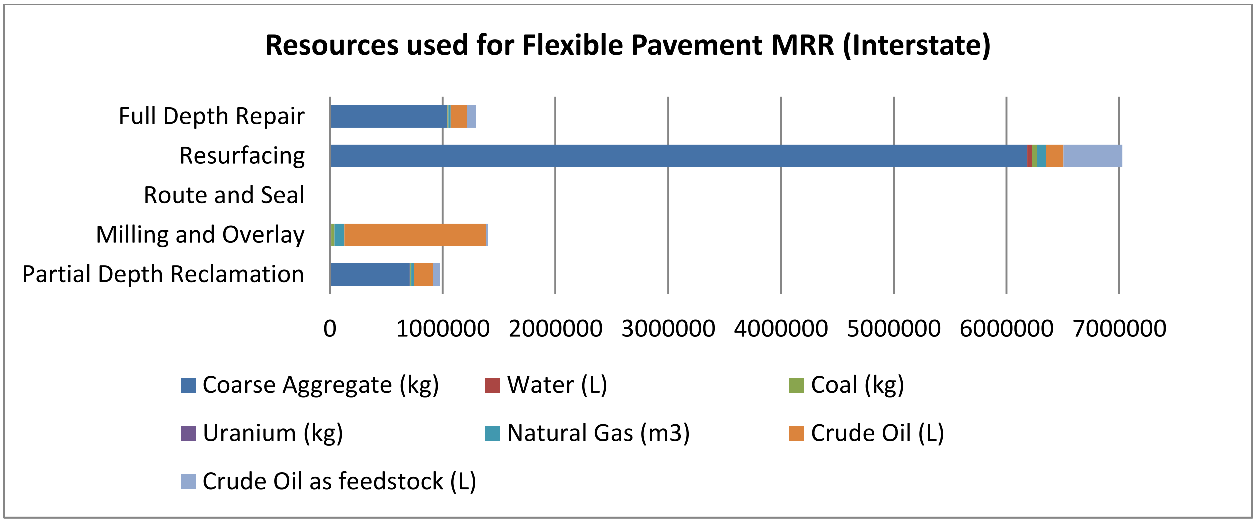

Figure 5: Resources used for Flexible Pavement MRR (Interstate)

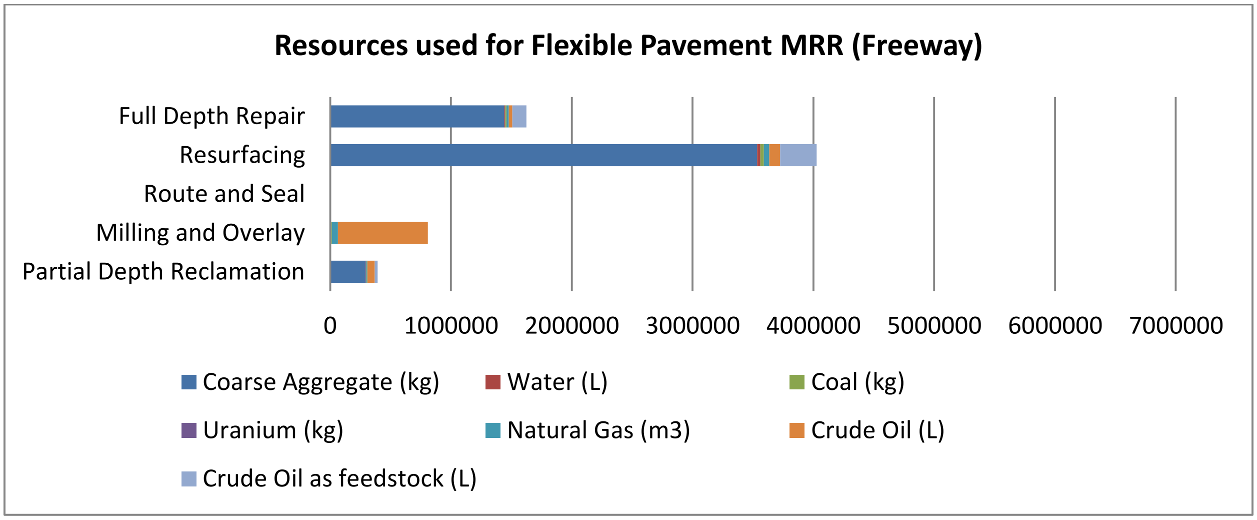

Figure 6: Resources used for Flexible Pavement MRR (Freeway)

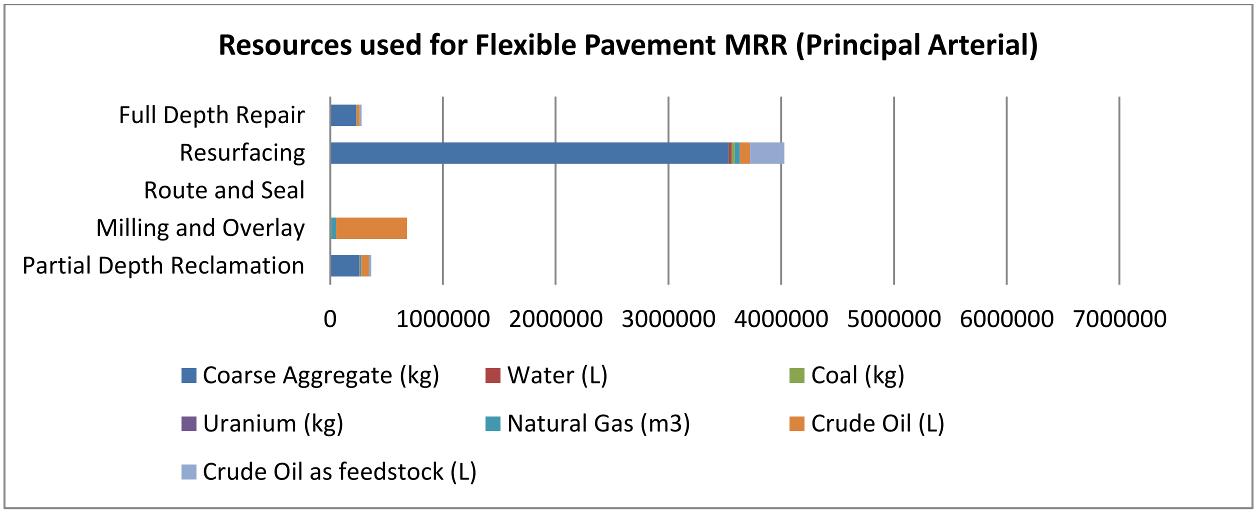

Figure 7: Resources used for Flexible Pavement MRR (Principal Arterial)

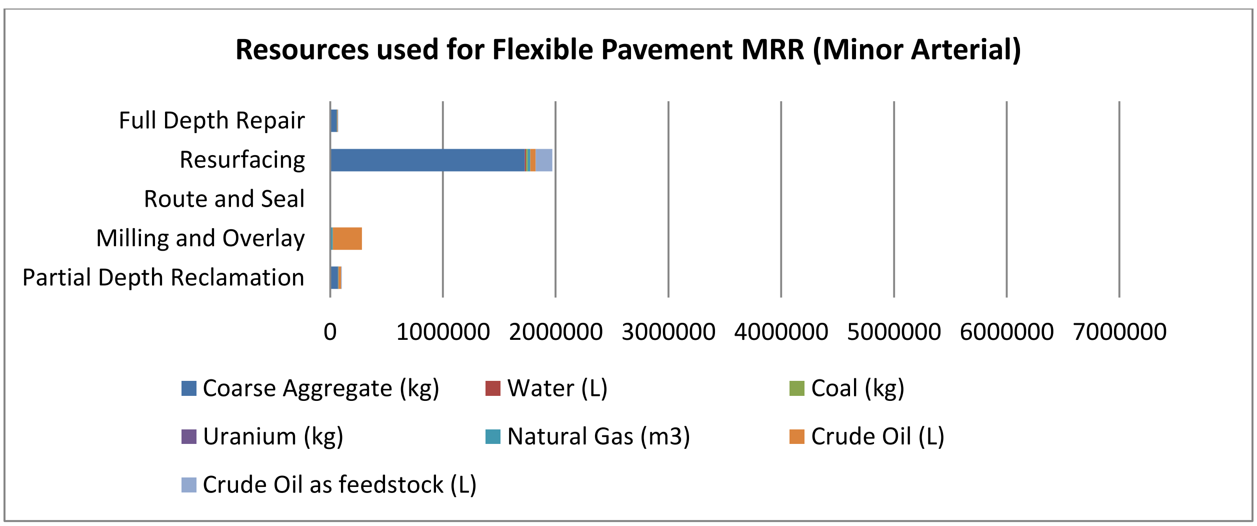

Figure 8: Resources used for Flexible Pavement MRR (Minor Arterial)

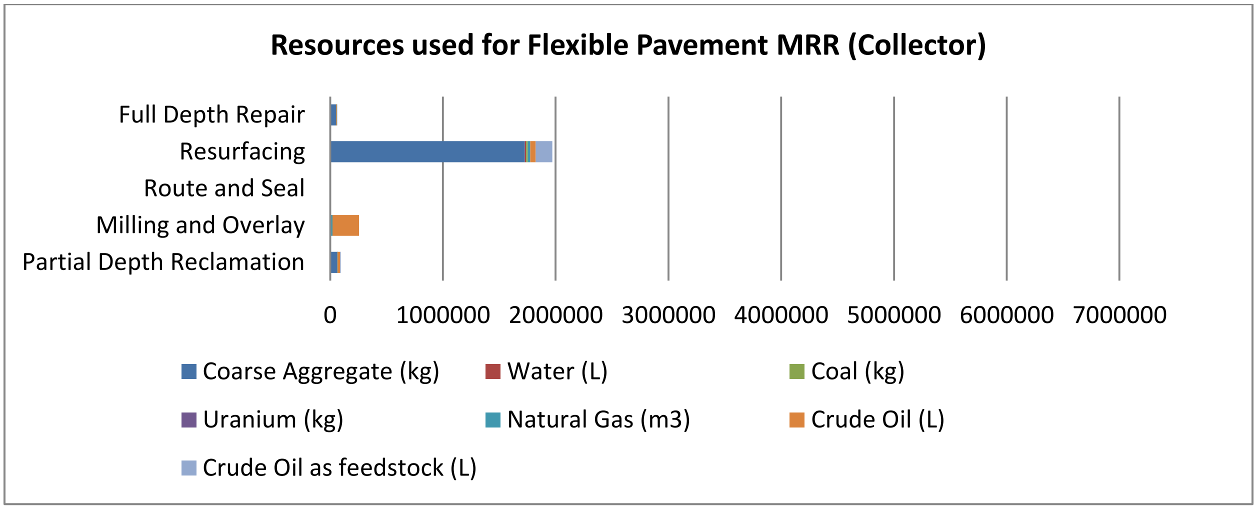

Figure 9: Resources used for Flexible Pavement MRR (Collector)

