Submission for
Verification of Eco-efficiency Analysis Under
NSF Protocol P352, Part B

Chip Seal Eco-efficiency Analysis
Final Report - November 2011

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1. Purpose and Intent of this Submission

1.1. The purpose of this submission is to provide a written report of the methods and findings of BASF Corporation’s “Chip Seal Eco-efficiency Analysis”, with the intent of having it verified under the requirements of NSF Protocol P352, Part B: Verification of Eco-efficiency Analysis Studies.

1.2. The Chip Seal Analysis was performed by BASF according to the methodology validated by NSF International under the requirements of Protocol P352. More information on BASF’s methodology and the NSF validation can be obtained at http://www/nsf.org/info/ecoefficiency or http://www.basf.com/group/corporate/en/sustainability/eco-efficiency-analysis/index

2. Content of this Submission

2.1. This submission outlines the study goals, procedures, and results for the Chip Seal Eco-efficiency Analysis (EEA) study, which was conducted in accordance with BASF Corporation’s EEA (BASF EEA) methodology. This submission will provide a discussion of the basis of the eco-analysis preparation and verification work.

2.2. As required under NSF P352 Part B, along with this document, BASF is submitting the final computerized model programmed in Microsoft® Excel. The computerized model, together with this document, will aid in the final review and ensure that the data and critical review findings have been satisfactorily addressed.

3. BASF’s EEA Methodology

3.1. Overview:
BASF EEA involves measuring the life cycle environmental impacts and life cycle costs for product alternatives for a defined level of output. At a minimum, BASF EEA evaluates the environmental impact of the production, use, and disposal of a product or process in the areas of energy and resource consumption, emissions, toxicity and risk potential, and land use. The EEA also evaluates the life cycle costs associated with the product or process by calculating the costs related to, at a minimum, materials, labor, manufacturing, waste disposal, and energy.

3.2. Preconditions: The basic preconditions of this eco-efficiency analysis are that all alternatives that are being evaluated are being compared against a common functional unit or customer benefit. This allows for an objective comparison between the various alternatives. The scoping and definition of the customer benefit are aligned with the goals and objectives of the study. Data gathering and constructing the system boundaries are consistent with the functional unit and consider both the environmental and economic impacts of each alternative over their life cycle in order to achieve the specified customer benefit. An overview of the scope of the environmental and economic assessment carried out is defined below.
3.2.1. Environmental Burden Metrics:
For BASF EEA environmental burden is characterized using eleven categories, at a minimum, including: primary energy consumption, raw material consumption, greenhouse gas emissions (GHG), ozone depletion potential (ODP), acidification potential (AP), photochemical ozone creation potential (POCP), water emissions, solid waste emissions, toxicity potential, risk potential, and land use. These are shown below in Figure 1. Metrics shown in yellow represent the six main categories of environmental burden that are used to construct the environmental fingerprint, burdens in blue represent all elements of the emissions category, and green show air emissions.

![Figure 1. Environmental Impact categories](image)

3.2.2. Economic Metrics:
It is the intent of the BASF EEA methodology to assess the economics of products or processes over their life cycle and to determine an overall total cost of ownership for the defined customer benefit ($/CB). The approaches for calculating costs vary from study to study. When chemical products of manufacturing are being compared, the sale price paid by the customer is predominately used. When different production methods are compared, the relevant costs include the purchase and installation of capital equipment, depreciation, and operating costs. The costs incurred are summed and combined in appropriate units (e.g. dollar or EURO) without additional weighting of individual financial amounts. The BASF EEA methodology will incorporate:
- the real costs that occur in the process of creating and delivering the product to the consumer;
• the subsequent costs which may occur in the future (due to tax policy changes, for example) with appropriate consideration for the time value of money; and
• costs having ecological aspect, such as the costs involved to treat wastewater generated during the manufacturing process.

3.3 Work Flow:
A representative flowchart of the overall process steps and calculations conducted for this eco-efficiency analysis is summarized in Figure 2 below.

4. Study Goals, Decision Criteria and Target Audience

4.1. Study Goals
The specific goal defined for the Chip Seal Eco-efficiency Analysis was to quantify the differences in life cycle environmental impacts and total life cycle costs of asphalt pavement preservation technologies in the United States. Chip seals described in this report are based on polymer modified asphalt binders and aggregate chips. The chip seal is constructed by spraying the asphalt binder onto the existing asphalt pavement and then dropping the aggregate chips. The purpose of the chip seal is to seal minor cracks in the surface of the asphalt pavement and provide additional friction as well as extend the lifetime of the underlying base course or substrate.

This study compares several different pavement preservation technologies for rural roads: (1) Hot Chip Seal, polymer modified, non-emulsified with Ground Tire Rubber (GTR) (2) Polymer modified chip seal, emulsified asphalt (CRS-2P) using SBR polymer (cold mix technology) (3) Polymer modified chip seal, emulsified asphalt (CRS-2P) using SBS polymer (cold mix technology) and (4) Polymer modified chip seal, emulsified asphalt (CRS-2P) using SBR polymer with fiberglass reinforcement (cold mix technology).
The study considered application of these technologies across the United States as a whole with no specific focus on one region (e.g. Southwest, Northeast). Thus average national data was used for key study input parameters such as expected durability for each alternative, material compositions, costs etc.