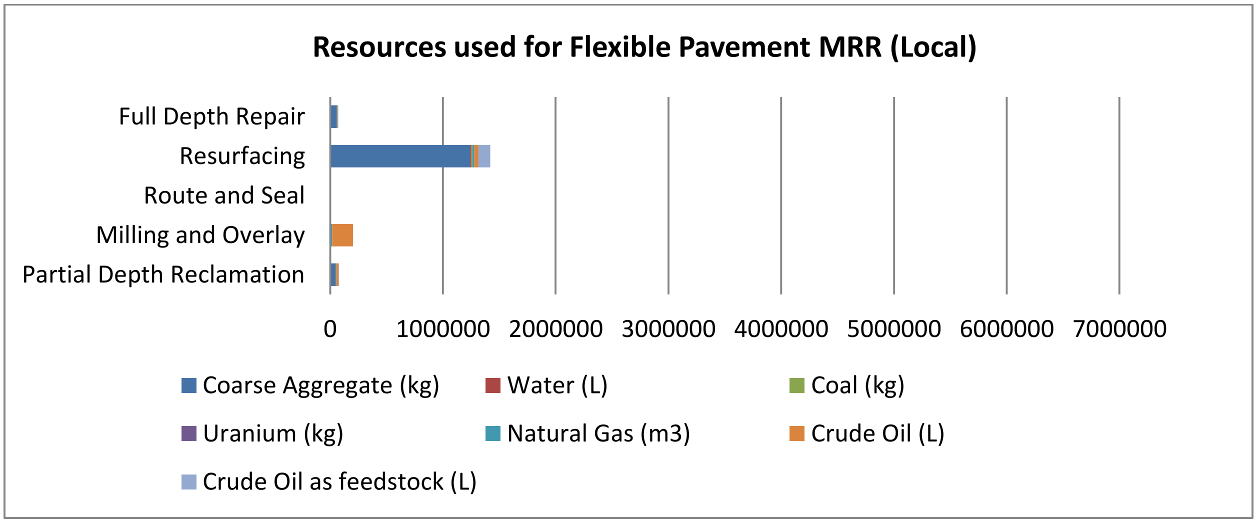

Figure 10: Resources used for Flexible Pavement MRR (Local)

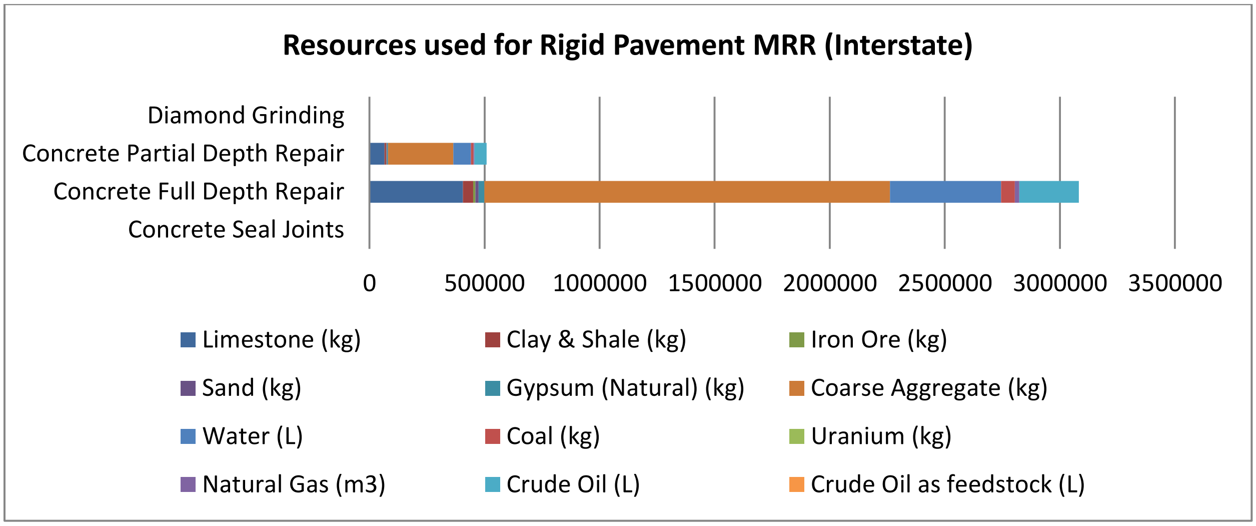

Figure 11: Resources used for Rigid Pavement MRR (Interstate)

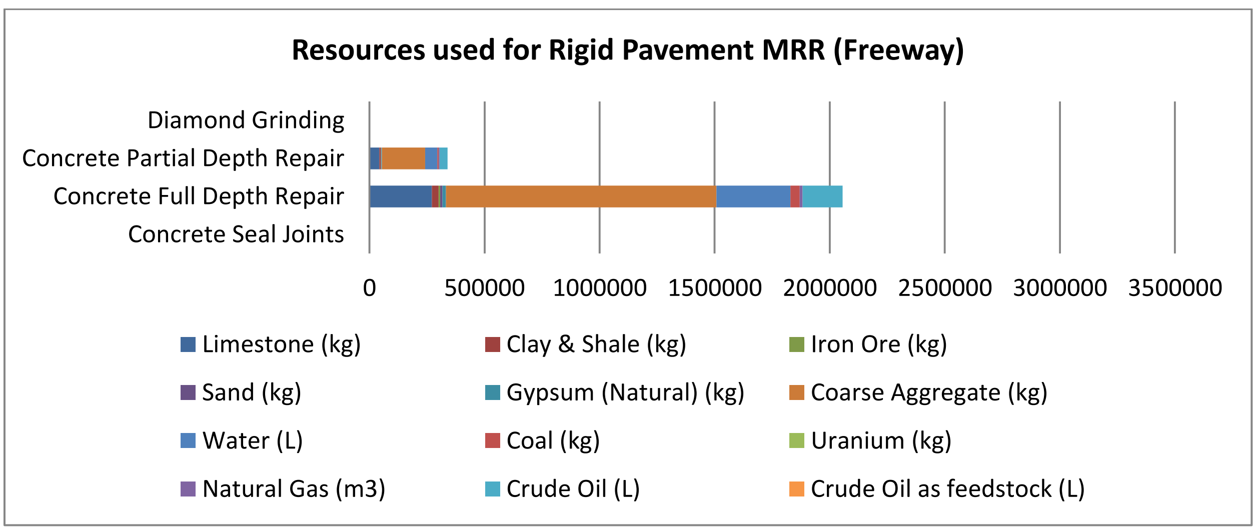

Figure 12: Resources used for Rigid Pavement MRR (Freeway)

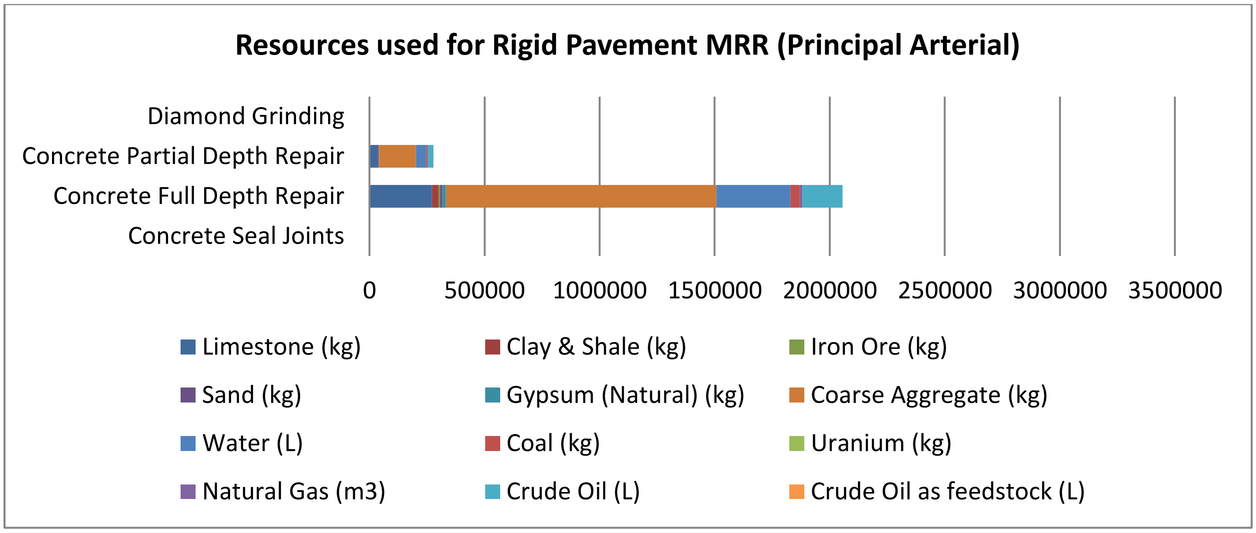

Figure 13: Resources used for Rigid Pavement MRR (Principal Arterial)

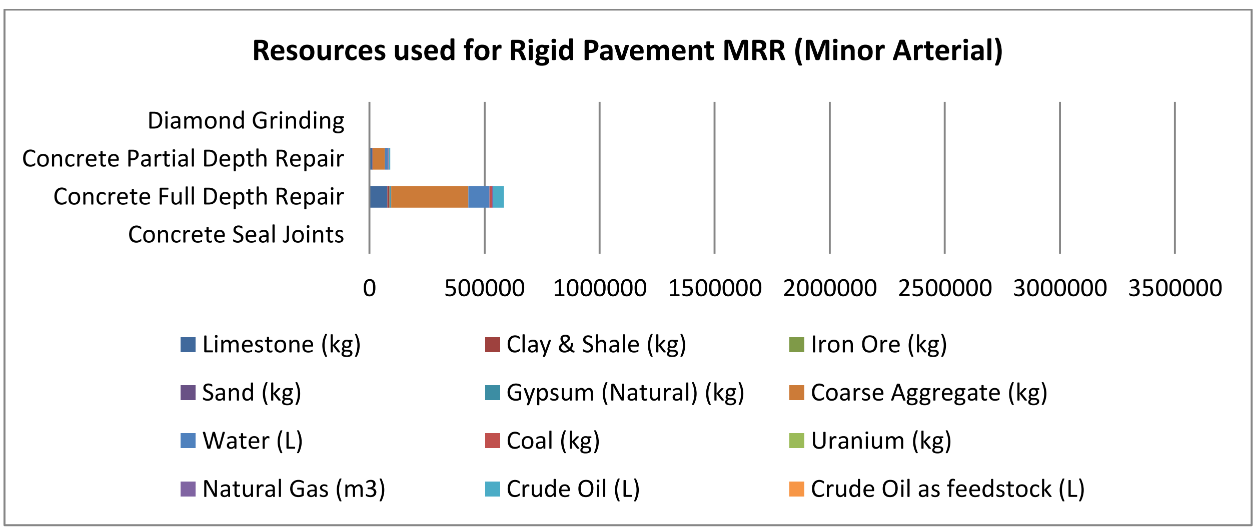

Figure 14: Resources used for Rigid Pavement MRR (Minor Arterial)

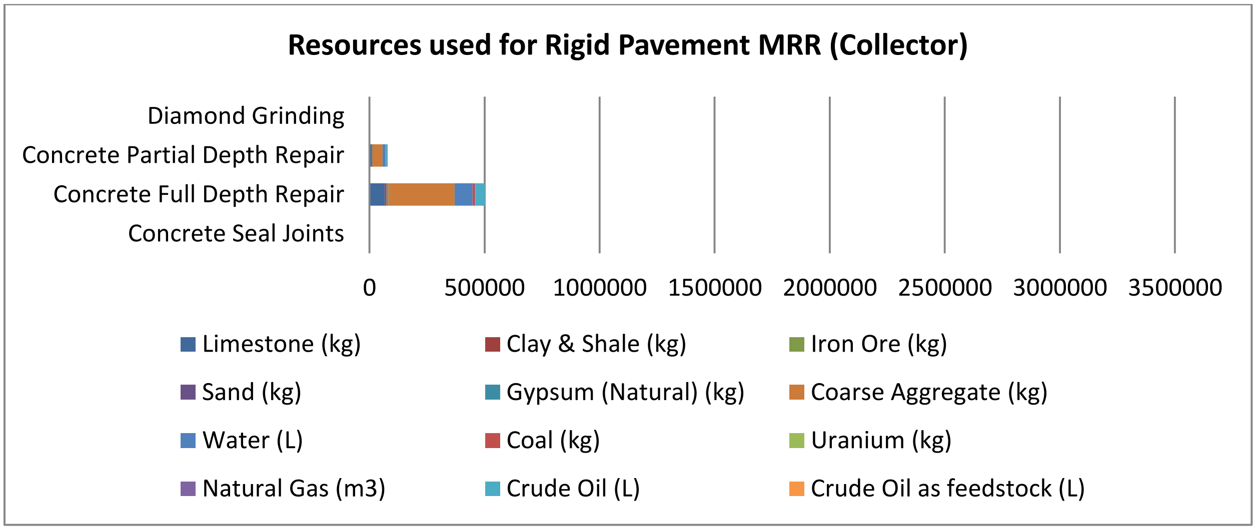

Figure 15: Resources used for Rigid Pavement MRR (Collector)

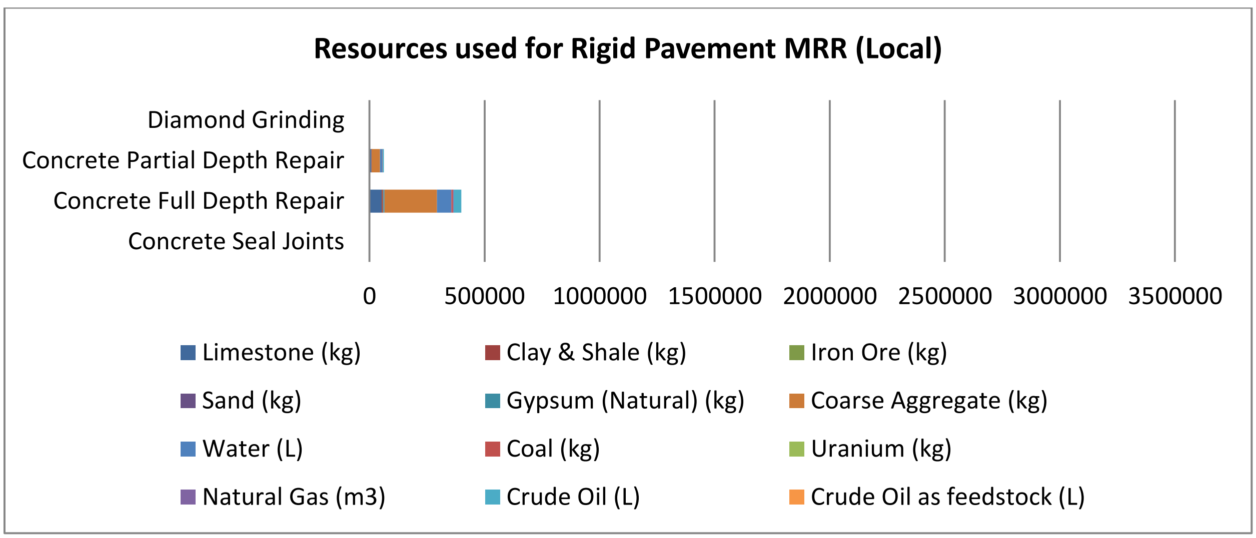

Figure 16: Resources used for Rigid Pavement MRR (Local)

6. Life Cycle Assessment Results

Both flexible pavement MRR and rigid pavement MRR were modeled in AIEH for one kilometer of pavement. Some data were obtained from the existing literature and compared with the analyzed data. The rehabilitation schedule and the corresponding expected life span extension are taken into consideration for calculating the life cycle environmental impacts. The types of materials added or removed during the preservation activity were studied. The LCA results include the environmental impacts in terms of global warming potential (in kg CO_2 eq), acidification potential (in moles of H+ eq), eutrophication potential (in kg N eq), ozone depletion potential (in kg CFC-11 eq), and smog potential (in kg O_3 eq).

Energy consumption for each MRR activity for different functional types of road are calculated in megajoules and categorized according to the energy source (i.e. hydro, coal, diesel, feedstock, gasoline, heavy fuel oil, liquefied petroleum gas, natural gas, and nuclear). The results also include the resources used during the preservation activities. All the above results are calculated for the design life of the pavements and are categorized into functional types. The results are further split as applicable to a) materials and equipment used and b) transportation of these materials and equipment. Detailed analysis results are presented in Appendix II. For a better comparison, the results were annualized for a square meter of the pavement by dividing each result by its corresponding life expectancy and number of treatments over the design life as mentioned in Table 6 and Table 7.

6.1. Environmental Impacts of Flexible Pavement MRR

The global warming potential (in kg CO_2 eq/sq.m.) and the energy usage (in MJ/sq.m) for flexible pavement MRR are summarized in Figure 17 and Figure 18. Results show that the traditional rehabilitation methods such as total asphalt reconstruction, pavement resurfacing, and milling and overlay have considerably higher energy consumption and GHG emissions in comparison to the innovative rehabilitation techniques. Modern techniques like partial depth reclamation and full depth reclamation are more sustainable options as they recycle the existing pavement and minimize the use of new resources. The environmental impacts due to repair activities like fog seal, crack seal, chip seal, microsurfacing and route/seal are minimal with substantial pavement life expectancy. Thus, from an environmental point of view, DOTs should lean more towards regular maintenance and innovative rehabilitation techniques if traditional rehabilitation is not absolutely necessary.

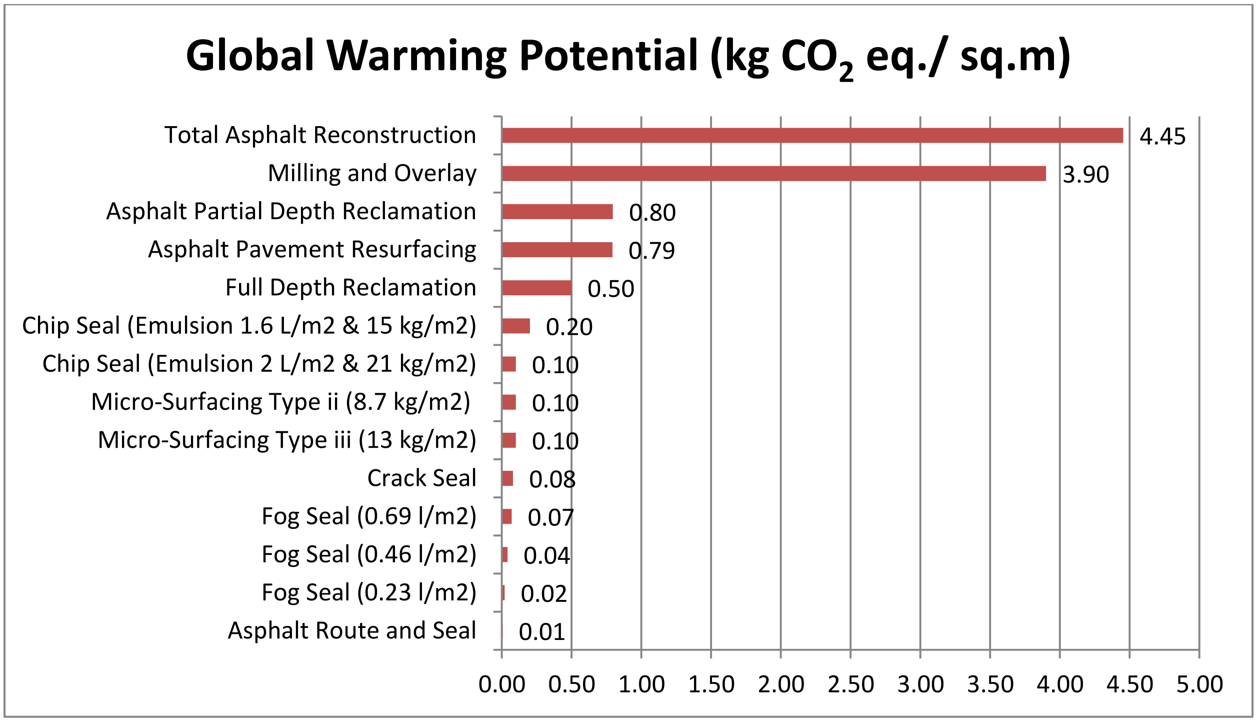

Figure 17: Global Warming Potential for Flexible Pavement MRR techniques

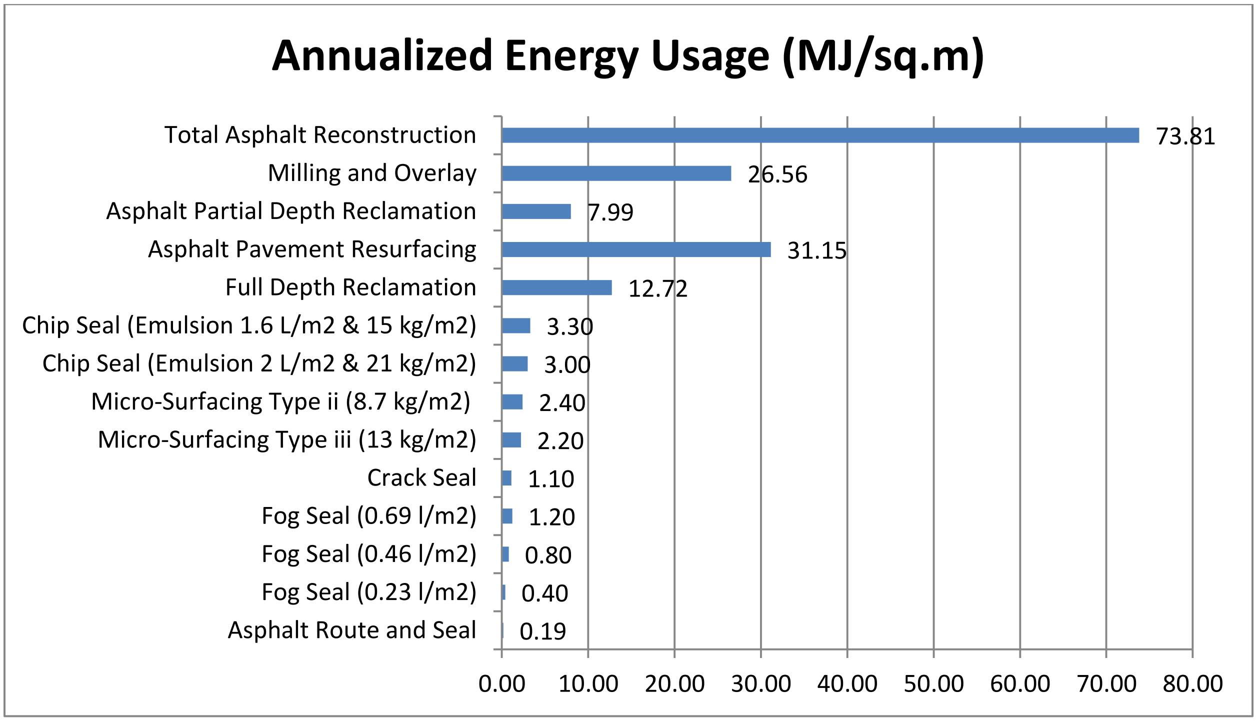

Figure 18: Annualized Energy Usage for Flexible Pavement MRR techniques

6.2. Environmental Impacts of Rigid Pavement MRR

For rigid pavements the difference between traditional and accelerated construction techniques is not considerably large when the life cycle impacts of the materials, equipment, and transportation means used are considered. Traditional concrete full depth repair and accelerated precast concrete pavement systems have similar environmental impacts with a GWP of 1.25 kg CO_2 eq./sq.m and 1.2025 kg CO_2 eq./sq.m respectively and with an annualized energy usage of 10.52 MJ/sq.m and 9.89 MJ/sq.m respectively.