It is well documented that the major factor influencing the lifetime environmental and cost impact of the road is how the profile and condition of the road influences the performance (fuel efficiency) of the traffic on the road\textsuperscript{21}. The general findings of the Joint EAPA / Eurobitume Task Group on Fuel Efficiency\textsuperscript{21} after a review of several relevant studies was that the differences in pavement types did not play a significant role in effecting the energy consumption of the traffic on the road. A more important factor influencing the fuel efficiency of the traffic was whether the pavement was in good condition with good surface characteristics (texture and roughness). Optimal maintenance and pavement preservation of the roads is therefore the key means to limit fuel consumption, greenhouse gas emissions and reduce the overall environmental impact of roads. Consistent with these findings, this study focused on several chip seal pavement maintenance technologies and assumed that these pavement preservation technologies were applied at a frequency and quality that the underlying performance and profile of the road remained the same for each alternative and thus no significant effect on the relative fuel efficiencies of the traffic was realized and thus did not need to be considered in the analysis as it was an identical impact for all alternatives.

Study results will be used as the basis to guide product development and manufacturing decisions that will result in more sustainable pavement preservation technologies as well as provide the necessary information to allow a clear comparison between the life cycle environmental and total cost impacts and benefits of various pavement preservation technologies. It will also facilitate the clear communications of these results as well to key stakeholders in the transportation industry who are challenged with evaluating and making strategic decisions related to the environmental and total costs trade-offs associated with different pavement preservation technologies.

4.2 Decision Criteria:

The context of this EEA study compared the environmental and cost impacts for pavement preservation technologies, specifically various polymer modified (SBR (styrene butadiene rubber) or SBS (styrene butadiene styrene)) chip seal technologies (emulsified and non-emulsified) for rural roads on a regional level over the road’s defined life cycle. Two of the alternatives are additionally enhanced with either GTR or fiberglass reinforcement. The study was technology driven and required supplier and customer engagement. The study goals, target audience, and context for decision criteria used in this study are displayed in Figure 3.
4.3. **Target Audience:**

The target audience for the study has been defined as state and federal government agencies (e.g. DOT, Department of Transportation), customers and trade associations. It is planned to communicate study results in marketing materials and at trade conferences.

5. **Customer Benefit, Alternatives and System Boundaries**

5.1. **Customer Benefit (CB):**

The Customer Benefit (identified also as CB) applied to all alternatives for the base case analysis is the preventive maintenance of a 1 mile stretch of a 12 foot lane of a rural road to a similar profile and performance using best engineering practices over a 40 year period. With regards to the life span to consider, the FHWA’s (Federal Highway Association) LCCA Policy statement\(^3\) states that an analysis period of at least 35 years be considered for pavement projects. Though this was specific to life cycle cost analyses, the same philosophy should apply to an eco-efficiency analysis.

5.2. **Alternatives:**

The product alternatives compared under this EEA study cover both asphalt cement binders and emulsion based binders for chip seal and are (1) Hot Chip Seal, polymer modified, non-emulsified with GTR (2) Polymer modified chip seal, emulsified asphalt (CRS-2P) using SBR polymer (3) Polymer modified chip seal, emulsified asphalt (CRS-2P) using SBS polymer and (4) Polymer modified chip seal, emulsified asphalt (CRS-2P) using SBR polymer with fiberglass reinforcement. These alternatives were selected as they represent the most commonly available technologies for pavement...
preservation for chip seal applications for rural roads and represent the majority of the market share. Both the leading binder compositions for both asphalt cement and emulsion based binders are included. A relatively recent chip seal technology introduced into the North American market, fiberglass reinforcement, was included as well in the comparison.

5.3. **System Boundaries.**

The system boundaries define the specific elements of the production, use, and disposal phases that are considered as part of the analysis. The system boundaries for the four alternatives evaluated in this study are shown in Figures 4 through 7. Sections identified in gray were excluded from the analysis as they represented identical impacts for both alternatives (e.g. fuel efficiency of traffic on the road).

![Figure 4. System boundaries – Polymer modified with Ground Tire Rubber](image-url)
Figure 5. System boundaries – Emulsified Asphalt with SBR polymer

Figure 6. System boundaries – Emulsified Asphalt with SBS polymer
Figure 7. System boundaries – Emulsified Asphalt, with SBR polymer and fiber reinforcement

5.4 Scenario Analyses:
In addition to the base case analysis, one additional scenario was evaluated to determine the sensitivity of the study final conclusions and results to key input parameters. The scenarios considered for this analysis were:

5.4.1. Scenario #1: Increased durability for Fiberglass Reinforced Chip Seal to 7 years

Results from these scenarios will be discussed along with the base case in Section 8, “Eco-efficiency analysis results and discussion.”

6. Input Parameters and Assumptions

6.1. Input Parameters:
A comprehensive list of input parameters were included for this study and considered all relevant material and operational characteristics. Absolute input values as opposed to relative values were used.