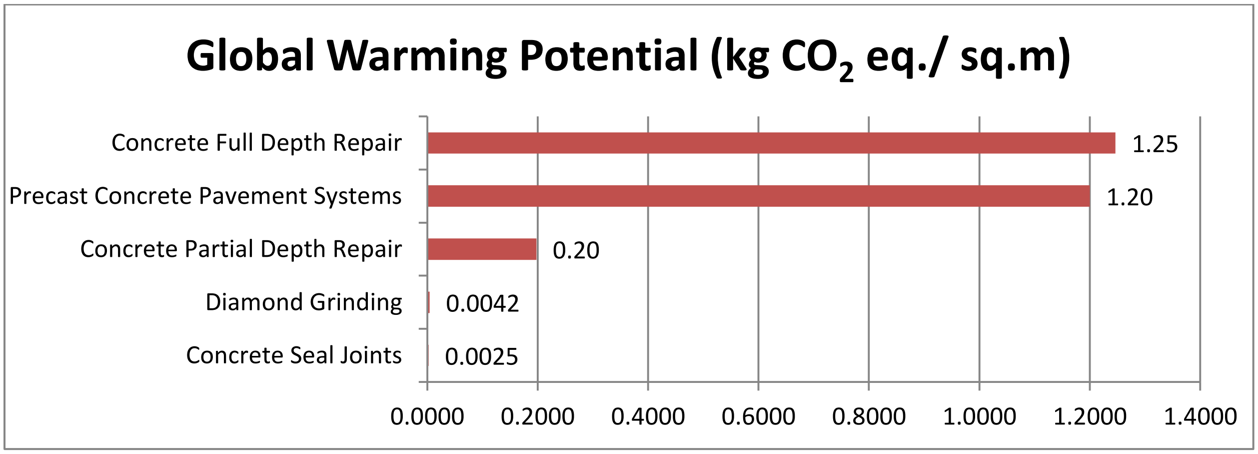

Figure 19: Global warming Potential of Rigid Pavement MRR Techniques

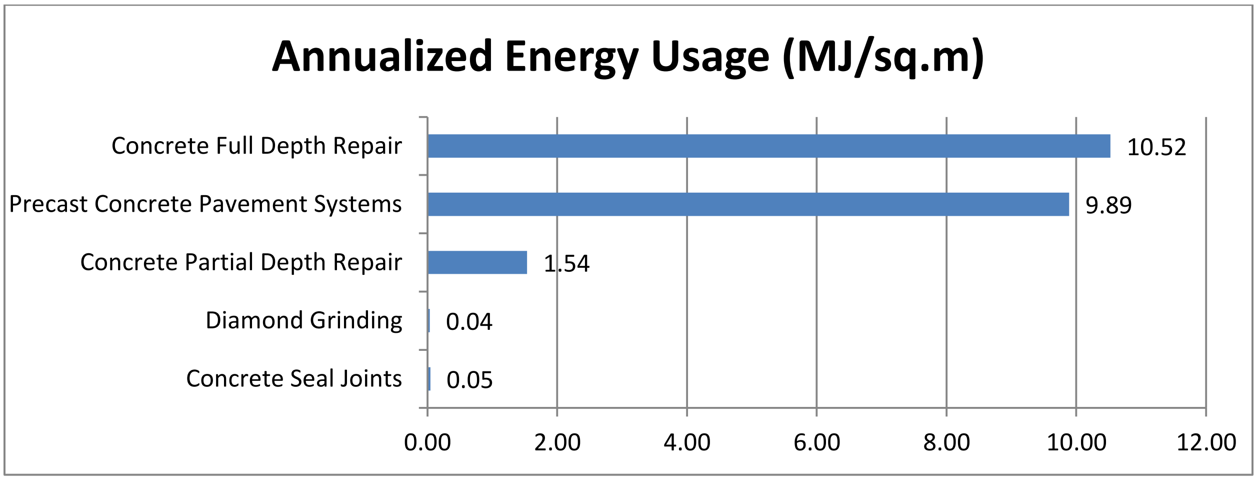

Figure 20: Annualized Energy Usage of Rigid Pavement MRR Techniques

6.3. Results Summary

The global warming potential and energy consumption results for the MRR activities over the design life of a pavement (for one lane kilometer) show that traditional asphalt pavement MRRs have considerably higher environmental impacts than that of concrete pavement MRRs. However, the innovative flexible pavement MRRs have similar environmental impacts as those of rigid pavement MRRs. The results are presented in Table 9, Table 10, Figure 21 and Figure 22.

Table 9: GWP (in Kg CO_2 Eq) of Pavement MRRs over the Design Life of Pavement (for 1 lane km)

	Functional Type	Interstate	Freeway	Principal Arterial	Minor Arterial	Collector	Local
MRR Type	Total Asphalt Reconstruction	6,420,772	3,535,031	3,049,699	1,523,766	1,381,676	1,110,128
	Milling and Overlay	4,004,848	2,363,599	1,997,127	827,450	750,373	596,218
	Asphalt Pavement Resurfacing	749,008	438,138	438,138	223,854	223,854	166,558
	Asphalt Full Depth Reclamation	501,302	154,919	83,153	24,291	22,460	24,291
	Asphalt Partial Depth Reclamation	563,037	198,379	217,606	74,158	70,641	63,606
	Concrete Full Depth Repair	1,094,009	730,054	730,054	202,667	174,383	138,922
	Concrete Partial Depth Repair	212,768	143,687	104,574	32,407	28,276	22,896
	Precast Concrete Pavement Systems	810,000	540,000	540,000	270,000	244,800	194,400
	Concrete Seal Joints	1,601	1,244	1,028	955	955	955
	Diamond Grinding	2,867	0	0	0	0	0

Table 10: Energy Consumption (in MJ) of Pavement MRRs over the Design Life of Pavement (for 1 lane km)

	Functional Type	Interstate	Freeway	Principal Arterial	Minor Arterial	Collector	Local
MRR Type	Total Asphalt Reconstruction	106,641,140	58,816,748	50,783,522	25,331,763	22,969,134	18,042,098
	Milling and Overlay	26,773,438	15,573,505	15,243,288	5,492,691	4,980,912	3,957,354
	Asphalt Pavement Resurfacing	30,473,477	17,625,351	17,625,351	8,654,087	8,654,087	6,250,684
	Asphalt Full Depth Reclamation	7,892,110	6,750,578	1,766,206	467,461	427,055	467,461
	Asphalt Partial Depth Reclamation	5,962,220	2,492,424	2,274,231	684,211	631,985	527,532
	Concrete Full Depth Repair	9,158,279	6,108,676	6,108,676	1,741,578	1,497,260	1,190,950
	Concrete Partial Depth Repair	1,519,479	1,019,685	831,112	276,810	240,316	192,789
	Precast Concrete Pavement Systems	6,675,750	4,450,500	4,450,500	2,225,250	2,017,560	1,602,180
	Concrete Seal Joints	56,849	33,217	17,014	14,228	14,228	14,228
	Diamond Grinding	25,418	0	0	0	0	0

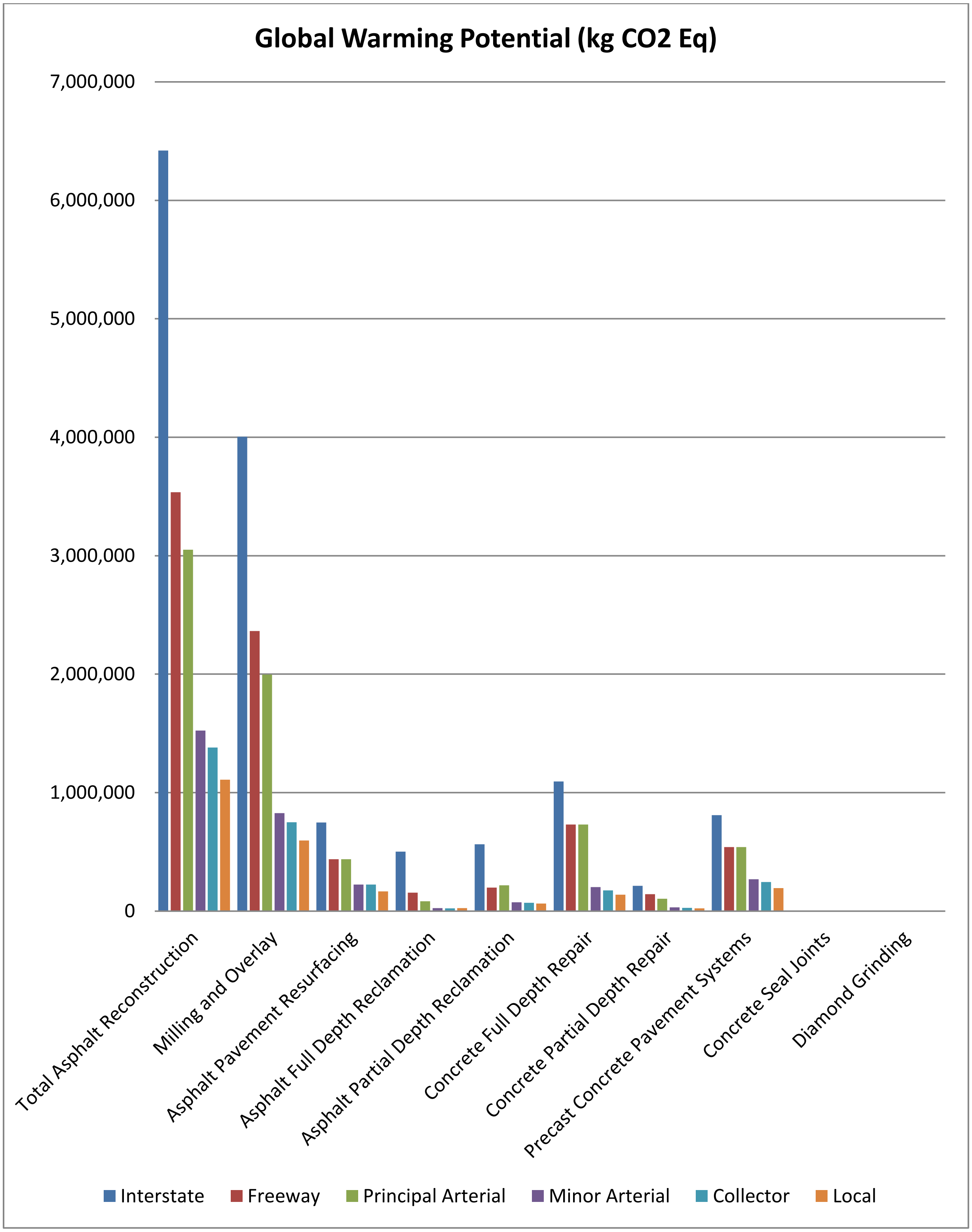

Figure 21: GWP of Pavement MRRS over the Design Life of Pavement (for one lane km)