6.1.1. Binder – Tack Coat Parameters:

The compositional data for the binders (CRS-2P for emulsified alternatives and AC-20-5TR for the ground tire rubber alternative) are based on representative compositions for the industry and shown below in Table 1. The chip seal binder compositions shown below were vendor supplied and reflect an average composition and are within the industry recommendations. The final distribution of aggregate and bitumen in the surface treatment is also summarized below.
Compositional Data

<table>
<thead>
<tr>
<th>Chip Seal Binder Composition</th>
<th>GTR</th>
<th>Fiber Reinforced</th>
<th>SBR Modified</th>
<th>SBS Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Tire Rubber %</td>
<td>7.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bitumen (asphalt cement) %</td>
<td>90.5%</td>
<td>67.6%</td>
<td>67.6%</td>
<td>67.6%</td>
</tr>
<tr>
<td>SBS %</td>
<td>2.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBR %</td>
<td></td>
<td>3.3%</td>
<td>3.3%</td>
<td>2.1%</td>
</tr>
<tr>
<td>Emulsifier %</td>
<td></td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Hydrochloric acid %</td>
<td></td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Water %</td>
<td>28.7%</td>
<td>28.7%</td>
<td>28.7%</td>
<td>29.9%</td>
</tr>
<tr>
<td>TOTAL %</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 1: General Product Formulations for study alternatives.

6.1.2. Production and Application Impacts for technologies

As the processing steps and temperatures required for the manufacture and application of the various alternatives are drastically different (see Figures 4 - 7 above) it is essential that these impacts are considered. Electricity requirements to shred and granulate tires into crumb rubber were based on plant and equipment data. Energy impacts related to the production and storage of the binder prior to application were provided by asphalt manufacturers. Impacts related to mixing and pre-coating energies for the hot mix asphalt alternative (GTR) were taken from Table 4.2.38.1 of the Life Cycle Assessment (LCA) report prepared for the Swedish National Road Administration by the IVL - Swedish Environmental Research Institute. Pre-coating aggregate helps improve the adhesion or binding properties between the aggregate and the binder. Most asphalt cement binders (AC-20-5TR) are used with pre-coated aggregate while emulsion binders are not. Application (laying) energies for all the alternatives were taken from Annex II of the lifecycle assessment report by Colas. These impacts are highlighted in Table 2 below.

The application amounts of binder and aggregate were taken from typical DOT combination rates and were confirmed by customers to be still representative of industry practice. Specifically, the values utilized for the binder (both on and outside of the wheel path) were 0.43 gal/yd² for the emulsion based alternatives and 0.345 gal/yd² for the asphalt cement (GTR) alternative. A grade 4 aggregate size was used with application rates (on wheel path) of 125 yd³/yd³ for the emulsion based binder alternatives and 139 yd³/yd³ for the ground tire rubber alternative.
6.1.3. GTR (Ground Tire Rubber)

Ground tire rubber can be blended with asphalt to beneficially modify the properties of the asphalt in highway construction. Per the E.P.A.\textsuperscript{25}, asphalt rubber is the largest single market for ground rubber, consuming an estimated 220 million pounds, or approximately 12 million tires. The hot asphalt cement alternative (AC-20-5TR) contains a minimum of 5\% ground tire rubber. Energy usage to convert the recycled tires into GTR or crumb rubber was included in the analysis and was calculated from manufacturer data as well as equipment energy consumption. No previous environmental impacts were burden to the GTR, only the energy required to create the crumb rubber from tires and energy related to transport. In addition, credit was given to the GTR alternative for diverting waste from the landfill.

6.2. Transportation

Maintaining an asphalt road over 40 years requires a significant quantity of material. Thus the environmental and cost impacts associated with transporting the materials to and from the job site are significant and are thus included in this analysis. The following assumptions were used when considering transportation:

- 100 km distance for binder, striping material and fiberglass
- 50 km for aggregate
- 100 km for distance to landfill or recycling location

Table 3 reflects the logistical impacts for the life cycle logistical impacts associated with the two alternatives.

<table>
<thead>
<tr>
<th>TRANSPORTATION</th>
<th>GTR</th>
<th>Fiber Reinforced</th>
<th>SBR Modified</th>
<th>SBS Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck fuel consumption M!/ton!km</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Chip seal binder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight transported kg/CB</td>
<td>66328</td>
<td>77109</td>
<td>77109</td>
<td>77109</td>
</tr>
<tr>
<td>distance km</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Aggregate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight transported kg/CB</td>
<td>70990</td>
<td>78909</td>
<td>78909</td>
<td>78909</td>
</tr>
<tr>
<td>distance km</td>
<td>60</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Fiberglass Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight transported kg/CB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>distance km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road Markings M!/m!a</td>
<td>1404</td>
<td>1404</td>
<td>1404</td>
<td>1404</td>
</tr>
<tr>
<td>M!/CB</td>
<td>9360</td>
<td>9360</td>
<td>9360</td>
<td>9360</td>
</tr>
<tr>
<td>Transportation Impact kg/CB</td>
<td>775919</td>
<td>870493</td>
<td>866507</td>
<td>866507</td>
</tr>
<tr>
<td>(minus road markings) total km</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>t!/km!/CB</td>
<td>42397</td>
<td>47680</td>
<td>47181</td>
<td>47181</td>
</tr>
</tbody>
</table>

DISPOSAL

<table>
<thead>
<tr>
<th></th>
<th>GTR</th>
<th>Fiber Reinforced</th>
<th>SBR Modified</th>
<th>SBS Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of Material kg/CB</td>
<td>787881</td>
<td>882461</td>
<td>878469</td>
<td>878469</td>
</tr>
<tr>
<td>Transportation Distance km</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Transportation Impact t!/km!/CB</td>
<td>78788</td>
<td>88246</td>
<td>87847</td>
<td>87847</td>
</tr>
</tbody>
</table>

Table 3: Logistical Impacts for each alternative
6.3. Costs

6.3.1. Life cycle costing

The long term economic impacts of the pavement preservation technologies evaluated were considered by conducting a life cycle cost analysis. Thus, in addition to initial costs (e.g. material and labor), all relevant future cost impacts are considered as well. Consistent with the guidance provided by the US DOT FHWA, constant dollars and real discount rates were considered\(^3\). For this study, both a financial discount rate and a social discount rate\(^{11}\) were used. See Section 6.3.3 for the justification for the specific rates used.

6.3.2. User Costs

User costs were evaluated for each alternative. User costs are defined as excess costs incurred by drivers on the road due to non-standard travel delays caused by agency (e.g. DOT) maintenance and construction activities which disrupt the normal flow of traffic. This approach is basically a way of placing a value on people’s time that is impacted or disrupted by traffic delays. The FHWA normally groups user costs as vehicle operating costs (VOC), user delay costs and crash costs. Guidance for these costs was obtained from LCA literature published by Hicks and Epps. Specific to this study, as most pavements on the National Highway System (NHS) have similar VOCs\(^8\), they were not considered for this study. In addition, crash costs were not considered. Consistent with the strategy proposed by Hicks and Epps, delay costs were accounted for by utilizing a simpler approach: lane rental fees. The value utilized for this study reflecting a moderately traveled rural road was estimated at $5,000 lane-mile/day\(^8\). Other research\(^{20}\) conducted on lane rental fees indicate that this value can vary significantly based on factors such as the time of the day and region of the country. Never the less, this research indicates that this value can be much higher, ranging from $5,000 - $20,000 /day for a single lane. Thus the assumption of$5,000 may be conservative.

6.3.3. Discount Rates

As previously described, comprehensive life cycle costing for roads needs to consider both the actual costs incurred as well as the intangible costs associated with user costs. As both of these costs are distinctly different, a single discount rate cannot be applied. Thus both a financial discount rate (FDR) and a social discount rate (SDR) need to be used. Corotis and Gransberg\(^{12}\) document the average US DOT financial discount rate as 4.8%, which falls within the FHWA range of 3-5%, and also cites additional research which places the range for the US DOT (FHWA) social discount rate between 4 - 8%. Thus for this assessment, 4.8% was used for the FDR and 6% for the SDR.
6.4. Durability

The durability or life expectancy of the pavement preservation technology will have a significant impact in determining the overall eco-efficiency of the alternatives. Durability will vary depending on the region of the country and climate, level and type of traffic usage, and the condition of the underlying pavement. Under the direction of the National Center for Pavement Preservation a survey was conducted of all state DOT agencies in order to collect a broad data set related to state DOT experiences with specific preservation technologies. Specific questions included:

- Agency’s years of experience with a specific technology
- Most recent usage of several preservation technologies
- Expected average service life for a specific technology
- Total monetary expenditure for specific technologies

Over 17 state agencies respond to the questionnaire. Seven specific responses for states with experience with GTR chip seals had an average life extension of 5.57 years and 11 respondents who have utilized polymer modified chip seals had an average life extension of 5.83 years. These correspond well with the value of 5.76 years for the survey conducted by Galehouse et. al.18 in 2003.

Based on the various data sources reviewed and the expert judgment and experiences of the team, a value of 6 years was assumed equally for all alternatives. Though initial test results of the fiber reinforced alternative indicate that it may extend the service life by more than 6 years, not enough long-term field test results exist. However, a scenario analysis (see section 8.4.1) will address the sensitivity of the results to the durability of fiber reinforced alternative.

6.5. Further Assumptions

6.5.1. Work Zone Accidents and Fatalities

A project specific impact accounting for work zone accidents and fatalities associated with road maintenance and construction activities was not included as the time to prepare and apply the chip seal for all alternatives was equivalent.

6.5.2. Lane Striping

The study assumed that each time a surface treatment was applied, new lane striping was applied. The striping material was based on an epoxy resin based thermoplastic (ETP) with glass beads. Material composition was obtained from a DOT standard14. Specific costs and application rates were provided by a vendor16.
6.5.3. Disposal – End of Life

It was also assumed that 90% of the road surface materials will be recycled in some capacity and thus will not be sent directly to the landfill. However, the logistical impacts of transporting the materials to their final end-of-life destination were considered.

7. Data Sources

7.1. The environmental impacts for the production, use, and disposal of the various alternatives were calculated from eco-profiles (a.k.a. life cycle inventories) for the individual components and for fuel usage and material disposal. Life cycle inventory data for these eco-profiles were from several data sources, including BASF specific manufacturing data and customer supplied data. Overall, the quality of the data was considered medium-high to high. None of the eco-profile data was considered to be of low data quality. A summary of the eco-profiles is provided in Table 4.

<table>
<thead>
<tr>
<th>Eco-Profile</th>
<th>Source, Year</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBS polymer</td>
<td>2003</td>
<td>ChemSystems PERP report</td>
</tr>
<tr>
<td>SBR Polymer</td>
<td>1999</td>
<td>ChemSystems PERP report Styrene Butadiene/Butadiene Rubber</td>
</tr>
<tr>
<td>Emulsifier</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Hydrochloric Acid</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Aggregate</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Bitumen</td>
<td>2001</td>
<td>IVL Report. LCA of Roads’</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Electricity</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Heating Oil - US</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Diesel Use - US</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
<tr>
<td>Material to Landfill</td>
<td>BUWAL 250, 1998</td>
<td></td>
</tr>
<tr>
<td>Lane Striping</td>
<td>2009</td>
<td>Dept. of Transportation’</td>
</tr>
<tr>
<td>Transport</td>
<td>US Avg., 1996</td>
<td>Most reliable profile available’</td>
</tr>
</tbody>
</table>

BASF data sources are internal data, while the others are external to BASF. Internal data is confidential to BASF; however, full disclosure was provided to NSF International for verification purposes.