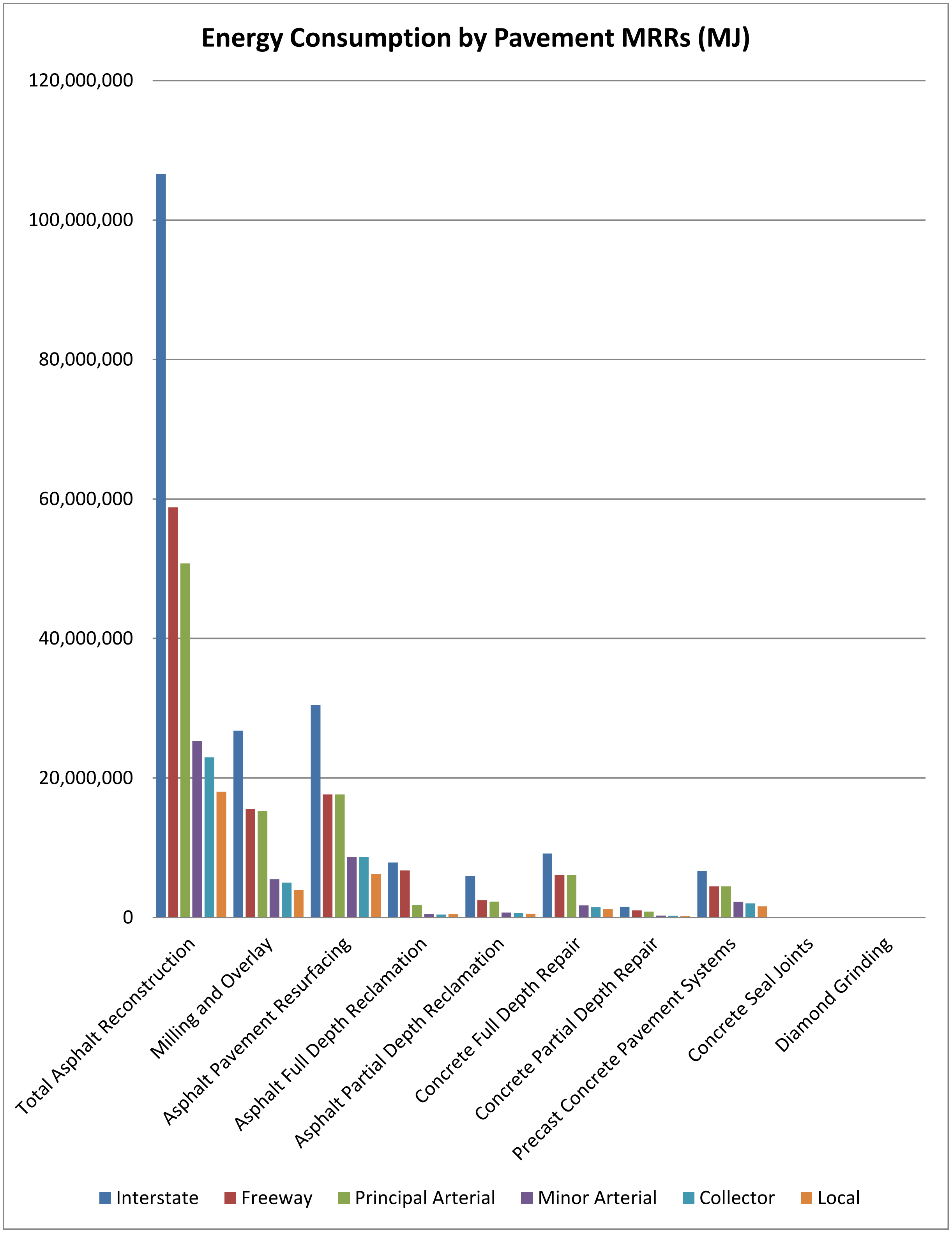

Figure 22: Energy Consumption of Pavement MRRS over the Design Life of Pavement (for one lane km)

7. Conclusion

The environmental impacts of the arterial improvement projects have been presented in this study from a life cycle assessment point of view. Both traditional and innovative MRR activities were considered. The treatment processes for flexible and rigid pavements are considerably different due to the structural nature of the pavements. As flexible pavements are older than rigid pavements, there are more innovative options available for flexible pavement MRR than that of rigid pavements. Life cycle assessment results are presented in two formats: a) annualized impact per square meter of the pavement, and b) impact over the design life of one center kilometer of a pavement.

LCA results showed that for flexible pavements, innovative rehabilitation techniques like partial or full depth reclamation have less life cycle environmental impacts than traditional techniques like milling and overlay or total reconstruction. One of the major reasons is that in pavement reclamation techniques the existing asphalt layer is recycled to produce a new stable layer which minimizes the need of raw virgin materials unlike traditional techniques. Again among maintenance processes, innovative techniques like microsurfacing have lesser resource usage, global warming potential, and energy consumption than traditional processes like chip seal. Minor treatment processes like fog seal, crack seal, and asphalt route and seal have minimum impacts with maximum benefits when the corresponding life extensions are compared. Thus, it was observed that products with lower asphalt content and a lesser heat requirement use less energy and have minimum GHG emissions.

For rigid pavements, all the rehabilitation techniques are comparatively new. The GHG emissions and energy consumption due to materials used, construction equipment, and transportation were found to be similar for both traditional techniques like full depth repair and accelerated techniques like precast concrete pavement systems. Similar to flexible pavements, minor treatment processes like concrete seal joints, diamond grinding, and partial depth repair have much less life cycle environmental impacts with substantial benefits in terms of life expectancy. Thus, it can be concluded that the DOTs should make maximum utilization of all the treatment processes, and preferably the innovative strategies using recycling techniques, to achieve a sustainable arterial maintenance, repair, and rehabilitation plan.

8. Recommendation

This study focuses only on the life cycle environmental impacts of the materials, equipment, and transportation used for arterial improvement projects. Pavement MRR processes may have considerable environmental impacts due to traffic disruptions associated with work zones. Future studies can be conducted to address these impacts using traffic simulation and emission modeling tools.

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Appendix I: Resource Usage of Pavement MRRs by Road Functional Type

Flexible Pavements

Resources	Coarse Aggregate (kg)	Water (L)	Coal (kg)	Uranium (kg)	Natural Gas (m3)	Crude Oil (L)	Crude Oil as feedstock (L)
MRRs	Interstate						
Partial Depth Reclamation	706963	5155	10082	0	24160	169511	60664
Milling and Overlay	0	12888	26723	0	87479	1259305	13388
Route and Seal	0	0	308	0	306	663	1965
Resurfacing	6185925	38664	48396	0	78812	152804	524115
Full Depth Repair	1038471	2578	9611	0	19704	146272	78993
	Freeway						
Partial Depth Reclamation	294568	2148	3680	0	8271	59765	25277
Milling and Overlay	0	0	14835	0	49867	743517	
Route and Seal	0	0	227	0	213	479	1490
Resurfacing	3534814	25776	28009	0	45545	90325	303319
Full Depth Repair	1442321	8592	10537	0	17128	29759	114919
	Principal Arterial						
Partial Depth Reclamation	259220	1890	4155	0	10325	67440	22243
Milling and Overlay	0	0	11960	0	40201	629234	
Route and Seal	0	0	60	0	55	163	396
Resurfacing	3534814	25776	28009	0	45545	90325	303319
Full Depth Repair	230771	859	1901	0	3539	23628	17852
	Minor Arterial						
Partial Depth Reclamation	69013	516	1277	0	3297	23592	5935
Milling and Overlay	0	0	5260	0	17734	259526	
Route and Seal	0	0	60	0	55	163	396
Resurfacing	1725326	12888	13809	0	22629	47448	148367
Full Depth Repair	57693	215	499	0	964	7063	4463
	Collector						
Partial Depth Reclamation	62572	467	1209	0	3158	22568	5381
Milling and Overlay	0	0	4770	0	16083	235354	0
Route and Seal	0	0	60	0	55	163	396
Resurfacing	1725326	12888	13809	0	22629	47448	148367
Full Depth Repair	52308	195	456	0	884	6547	4046
	Local						
Partial Depth Reclamation	49689	371	1073	0	2879	20520	4273
Milling and Overlay	0	0	3791	0	12780	187009	0
Route and Seal	0	0	60	0	55	163	396
Resurfacing	1242235	9279	10006	0	16502	35991	106825
Full Depth Repair	57693	215	499	0	964	7063	4463

Rigid Pavements

Resources	Limestone (kg)	Clay & Shale (kg)	Iron Ore (kg)	Sand (kg)	Gypsum (Natural) (kg)	Coarse Aggregate (kg)	Water (L)	Coal (kg)	Uranium (kg)	Natural Gas (m3)	Crude Oil (L)	Crude Oil as feedstock (L)
MRRs	Interstate											
Concrete Seal Joints	0	0	0	0	0	0	0	153	0	126	350	1055
Concrete Full Depth Repair	406063	44786	8957	14929	23886	1763621	482136	59489	0	19134	259698	0
Concrete Partial Depth Repair	65295	7202	1440	2401	3841	283590	77527	9928	0	4303	53238	0
Diamond Grinding	0	0	0	0	0	0	0	15	0	51	928	0
	Freeways											
Concrete Seal Joints	0	0	0	0	0	0	0	90	0	84	314	593
Concrete Full Depth Repair	270709	29858	5972	9953	15924	1175748	321424	39666	0	12778	173371	0
Concrete Partial Depth Repair	43530	4801	960	1600	2561	189060	51685	6640	0	2940	36118	0
Diamond Grinding	0	0	0	0	0	0	0	0	0	0	0	0
	Principal Arterial											
Concrete Seal Joints	0	0	0	0	0	0	0	47	0	56	288	277
Concrete Full Depth Repair	270709	29858	5972	9953	15924	1175748	321424	39666	0	12778	173371	0
Concrete Partial Depth Repair	36275	4001	800	1334	2134	157550	43071	5370	0	1897	25377	0
Diamond Grinding	0	0	0	0	0	0	0	0	0	0	0	0
	Minor Arterial											
Concrete Seal Joints	0	0	0	0	0	0	0	40	0	51	284	222
Concrete Full Depth Repair	77152	8509	1702	2836	4538	335088	91606	11266	0	3509	47765	0
Concrete Partial Depth Repair	11938	1317	263	439	702	51850	14175	1754	0	579	7759	0
Diamond Grinding	0	0	0	0	0	0	0	0	0	0	0	0
	Collector											
Concrete Seal Joints	0	0	0	0	0	0	0	40	0	51	284	222

Resources	Limestone (kg)	Clay & Shale (kg)	Iron Ore (kg)	Sand (kg)	Gypsum (Natural) (kg)	Coarse Aggregate (kg)	Water (L)	Coal (kg)	Uranium (kg)	Natural Gas (m3)	Crude Oil (L)	Crude Oil as feedstock (L)
Concrete Full Depth Repair	66270	7309	1462	2436	3898	287823	78685	9679	0	3023	41129	0
Concrete Partial Depth Repair	10309	1137	227	379	606	44772	12240	1518	0	509	6798	0
Diamond Grinding	0	0	0	0	0	0	0	0	0	0	0	0
	Local											
Concrete Seal Joints	0	0	0	0	0	0	0	40	0	51	284	222
Concrete Full Depth Repair	52626	5804	1161	1935	3096	228565	62485	7691	0	2415	32809	0
Concrete Partial Depth Repair	8186	903	181	301	482	35555	9720	1209	0	418	5547	0
Diamond Grinding	0	0	0	0	0	0	0	0	0	0	0	0

Appendix II: Environmental Impacts and Energy Consumption of Pavement MRRs by Road Functional Type

Asphalt Partial Depth Reclamation – Spot Repair

Asphalt Partial Depth Reclamation - Spot Repair	MATERIALS & EQUIPMENT					
Environmental Impacts	Interstate	Freeway	Principal Arterial	Minor Arterial	Collector	Local
Global Warming Potential (kg CO2 eq)	455662.72	147205.17	140228.80	34312.87	31110.34	24705.27
Acidification Potential (moles of H+ eq)	150302.84	49266.57	46723.48	11487.99	10415.78	8271.35
Eutrophication Potential (kg N eq)	140.40	45.85	43.41	10.70	9.70	7.70
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	63731.18	20470.19	19476.23	4775.43	4329.73	3438.31
Energy Consumption						
Hydro (MJ)	5080.94	1895.48	1722.46	443.70	402.28	319.46
Coal (MJ)	144222.99	56856.54	50829.20	13326.51	12082.71	9595.09
Diesel (MJ)	1925936.95	801364.96	705513.04	192199.03	174260.46	138383.30
Feedstock (MJ)	2538176.52	1057573.55	930664.72	248307.84	225132.44	178781.65
Gasoline (MJ)	2368.80	987.00	868.56	231.51	209.90	166.69
Heavy Fuel Oil (MJ)	390195.41	152151.07	136425.79	35630.24	32304.75	25653.77
LPG (MJ)	19024.71	7436.60	6665.45	1740.65	1578.19	1253.27
Natural Gas (MJ)	512119.03	191631.63	174216.97	44820.70	40637.43	32270.90
Nuclear (MJ)	8922.05	2867.44	2731.87	668.60	606.20	481.39
Total Primary Energy Consumption (MJ)	5546047.39	2272764.28	2009638.06	537368.78	487214.36	386905.52
Resources Used						
Coarse Aggregate (kg)	706962.80	294567.83	259219.69	69013.04	62571.82	49689.39
Water (L)	5155.15	2147.98	1890.22	515.52	467.40	371.17
Coal (kg)	8211.97	2967.34	2756.40	691.71	627.15	498.03
Uranium (kg)	0.03	0.01	0.01	0.00	0.00	0.00
Natural Gas (m3)	18014.31	5929.85	5729.98	1374.66	1246.36	989.75
Crude Oil (L)	131858.08	42172.10	40206.41	9834.50	8916.61	7080.84
Crude Oil as feedstock (L)	60663.87	25276.61	22243.42	5934.70	5380.79	4272.98

Asphalt Partial Depth Reclamation - Spot Repair	**TRANSPORTATION**					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	107374.05	51173.52	77377.35	39845.24	39530.46	38900.92
Acidification Potential (moles of H+ eq)	32955.55	15706.25	23748.90	12229.37	12132.76	11939.54
Eutrophication Potential (kg N eq)	35.81	17.07	25.81	13.29	13.18	12.97
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	17510.72	8345.41	12618.82	6497.99	6446.66	6343.99
Energy Consumption						
Hydro (MJ)	618.21	294.64	445.51	229.41	227.60	223.97
Coal (MJ)	9021.17	4299.41	6500.96	3347.65	3321.20	3268.31
Diesel (MJ)	317899.60	172823.92	193774.40	110373.95	108590.30	105022.99
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	29806.75	14205.63	21479.75	11060.93	10973.55	10798.79
LPG (MJ)	1349.52	643.17	972.51	500.79	496.83	488.92
Natural Gas (MJ)	55097.72	26259.08	39705.27	20446.11	20284.59	19961.54
Nuclear (MJ)	2379.73	1134.16	1714.91	883.09	876.11	862.16
Total Primary Energy Consumption (MJ)	416172.71	219660.01	264593.30	146841.93	144770.18	140626.70
Resources Used						
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	1869.74	712.30	1398.14	584.91	581.50	574.70
Uranium (kg)	0.02	0.01	0.01	0.00	0.00	0.00
Natural Gas (m3)	6145.58	2341.24	4595.48	1922.51	1911.32	1888.95
Crude Oil (L)	37652.78	17592.55	27233.87	13757.78	13651.50	13438.93
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Asphalt Partial Depth Reclamation -Milling

Asphalt Partial Depth Reclamation -Milling	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	3863560.62	2298807.40	1953163.03	813883.41	737920.96	585996.05
Acidification Potential (moles of H+ eq)	1201166.94	713413.18	605890.05	252675.80	229092.72	181926.57
Eutrophication Potential (kg N eq)	1207.47	718.11	611.69	253.73	230.05	182.68
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	584376.81	348066.79	296587.84	122945.82	111470.88	88520.99
Energy Consumption						
Hydro (MJ)	21112.02	12290.17	10456.77	4346.33	3940.67	3129.36
Coal (MJ)	320274.74	179397.49	152630.73	63444.14	57522.68	45679.78
Diesel (MJ)	22311609.31	13307806.35	13300009.83	4697082.51	4258688.14	3381899.40
Feedstock (MJ)	560141.84	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	281.47	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	1008998.84	588048.84	500710.53	207827.59	188430.34	149635.86
LPG (MJ)	45545.22	26948.20	22917.91	9533.49	8643.70	6864.11
Natural Gas (MJ)	1925771.09	1130914.79	959197.91	400986.63	363561.21	288710.37
Nuclear (MJ)	79347.82	47257.61	40212.35	16710.83	15151.16	12031.80
Total Primary Energy Consumption (MJ)	26273082.36	15292663.45	14986136.02	5399931.51	4895937.90	3887950.68
Resources Used						
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	12887.89	0.00	0.00	0.00	0.00	0.00
Coal (kg)	24906.00	14180.41	11597.99	5165.98	4683.82	3719.51
Uranium (kg)	0.20	0.12	0.10	0.04	0.04	0.03
Natural Gas (m3)	81506.00	47716.01	39009.93	17424.33	15798.06	12545.52
Crude Oil (L)	1211027.80	721730.77	614611.80	255048.24	231243.74	183634.73
Crude Oil as feedstock (L)	13387.71	0.00	0.00	0.00	0.00	0.00

Asphalt Partial Depth Reclaimation - Milling	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	141287.35	64791.83	43963.53	13567.08	12451.93	10221.62
Acidification Potential (moles of H+ eq)	43364.05	19885.90	13493.25	4163.99	3821.73	3137.20
Eutrophication Potential (kg N eq)	47.12	21.61	14.66	4.52	4.15	3.41
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	23041.18	10566.23	7169.53	2212.50	2030.65	1666.93
Energy Consumption						
Hydro (MJ)	813.47	373.04	253.12	78.11	71.69	58.85
Coal (MJ)	11870.44	5443.57	3693.65	1139.86	1046.16	858.78
Diesel (MJ)	371044.12	221541.12	216914.93	80342.49	73577.77	60048.32
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	39220.99	17986.04	12204.16	3766.19	3456.62	2837.49
LPG (MJ)	1775.75	814.33	552.55	170.52	156.50	128.47
Natural Gas (MJ)	72499.91	33247.15	22559.36	6961.78	6389.56	5245.10
Nuclear (MJ)	3131.34	1435.98	974.36	300.69	275.97	226.54
Total Primary Energy Consumption (MJ)	500356.03	280841.22	257152.13	92759.63	84974.27	69403.55
Resources Used						
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	1817.27	654.38	362.28	94.32	86.64	71.28
Uranium (kg)	0.02	0.01	0.00	0.00	0.00	0.00
Natural Gas (m3)	5973.11	2150.85	1190.75	310.03	284.79	234.30
Crude Oil (L)	48277.66	21786.46	14621.75	4477.81	4109.89	3374.07
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Asphalt Route and Seal

Asphalt Route and Seal	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	1338.05	1014.27	269.74	269.74	269.74	269.74
Acidification Potential (moles of H+ eq)	739.48	560.55	149.08	149.08	149.08	149.08
Eutrophication Potential (kg N eq)	0.48	0.37	0.10	0.10	0.10	0.10
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	109.53	83.02	22.08	22.08	22.08	22.08
Energy Consumption						
Hydro (MJ)	143.92	109.10	29.02	29.02	29.02	29.02
Coal (MJ)	5651.90	4284.50	1139.49	1139.49	1139.49	1139.49
Diesel (MJ)	268.45	203.50	54.12	54.12	54.12	54.12
Feedstock (MJ)	82235.66	62339.93	16579.77	16579.77	16579.77	16579.77
Gasoline (MJ)	41.32	31.33	8.33	8.33	8.33	8.33
Heavy Fuel Oil (MJ)	3351.31	2540.49	675.66	675.66	675.66	675.66
LPG (MJ)	52.95	40.14	10.67	10.67	10.67	10.67
Natural Gas (MJ)	6587.77	4993.93	1328.17	1328.17	1328.17	1328.17
Nuclear (MJ)	16.14	12.23	3.25	3.25	3.25	3.25
Total Primary Energy Consumption (MJ)	98349.41	74555.15	19828.49	19828.49	19828.49	19828.49
Resources Used						
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	267.37	202.68	53.90	53.90	53.90	53.90
Uranium (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	174.46	132.25	35.17	35.17	35.17	35.17
Crude Oil (L)	96.18	72.90	19.38	19.38	19.38	19.38
Crude Oil as feedstock (L)	1965.48	1489.96	396.27	396.27	396.27	396.27

Asphalt Rout and Seal	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	1540.26	1132.09	415.99	415.99	415.99	415.99
Acidification Potential (moles of H+ eq)	472.75	347.47	127.68	127.68	127.68	127.68
Eutrophication Potential (kg N eq)	0.51	0.38	0.14	0.14	0.14	0.14
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	251.19	184.62	67.84	67.84	67.84	67.84
Energy Consumption						
Hydro (MJ)	8.87	6.52	2.40	2.40	2.40	2.40
Coal (MJ)	129.41	95.11	34.95	34.95	34.95	34.95
Diesel (MJ)	3549.62	3027.84	1273.85	1273.85	1273.85	1273.85
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	427.57	314.27	115.48	115.48	115.48	115.48
LPG (MJ)	19.36	14.23	5.23	5.23	5.23	5.23
Natural Gas (MJ)	790.37	580.92	213.46	213.46	213.46	213.46
Nuclear (MJ)	34.14	25.09	9.22	9.22	9.22	9.22
Total Primary Energy Consumption (MJ)	4959.34	4063.98	1654.58	1654.58	1654.58	1654.58
Resources Used						
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	40.16	24.43	6.12	6.12	6.12	6.12
Uranium (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	131.99	80.30	20.13	20.13	20.13	20.13
Crude Oil (L)	566.41	406.29	143.67	143.67	143.67	143.67
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Asphalt Paving - Resurfacing