8. Eco-efficiency Analysis Results and Discussion

8.1. Environmental Impact Results: The environmental impact results for the Chip Seal EEA are generated as defined in Section 6 of the BASF EEA methodology. The results for the base case scenario are presented below in sections 8.1.1 through 8.1.9. The eco-efficiency portfolio results for the scenario analyses are presented in section 8.4.

8.1.1. Primary energy consumption: Energy consumption, measured over the entire life cycle and depicted in Figure 8, shows that polymer modified chip seal with GTR has the highest energy consumption, using approximately 6,200,000
MJ of energy per customer benefit. This is over 20% more energy consumption relative to the other chip seal alternatives. The SBR modified chip seal had the lowest energy consumption of approximately 5,050,000 MJ/CB. The biggest contributor to energy consumption for each alternative is the manufacture of the asphalt binder. GTR chip seal has the highest impact based on the extra requirements for pre-coating the aggregate as well as higher manufacturing and application temperatures. Road markings are a significant contributor in energy consumption for each alternative. The embodied energy of each individual material was provided in the eco-profiles supplied to NSF as part of this verification. By looking at only the unit operations in Figures 4 - 7 related to the production phase of the alternatives, it can be concluded that in addition to having a higher life cycle energy requirement, the embodied energy of the chip seal surfacing technology with ground tire rubber is also higher than the other emulsified chip seal alternatives. This is mainly due to the significantly higher production and storage temperatures relative to the other alternatives and the additional energy requirements for producing the crumb rubber.

**Figure 8.** Primary energy consumption.

8.1.2. *Raw material consumption.* Figures 9 shows that the key drivers for the raw material or resource consumption are the asphalt binder, aggregate, road markings and the disposal/transportation modules. The chip seal alternative with GTR uses about 12% more resources over the defined life cycle than the other alternatives. The only differences between the other emulsified alternatives and the best performing alternative (SBR modified) are the additional resource of the fiberglass for the fiber reinforced alternative and the slightly higher energy requirements for the SBS modified alternative. It should be noted that raw material consumption is the most relevant environmental impact category for this study.

Per the BASF EEA Methodology, individual raw materials are weighted according to their available reserves and current consumption profile. These weighting factors are appropriate considering the context of this study. As to be expected and indicated in Figure 10, oil is the most significant resource consumed. Though it is the largest resource used by weight, the lower relative weighting applied to the aggregate compared to oil, allows the
aggregate to have a much lower overall weighting. As highlighted above, the emulsified chip seal alternatives utilize less oil and natural gas over the life cycle to achieve the same desired performance and profile of the road relative to the non-emulsified GTR chip seal. Titanium, a scarce resource, is a noticeable resource being consumed due to its use as a pigment material in the lane striping.

![Figure 9. Raw Material consumption by Module.](image)

![Figure 10. Raw Material consumption by Type.](image)

8.1.3. Air Emissions.

8.1.3.1. Greenhouse Gases (GHG): Figure 11 shows that the highest carbon fingerprint occurred in the GTR chip seal alternative, with a measurement of nearly 190,150 kg of CO₂ equivalents per customer benefit. The SBR modified, emulsified chip seal had the lowest carbon footprint, which resulted in the emission of around 126,600 kg of CO₂ equivalents per customer benefit. This is almost a 35% reduction. The higher GHG emissions for the GTR chip seal are primarily a result of the increased energy required to produce and store the material in addition to the additional energy required to pre-coat the aggregate.
The lane striping material is also a significant contributor to greenhouse gases for all alternatives due to the emissions related to the manufacture of the epoxy resin.

8.1.3.2. **Photochemical ozone creation potential (smog):** The lowest contributor to ground level ozone creation potential occurs for the SBR modified chip seal. Figure 12 shows that POCP is highest for GTR chip seal alternative because of the extra energy requirements noted previously. The use/combustion of the additional fuel/energy contributes to the emissions of methane and non-methane VOCs.

8.1.3.3. **Ozone depletion potential (ODP):** All of the alternatives result in a minimal ozone depletion potential, measured at about 135 g CFC equivalents per customer benefit. Figure 13 indicates that the ODP comes predominately from the pre-chain chemistries involved in the precursor materials used in the thermoplastic striping material used in the road markings. Overall, ODP is the least relevant air emission and accounts for less than 0.5% of the total environmental impact for each of the systems.
8.1.3.4. **Acidification potential (AP):** It can be seen from Figure 14 that overall, emulsified chip seal alternatives have significantly lower acidification potential over the entire life cycle than the hotter GTR chip seal, with emissions of around 1,000 kg of SO₂ equivalents per customer benefit. The GTR chip seal alternative has the highest acidification potential, with emissions of 1,840 kg of SO₂ equivalent per customer benefit. This large difference in acidification potential primarily results from NOₓ, and SOₓ generated during the burning of the fuel oil for the heating of the aggregate and asphalt for pre-coating as well as the overall hotter temperatures required during production and storage of the GTR chip seal.