Asphalt Paving-Resurfacing	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	545596.45	313540.46	313540.46	153186.40	153186.40	110294.21
Acidification Potential (moles of H+ eq)	243893.41	140493.74	140493.74	68668.58	68668.58	49441.38
Eutrophication Potential (kg N eq)	165.02	95.21	95.21	46.55	46.55	33.51
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	43429.95	25022.21	25022.21	12230.36	12230.36	8805.86
Energy Consumption						
Hydro (MJ)	25944.53	14967.19	14967.19	7317.23	7317.23	5268.40
Coal (MJ)	985621.38	568739.54	568739.54	278059.73	278059.73	200203.01
Diesel (MJ)	395923.08	226577.80	226577.80	110619.65	110619.65	79646.15
Feedstock (MJ)	21928973.65	12690882.61	12690882.61	6207696.08	6207696.08	4469541.18
Gasoline (MJ)	20586.26	11844.00	11844.00	5787.70	5787.70	4167.15
Heavy Fuel Oil (MJ)	2531970.32	1453345.17	1453345.17	709913.07	709913.07	511137.41
LPG (MJ)	126165.86	72190.99	72190.99	35244.10	35244.10	25375.76
Natural Gas (MJ)	2761955.93	1586061.90	1586061.90	774800.25	774800.25	557856.18
Nuclear (MJ)	7829.18	4496.23	4496.23	2196.47	2196.47	1581.46
Total Primary Energy Consumption (MJ)	28784970.19	16629105.42	16629105.42	8131634.29	8131634.29	5854776.69
Resources Used						
Coarse Aggregate (kg)	6185924.52	3534814.01	3534814.01	1725325.89	1725325.89	1242234.64
Water (L)	38663.66	25775.77	25775.77	12887.89	12887.89	9279.28
Coal (kg)	46747.84	26973.69	26973.69	13187.52	13187.52	9495.02
Uranium (kg)	0.01	0.01	0.01	0.00	0.00	0.00
Natural Gas (m3)	73394.00	42142.94	42142.94	20587.01	20587.01	14822.65
Crude Oil (L)	85206.22	48869.11	48869.11	23867.92	23867.92	17184.90
Crude Oil as feedstock (L)	524115.05	303319.37	303319.37	148367.50	148367.50	106824.60

Asphalt Paving-Resurfacing	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	203411.87	124597.33	124597.33	70667.35	70667.35	56263.73
Acidification Potential (moles of H+ eq)	62430.97	38241.30	38241.30	21689.17	21689.17	17268.43
Eutrophication Potential (kg N eq)	67.84	41.55	41.55	23.57	23.57	18.76
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	33172.22	20319.22	20319.22	11524.38	11524.38	9175.45
Energy Consumption						
Hydro (MJ)	1171.16	717.38	717.38	406.87	406.87	323.94
Coal (MJ)	17089.91	10468.21	10468.21	5937.21	5937.21	4727.07
Diesel (MJ)	1502336.46	882209.37	882209.37	457774.80	457774.80	344412.51
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	56466.57	34587.88	34587.88	19617.06	19617.06	15618.66
LPG (MJ)	2556.56	1565.99	1565.99	888.17	888.17	707.14
Natural Gas (MJ)	104378.34	63935.61	63935.61	36262.10	36262.10	28871.05
Nuclear (MJ)	4508.20	2761.44	2761.44	1566.19	1566.19	1246.97
Total Primary Energy Consumption (MJ)	1688507.20	996245.87	996245.87	522452.41	522452.41	395907.34
Resources Used						
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	1648.52	1035.17	1035.17	621.38	621.38	510.87
Uranium (kg)	0.01	0.01	0.01	0.01	0.01	0.00
Natural Gas (m3)	5418.46	3402.47	3402.47	2042.39	2042.39	1679.16
Crude Oil (L)	67597.83	41456.23	41456.23	23580.10	23580.10	18805.75
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Asphalt Full Depth Reclamation

Full Depth Reclamation	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	444485.48	119572.92	70945.10	17736.27	16080.89	17736.27
Acidification Potential (moles of H+ eq)	148874.62	53393.93	24470.83	6117.71	5546.72	6117.71
Eutrophication Potential (kg N eq)	138.44	35.48	22.23	5.56	5.04	5.56
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	61618.65	9130.83	9543.53	2385.88	2163.20	2385.88
Energy Consumption						
Hydro (MJ)	5944.28	5757.62	1183.63	295.91	268.29	295.91
Coal (MJ)	180527.92	218978.35	38381.40	9595.35	8699.78	9595.35
Diesel (MJ)	2880543.36	91425.94	639516.11	159879.03	144956.98	159879.03
Feedstock (MJ)	3305068.65	4808206.06	746907.30	186726.82	169298.99	186726.82
Gasoline (MJ)	3266.86	4646.77	732.22	183.06	165.97	183.06
Heavy Fuel Oil (MJ)	501217.11	575766.25	104820.54	26205.13	23759.32	26205.13
LPG (MJ)	25100.57	29103.86	5259.28	1314.82	1192.10	1314.82
Natural Gas (MJ)	618729.79	625913.01	124208.37	31052.09	28153.90	31052.09
Nuclear (MJ)	8654.77	1697.59	1354.96	338.74	307.12	338.74
Total Primary Energy Consumption (MJ)	7529053.30	6361495.46	1662363.81	415590.95	376802.46	415590.95
Resources Used						
Coarse Aggregate (kg)	1038471.47	1442321.48	230771.44	57692.86	52308.19	57692.86
Water (L)	2577.58	8591.92	859.19	214.80	194.75	214.80
Coal (kg)	9059.64	10366.81	1824.64	456.16	413.58	456.16
Uranium (kg)	0.02	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	17892.32	16567.79	3287.69	821.92	745.21	821.92
Crude Oil (L)	127211.49	18241.50	19615.66	4903.91	4446.22	4903.91
Crude Oil as feedstock (L)	78993.04	114918.88	17851.51	4462.88	4046.34	4462.88

Full Depth Reclamation	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	56816.42	35346.22	12207.89	6554.97	6379.10	6554.97
Acidification Potential (moles of H+ eq)	17438.08	10848.38	3746.82	2011.84	1957.86	2011.84
Eutrophication Potential (kg N eq)	18.95	11.79	4.07	2.19	2.13	2.19
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	9265.59	5764.20	1990.85	1068.98	1040.30	1068.98
Energy Consumption						
Hydro (MJ)	327.12	203.51	70.29	37.74	36.73	37.74
Coal (MJ)	4773.51	2969.66	1025.66	550.72	535.95	550.72
Diesel (MJ)	311055.59	356731.99	92668.56	45870.55	44414.61	45870.55
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	15772.08	9812.01	3388.88	1819.64	1770.82	1819.64
LPG (MJ)	714.09	444.24	153.43	82.39	80.18	82.39
Natural Gas (MJ)	29154.66	18137.48	6264.33	3363.60	3273.36	3363.60
Nuclear (MJ)	1259.22	783.37	270.56	145.28	141.38	145.28
Total Primary Energy Consumption (MJ)	363056.28	389082.27	103841.71	51869.92	50253.02	51869.92
Resources Used						
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	551.32	170.45	76.42	43.19	42.15	43.19
Uranium (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	1812.11	560.23	251.18	141.95	138.56	141.95
Crude Oil (L)	19060.33	11517.58	4012.54	2158.76	2101.09	2158.76
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Concrete Seal Joints

Concrete Seal Joints	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	718.32	404.07	188.57	151.52	151.52	151.52
Acidification Potential (moles of H+ eq)	396.92	223.27	104.20	83.72	83.72	83.72
Eutrophication Potential (kg N eq)	0.26	0.15	0.07	0.05	0.05	0.05
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	58.82	33.09	15.44	12.41	12.41	12.41
Energy Consumption						
Hydro (MJ)	77.23	43.44	20.27	16.29	16.29	16.29
Coal (MJ)	3033.10	1706.03	796.20	639.79	639.79	639.79
Diesel (MJ)	146.21	82.24	38.38	30.84	30.84	30.84
Feedstock (MJ)	44131.62	24822.73	11584.74	9308.90	9308.90	9308.90
Gasoline (MJ)	22.18	12.47	5.82	4.68	4.68	4.68
Heavy Fuel Oil (MJ)	1798.54	1011.63	472.13	379.38	379.38	379.38
LPG (MJ)	28.42	15.98	7.46	5.99	5.99	5.99
Natural Gas (MJ)	3535.45	1988.60	928.07	745.75	745.75	745.75
Nuclear (MJ)	8.66	4.87	2.27	1.83	1.83	1.83
Total Primary Energy Consumption (MJ)	52781.41	29688.01	13855.35	11133.44	11133.44	11133.44
Resources Used						
Limestone (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Clay & Shale (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Iron Ore (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Sand (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Gypsum (Natural) (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	143.48	80.71	37.67	30.27	30.27	30.27
Uranium (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	93.63	52.66	24.58	19.75	19.75	19.75
Crude Oil (L)	51.70	29.09	13.57	10.91	10.91	10.91
Crude Oil as feedstock (L)	1054.77	593.28	276.88	222.49	222.49	222.49

Concrete Seal Joints	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	882.32	839.45	839.45	803.60	803.60	803.60
Acidification Potential (moles of H+ eq)	270.80	257.64	257.64	246.64	246.64	246.64
Eutrophication Potential (kg N eq)	0.29	0.28	0.28	0.27	0.27	0.27
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	143.89	136.90	136.90	131.05	131.05	131.05
Energy Consumption						
Hydro (MJ)	5.08	4.83	4.66	4.63	4.63	4.63
Coal (MJ)	74.13	70.53	67.97	67.52	67.52	67.52
Diesel (MJ)	3259.79	2760.47	2418.12	2359.26	2359.26	2359.26
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	244.93	233.03	224.57	223.08	223.08	223.08
LPG (MJ)	11.09	10.55	10.17	10.10	10.10	10.10
Natural Gas (MJ)	452.75	430.75	415.12	412.36	412.36	412.36
Nuclear (MJ)	19.55	18.60	17.93	17.81	17.81	17.81
Total Primary Energy Consumption (MJ)	4067.32	3528.76	3158.52	3094.74	3094.74	3094.74
Resources Used						
Limestone (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Clay & Shale (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Iron Ore (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Sand (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Gypsum (Natural) (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	9.80	9.61	9.47	9.44	9.44	9.44
Uranium (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	32.21	31.59	31.11	31.02	31.02	31.02
Crude Oil (L)	298.43	284.50	274.57	272.82	272.82	272.82
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Concrete Full Depth Repair