Utilizing the calculation factors shown in Figure xx, Figure 15 shows the normalized and weighted impacts for the four air emissions categories (GWP, AP, POCP and ODP) for each alternative. Mostly attributable to its significantly higher acidification potential, the GTR chip seal has the highest overall air emissions.
8.1.4. **Water emissions.** Figure 16 displays that overall water emissions is equivalent for all alternatives since the predominate impact comes from the line striping. These specific water emissions are attributed to the hydrocarbons, COD and Cl⁻ emissions generated during the manufacture of the thermoplastic striping material, specifically the epoxy resins. Excluding the impact of the road markings, the remaining water emissions for each alternative are also similar with the emissions related to the fiber reinforcement being the only differentiator.

![Figure 15. Overall Air Emissions](image)

8.1.5 **Solid waste generation.** Solid waste emission categories considered for this study included municipal, special, construction and mining wastes. Solid waste emissions for each alternative are depicted below in Figure 17 and are mostly the result of material sent to landfill (disposal module). This impact relates directly to the total weight of the alternatives and how much can be recycled. Material sent to landfill does take into consideration that 90% of the pavement materials can be recycled in some form. The GTR chip seal has the lowest impact in this category as it is given a significant credit for diverting tires from landfill and incorporating them into the product. This resulted in an overall reduction in solid waste generation over the life cycle of the GTR chips seal relative to the emulsified alternatives of over 20%.

![Figure 16. Water emissions.](image)
Utilizing the calculation factors shown in Figure 31, a composite of the cumulative impact of the three main emission areas of air, water and solid waste is depicted in Figure 18. GTR chips seal scores higher overall and has the highest score for air emissions, though it did have the lowest score for solid waste emissions.

8.1.6 Land use. As displayed in Figure 19, energy required for the aggregate pre-coating and the production and storage of the non-emulsified chip seal with GTR is the largest contributor to land use. Mining wastes (aggregate production) as well as solid waste disposal of the materials not recycled also contribute. Overall the chip seal with GTR alternative utilizes about two and half times more land than the emulsified chip seal alternatives which all scored about the same.
8.1.7 **Toxicity potential.** The toxicity potential for the various pavement preservation alternatives was analyzed for the production, use and disposal phases of their respective life cycles. For the production phase, not only were the final products considered but the entire pre-chain of chemicals required to manufacture the products were considered as well. Human health impact potential in the Use phase consists of the material applications (e.g. asphalt, lane striping, fiberglass). Toxicity potential in the Disposal phase comes from the removal and transport of the materials to a landfill or other end-of-life destination. Nanoparticles were not included in the chemical inputs of any of the alternatives.

Inventories of all relevant materials were quantified for the three life cycle stages (production, use and disposal). Consistent with our methodology’s approach for assessing the human health impact of these materials (ref. Section 6.8 of Part A submittal), a detailed scoring table was developed for each alternative broken down per life cycle stage. This scoring table with all relevant material quantities considered as well as their R-phrase and pre-chain toxicity potential scores were provided to NSF International as part of the EEA model which was submitted as part of this verification. Figure 20 shows how each module contributed to the overall toxicity potential score for each alternative. The values have been normalized and weighted. The toxicity potential weightings for the individual life cycle phases were production (20%), use (70%) and disposal (10%). These standard values were not modified for this study from our standard weightings.

As to be expected the application of the materials (binder, asphalt, striping material) as well as the higher weighting placed on the exposure during the use phase contributed the largest amount to the toxicity potential for each alternative. As the materials themselves are quite similar or identical in the case of the striping material, the main difference between the alternatives is thus the quantity of materials applied. As described in section 6.1.2 (Application Inputs), the application amount of the emulsified chip seals is significantly higher (0.43 gal/yd² vs. 0.345 gal/yd²) than that recommended for the GTR chip seal. Though this extra amount is attributed mostly to the water content in the emulsified alternatives, overall it still contributes to a higher mass of material being applied.
and thus a higher score for the emulsified alternatives relative to the GTR chip seal. As the Use phase is appropriately given higher weighting than the other life cycle stages, this distinct difference in application amounts, allows the GTR chip seal to score lowest in the Use phase as well as overall in the Toxicity Potential impact category. Production of the binder and road markings as well as the impacts from disposal also contribute but are mostly equivalent for all alternatives.

Figure 21 shows how the scoring is distributed across the life cycle stages. Consistent with the discussion above, the Use phase is the most significant, followed by the production and the final disposal. A high safety standard was assumed for the manufacturing processes for the raw materials. For the Use phase, an allowance was made to take into consideration the open nature of the application process. Finally, no reduction in the scores based on exposure conditions was applied for the disposal phase of the materials as the potential for human contact during removal and disposal of the materials is high.

8.1.8. Risk (Occupational Illnesses and Accidents potential):
All the materials and activities accounted for in the various life cycle stages were assigned specific NACE codes. NACE (Nomenclature des Activités Economiques) is a European nomenclature which is very similar to the NAICS codes in North
America. The NACE codes are utilized in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the business economy and is broken down by specific industries. Specific to this impact category, the NACE codes track, among other metrics, the number of working accidents, fatalities and illnesses and diseases associated with certain industries (e.g. chemical manufacturing, petroleum refinery, inorganics etc.) per defined unit of output. By applying these incident rates to the amount of materials required for each alternative, a quantitative assessment of risk is achieved.