Concrete Full Depth Repair	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	1030151.65	686767.77	686767.77	189153.63	162473.01	129022.68
Acidification Potential (moles of H+ eq)	281701.63	187801.09	187801.09	51477.90	44216.81	35113.35
Eutrophication Potential (kg N eq)	237.84	158.56	158.56	43.17	37.08	29.44
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	114784.26	76522.84	76522.84	20829.73	17891.64	14208.07
Energy Consumption						
Hydro (MJ)	17025.79	11350.52	11350.52	3200.02	2748.65	2182.75
Coal (MJ)	1231526.87	821017.91	821017.91	233480.92	200547.82	159258.57
Diesel (MJ)	5983460.85	3988973.90	3988973.90	1136709.25	976373.42	775355.36
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	2974.93	1983.29	1983.29	565.24	485.51	385.55
Heavy Fuel Oil (MJ)	711482.47	474321.65	474321.65	133520.23	114686.85	91074.85
LPG (MJ)	10617.57	7078.38	7078.38	1940.67	1666.93	1323.74
Natural Gas (MJ)	578715.26	385810.17	385810.17	106689.33	91640.52	72773.35
Nuclear (MJ)	16583.05	11055.37	11055.37	3016.76	2591.24	2057.75
Total Primary Energy Consumption (MJ)	8552386.79	5701591.19	5701591.19	1619122.42	1390740.94	1104411.93
Resources Used						
Limestone (kg)	406063.22	270708.82	270708.82	77152.01	66269.52	52625.79
Clay & Shale (kg)	44786.39	29857.59	29857.59	8509.41	7309.14	5804.32
Iron Ore (kg)	8957.28	5971.52	5971.52	1701.88	1461.83	1160.86
Sand (kg)	14928.80	9952.53	9952.53	2836.47	2436.38	1934.77
Gypsum (Natural) (kg)	23886.07	15924.05	15924.05	4538.35	3898.21	3095.63
Coarse Aggregate (kg)	1763621.33	1175747.55	1175747.55	335088.05	287823.00	228565.32
Water (L)	482135.53	321423.69	321423.69	91605.75	78684.52	62484.76
Coal (kg)	59091.00	39394.00	39394.00	11178.16	9601.46	7624.68
Uranium (kg)	0.03	0.02	0.02	0.01	0.00	0.00
Natural Gas (m3)	17827.32	11884.88	11884.88	3221.57	2767.16	2197.45
Crude Oil (L)	238340.31	158893.54	158893.54	43246.94	37146.84	29498.96
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Concrete Full Depth Repair	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	63857.14	43286.48	43286.48	13512.99	11909.53	9899.22
Acidification Potential (moles of H+ eq)	19877.75	13471.30	13471.30	4200.36	3700.76	3074.39
Eutrophication Potential (kg N eq)	21.61	14.64	14.64	4.57	4.02	3.34
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	10585.94	7173.90	7173.90	2236.40	1970.29	1636.67
Energy Consumption						
Hydro (MJ)	367.67	249.23	249.23	77.80	68.57	57.00
Coal (MJ)	5365.13	3636.83	3636.83	1135.33	1000.61	831.71
Diesel (MJ)	547446.28	367466.44	367466.44	110088.12	95618.75	77478.05
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	17726.85	12016.39	12016.39	3751.22	3306.10	2748.03
LPG (MJ)	802.59	544.05	544.05	169.84	149.69	124.42
Natural Gas (MJ)	32768.04	22212.28	22212.28	6934.13	6111.32	5079.73
Nuclear (MJ)	1415.70	959.65	959.65	299.57	264.02	219.45
Total Primary Energy Consumption (MJ)	605892.25	407084.87	407084.87	122456.01	106519.05	86538.38
Resources Used						
Limestone (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Clay & Shale (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Iron Ore (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Sand (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Gypsum (Natural) (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	397.58	271.77	271.77	87.43	77.94	66.04
Uranium (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	1306.79	893.27	893.27	287.38	256.19	217.08
Crude Oil (L)	21357.76	14477.95	14477.95	4518.02	3982.06	3310.12
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Concrete Full Depth Repair

Concrete Partial Depth Repair	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	195731.82	130487.88	96664.12	28542.30	24646.05	19571.87
Acidification Potential (moles of H+ eq)	54687.76	36458.51	26607.90	7739.46	6682.96	5307.06
Eutrophication Potential (kg N eq)	47.34	31.56	22.68	6.46	5.57	4.43
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	22842.19	15228.13	10944.71	3114.89	2689.68	2135.92
Energy Consumption						
Hydro (MJ)	2895.66	1930.44	1545.57	491.31	424.24	336.90
Coal (MJ)	200335.48	133556.99	110375.51	36071.82	31147.73	24734.96
Diesel (MJ)	962871.22	641914.14	534627.10	175874.41	151866.15	120599.59
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	478.37	318.91	265.76	87.46	75.52	59.97
Heavy Fuel Oil (MJ)	121884.51	81256.34	64730.85	20476.87	17681.61	14041.28
LPG (MJ)	2055.60	1370.40	1002.57	291.82	251.98	200.10
Natural Gas (MJ)	108200.86	72133.91	54002.35	16147.73	13943.44	11072.73
Nuclear (MJ)	3272.87	2181.92	1575.94	451.99	390.29	309.94
Total Primary Energy Consumption (MJ)	1401994.57	934663.05	768125.66	249893.40	215780.97	171355.48
Resources Used						
Limestone (kg)	65294.97	43529.98	36274.98	11938.26	10308.59	8186.23
Clay & Shale (kg)	7201.65	4801.10	4000.92	1316.72	1136.98	902.89
Iron Ore (kg)	1440.33	960.22	800.18	263.34	227.40	180.58
Sand (kg)	2400.55	1600.37	1333.64	438.91	378.99	300.96
Gypsum (Natural) (kg)	3840.88	2560.59	2133.82	702.25	606.39	481.54
Coarse Aggregate (kg)	283590.31	189060.21	157550.17	51850.47	44772.47	35554.61
Water (L)	77527.39	51684.93	43070.77	14174.78	12239.81	9719.85
Coal (kg)	9775.23	6516.82	5313.44	1724.24	1488.87	1182.34
Uranium (kg)	0.01	0.01	0.00	0.00	0.00	0.00
Natural Gas (m3)	3802.07	2534.71	1709.38	480.19	414.64	329.27
Crude Oil (L)	47488.43	31658.95	22728.86	6466.67	5583.92	4434.29
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Concrete Partial Depth Repair	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	17036.25	13199.10	7910.18	3864.67	3629.95	3324.25
Acidification Potential (moles of H+ eq)	5273.59	4080.95	2452.69	1194.34	1121.18	1025.90
Eutrophication Potential (kg N eq)	5.73	4.44	2.67	1.30	1.22	1.11
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential (kg O3 eq)	2805.95	2170.96	1305.37	635.31	596.34	545.59
Energy Consumption						
Hydro (MJ)	98.09	76.00	45.54	22.25	20.90	19.14
Coal (MJ)	1431.34	1108.95	664.59	324.70	304.98	279.29
Diesel (MJ)	101892.34	72940.98	55746.41	23379.09	21212.39	18390.65
Feedstock (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline (MJ)	0.00	0.00	0.00	0.00	0.00	0.00
Heavy Fuel Oil (MJ)	4729.26	3664.06	2195.87	1072.83	1007.67	922.81
LPG (MJ)	214.12	165.89	99.42	48.57	45.62	41.78
Natural Gas (MJ)	8742.03	6773.01	4059.06	1983.13	1862.68	1705.81
Nuclear (MJ)	377.64	292.58	175.35	85.67	80.46	73.68
Total Primary Energy Consumption (MJ)	117484.82	85021.47	62986.25	26916.24	24534.70	21433.17
Resources Used						
Limestone (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Clay & Shale (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Iron Ore (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Sand (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Gypsum (Natural) (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Coarse Aggregate (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Water (L)	0.00	0.00	0.00	0.00	0.00	0.00
Coal (kg)	152.31	123.43	56.99	30.07	28.72	26.96
Uranium (kg)	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas (m3)	500.62	405.71	187.33	98.85	94.40	88.60
Crude Oil (L)	5749.57	4458.78	2648.03	1292.82	1214.40	1112.27
Crude Oil as feedstock (L)	0.00	0.00	0.00	0.00	0.00	0.00

Diamond Grinding

Diamond Grinding	MATERIALS & EQUIPMENT					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	1189.65	0	0	0	0	0
Acidification Potential (moles of H+ eq)	368.22	0	0	0	0	0
Eutrophication Potential (kg N eq)	0.38	0	0	0	0	0
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0	0	0	0	0
Smog Potential (kg O3 eq)	183.21	0	0	0	0	0
Energy Consumption		0	0	0	0	0
Hydro (MJ)	6.41	0	0	0	0	0
Coal (MJ)	93.59	0	0	0	0	0
Diesel (MJ)	10552.80	0	0	0	0	0
Feedstock (MJ)	0.00	0	0	0	0	0
Gasoline (MJ)	0.00	0	0	0	0	0
Heavy Fuel Oil (MJ)	308.25	0	0	0	0	0
LPG (MJ)	14.02	0	0	0	0	0
Natural Gas (MJ)	579.05	0	0	0	0	0
Nuclear (MJ)	24.68	0	0	0	0	0
Total Primary Energy Consumption (MJ)	11578.81	0	0	0	0	0
Resources Used		0	0	0	0	0
Limestone (kg)	0.00	0	0	0	0	0
Clay & Shale (kg)	0.00	0	0	0	0	0
Iron Ore (kg)	0.00	0	0	0	0	0
Sand (kg)	0.00	0	0	0	0	0
Gypsum (Natural) (kg)	0.00	0	0	0	0	0
Coarse Aggregate (kg)	0.00	0	0	0	0	0
Water (L)	0.00	0	0	0	0	0
Coal (kg)	5.74	0	0	0	0	0
Uranium (kg)	0.00	0	0	0	0	0
Natural Gas (m3)	19.07	0	0	0	0	0
Crude Oil (L)	378.60	0	0	0	0	0
Crude Oil as feedstock (L)	0.00	0	0	0	0	0

Diamond Grinding	TRANSPORTATION					
Environmental Impacts	**Interstate**	**Freeway**	**Principal Arterial**	**Minor Arterial**	**Collector**	**Local**
Global Warming Potential (kg CO2 eq)	1676.86	0	0	0	0	0
Acidification Potential (moles of H+ eq)	514.66	0	0	0	0	0
Eutrophication Potential (kg N eq)	0.56	0	0	0	0	0
Ozone Depletion Potential (kg CFC-11 eq)	0.00	0	0	0	0	0
Smog Potential (kg O3 eq)	273.46	0	0	0	0	0
Energy Consumption						
Hydro (MJ)	9.65	0	0	0	0	0
Coal (MJ)	140.88	0	0	0	0	0
Diesel (MJ)	12304.82	0	0	0	0	0
Feedstock (MJ)	0.00	0	0	0	0	0
Gasoline (MJ)	0.00	0	0	0	0	0
Heavy Fuel Oil (MJ)	465.49	0	0	0	0	0
LPG (MJ)	21.08	0	0	0	0	0
Natural Gas (MJ)	860.46	0	0	0	0	0
Nuclear (MJ)	37.16	0	0	0	0	0
Total Primary Energy Consumption (MJ)	13839.55	0	0	0	0	0
Resources Used						
Limestone (kg)	0.00	0	0	0	0	0
Clay & Shale (kg)	0.00	0	0	0	0	0
Iron Ore (kg)	0.00	0	0	0	0	0
Sand (kg)	0.00	0	0	0	0	0
Gypsum (Natural) (kg)	0.00	0	0	0	0	0
Coarse Aggregate (kg)	0.00	0	0	0	0	0
Water (L)	0.00	0	0	0	0	0
Coal (kg)	9.66	0	0	0	0	0
Uranium (kg)	0.00	0	0	0	0	0
Natural Gas (m3)	31.77	0	0	0	0	0
Crude Oil (L)	549.52	0	0	0	0	0
Crude Oil as feedstock (L)	0.00	0	0	0	0	0