In Figure 22, the greatest Occupational Illnesses and Accident potential occurs for the non-emulsified chip seal with GTR. The module which contributes to the highest risk potential for occupational illnesses and accidents is the aggregate, by far the largest single resource used in the alternatives. The construction time required to apply the alternatives (though equivalent for each alternative) exposes the construction workers to a high risk of construction related injuries and fatalities. Road Markings and the higher production and storage temperatures required by the chip seal with GTR alternative also contribute.

This study put a 10% weighting on a risk category associated with the risk of burns, fires and injuries related to the production and application temperatures for each alternative. Figure 23 shows the normalized and weighted overall risk category score for each alternative with this additional impact considered. Naturally, as the production, storage and application temperatures are much higher for the chip seal with GTR compared to the colder emulsified alternatives (see section 5.3 System boundaries; Figures 4-7), the GTR chip seal alternative scores highest in this specific risk category as well as overall.

Figure 22. Risk Potential (Occupational Illnesses and Accidents) - per module
8.1.9. *Environmental fingerprint.* Following normalization, or normalization and weighting with regards to the emissions categories, the relative impact for all six of the main environmental categories for each alternative is shown in the environmental fingerprint (Figure 24). Chip Seal with GTR has the highest environmental impact on a weighted basis in all of the main categories except toxicity potential. In addition, it also perform better than the other emulsified chip seals in the solid waste emission subcategory. All the emulsified chip seals performed similarly in all of the main categories on a weighted basis with the fiber reinforced alternative having slightly higher impacts. The emulsified alternatives differentiation themselves and demonstrate about a 15% overall lower environmental impact relative to the chip seal with GTR due to their requirements for lower production, storage and application temperatures while still maintaining the desired road characteristics and performance.

8.2. *Economic Cost Results.*

The life cycle cost data for Micro Surfacing EEA are generated as defined in Section 7 of the BASF EEA methodology and described in section 6.3 above. As highlighted in section 6.3.3 the study considered the time value of money and calculated the net present value of future costs. The results of the life cycle cost analysis and depicted in Table 5 and Figure 24 found that the alternatives with the lowest life cycle costs were the SBR and SBS modified chip seals and the alternative with the highest life
cycle cost was the fiber reinforced chip seal. Differences in overall life cycle costs were driven predominately by the chip seal material cost. Current average pricing was obtained from both customers and manufacturers. The fiber reinforced chip seal alternative is priced at a premium above the traditional CRS-2P chip seals.

Material costs, which also include the labor charges associated with the installation, are obviously the main contributor to the overall life cycle costs. Representative average material costs were obtained for each alternative from multiple manufacturers. The costs compare favorable to the range of costs cited in a recent presentation by Sorenson and Galehouse\(^9\). They quote a recent project with an average chip seal cost of around $2,800 / lane-mile * year. This was based on a 5 year life extension. If a life extension of 6 years was assumed (the basis for our analysis), the cost would drop to around $2,300 / lane-mile * year. For our study, which considered a 40 year life cycle and an average life extension of 6 years, the lane-mile costs ranged from $2,250 - $2,500.

<table>
<thead>
<tr>
<th>LIFE CYCLE COSTS</th>
<th>GTR</th>
<th>Fiber Reinforced</th>
<th>SBR Modified</th>
<th>SBS Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip Seal Material Cost</td>
<td>$1/yd2</td>
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<td>$2.63</td>
<td>$2.36</td>
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<tr>
<td>Pavement Costs</td>
<td>$/CB</td>
<td>$67,519</td>
<td>$64,842</td>
<td>$64,898</td>
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<td>Stripping Material Cost</td>
<td>$/CB</td>
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<td>$15,633</td>
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<tr>
<td>Lane Rental Fees</td>
<td>$/CB</td>
<td>$15,481</td>
<td>$15,481</td>
<td>$15,481</td>
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<tr>
<td>Total Cost</td>
<td>$/CB</td>
<td>$81,598</td>
<td>$89,076</td>
<td>$89,218</td>
</tr>
</tbody>
</table>

Table 5: Life cycle costs

8.3. *Eco-efficiency Analysis Portfolio.*

The eco-efficiency analysis portfolio for the Chip Seal EEA has been generated as defined in Section 9.5 of the BASF EEA methodology. Utilizing relevance and calculation factors, the relative importance of each of the individual environmental impact categories are used to determine and translate the fingerprint results to the position on the environmental axis for each alternative shown. For a clearer understanding of how weighting and normalization is determined and applied please reference Section 8 of BASF's Part A submittal to P-352. Specific to this study, the worksheets “Relevance” and “Evaluation” in the EEA model provided to NSF as part of this verification process should be consulted to see the specific values utilized and
how they were applied to determine the appropriate calculation factors. Specific to the choice of environmental relevance factors and social weighting factors applied to this study, factors for the USA (national average) were utilized. The environmental relevance values utilized were last reviewed in 2007 and the social weighting factors were recently updated in 2009 by an external, qualified third party organization.

Figure 26 displays the eco-efficiency portfolio for the base case analysis and shows the results when all six individual environmental categories are combined into a single relative environmental impact and combined with the life cycle cost impact. Because environmental impact and cost are equally important, the most eco-efficient alternative is the one with the largest perpendicular distance above the diagonal line and the results from this study find that the SBS and SBR modified chip seals are the most eco-efficient alternatives due to their combination of lower environmental burden and having the lowest life cycle costs. The fiber reinforced alternative is about 8% less eco-efficient and the hot chip seal with GTR 13% less eco-efficient than the leading alternatives. Though higher in life cycle costs, the fiber reinforced alternative is more eco-efficient than the GTR alternative due to its much lower environmental impact.

8.4. Scenario Analysis:

8.4.1. Scenario #1: Increased Durability for Fiber Reinforced Alternative:

Fiber, specifically fiberglass, reinforced chip seals, are stand alone pavement preservation surface treatments, specifically designed to not only provide a waterproof membrane but also absorb pavement stresses that lead to cracking,
reflected or generated in the pavement better than conventional chip seals. This is accomplished by reinforcing the conventional modified asphalt emulsion with engineered fiberglass strands. A typical cross section of the process by one leading manufacturer\textsuperscript{22} is provided in Figure 27. University research and field tests\textsuperscript{22} have confirmed that pavement life can be extended with fiber reinforced chip seals relative to conventional chip seal applications. As this technology is a relatively new innovation in the marketplace, extensive, long term (> 8 year) field data does not exist however current field tests\textsuperscript{22} indicated that additional life extension relative to conventional chip seals should be expected. This scenario looks at the impact, one year of additional life extension (7 years vs. base case 6 years), will have on the eco-efficient positioning of the fiber reinforced alternative.

As expected for this scenario analysis, with a minimum 7 year durability, the fiber reinforced chip seal saw a significant improvement in its environmental profile and life cycle cost. In contrast to the results shown in Figure 26, the fiber reinforced alternative now achieves both the lowest life cycle cost and the lowest environmental impact (Figure 28). The one year enhancement in durability has reduced the fiber reinforced alternatives overall life cycle cost by almost 13%.

\textbf{Figure 27.} Cross Section of Fiber Reinforced Chip Seal\textsuperscript{22}

\textbf{Figure 27.} Environmental Fingerprint, Scenario #1 Chip Seal Eco-efficiency study
9. Data Quality Assessment

9.1. Data Quality Statement: The data used for parameterization of the EEA was sufficient with most parameters of high data quality. Moderate data is where industry average values or assumptions pre-dominate the value. No critical uncertainties or significant data gaps were identified within the parameters and assumptions that could have a significant effect on the results and conclusions. The Eco-profiles utilized were deemed of sufficient quality and appropriateness considering both the geographic specificity of the study as well as the time horizon considered. Table 7 provides a summary of the data quality for the EEA.
Table 7: Data quality evaluation for EEA parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quality Statement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Binder Formulation</td>
<td>High</td>
<td>Known formulations from manufacturer. Eco-profiles developed specifically for this study are based on current technologies and company data.</td>
</tr>
<tr>
<td>Tack Coat Formulation</td>
<td>High</td>
<td>Known formulation based on current industry data.</td>
</tr>
<tr>
<td>Production and Application Impacts</td>
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<td>External life cycle analysis by Swedish IVL Research Institute.</td>
</tr>
<tr>
<td>Application Rates</td>
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<td>Industry guidelines. Assumed values are reasonable given study context and goals.</td>
</tr>
<tr>
<td>Waste Parameters</td>
<td></td>
<td></td>
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<tr>
<td>Disposal methods</td>
<td>Moderate-High</td>
<td>Assumed method and values are reasonable given study context and goals.</td>
</tr>
<tr>
<td>Transportation Distances</td>
<td>Moderate-High</td>
<td>Assumed values are reasonable given study context and goals.</td>
</tr>
<tr>
<td>Distance and fuel consumption</td>
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<td>Assumed values are reasonable given study context and goals.</td>
</tr>
<tr>
<td>Durability</td>
<td>High</td>
<td>State Agency survey by 3rd party. Manufacturers/Customer</td>
</tr>
<tr>
<td>Costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pavement Preservation Technology</td>
<td>High</td>
<td>Supplier provided data.</td>
</tr>
<tr>
<td>Disposal Costs</td>
<td>Moderate-High</td>
<td>Current price for region of study. Assumed values are reasonable given study context and goals.</td>
</tr>
<tr>
<td>Lane Rental Fees</td>
<td>Moderate-High</td>
<td>Recommendation from industry literature.</td>
</tr>
<tr>
<td>Lane Striping Fees</td>
<td>High</td>
<td>Supplier provided data.</td>
</tr>
</tbody>
</table>

10. Sensitivity and Uncertainty Analysis

10.1. Sensitivity and Uncertainty Considerations:

A sensitivity analysis of the final results indicates that the environmental impacts were more influential or relevant in determining the final relative eco-efficiency positions of the alternatives. This conclusion is supported by reviewing the BIP Relevance (or GDP-Relevance) factor calculated for the study. The BIP Relevance indicates for each individual study whether the environmental impacts or the economic impacts were more influential in determining the final results of the study. For this study, the BIP Relevance indicated that the environmental impacts were significantly more influential in impacting the results than the economic impacts (reference the “Evaluation” worksheet in the Excel model for the BIP Relevance calculation). The main assumptions and data related to environmental impacts were:

- Durability
Application Rates

Energy Intensities for Asphalt Manufacturing / Storage / Application

As the data quality related to these main contributors were of high to moderate high quality, this strengthened our confidence in the final conclusions indicated by the study. A closer look at the analysis (see Figure 29) indicates that the impact with the highest environmental relevance was resource consumption followed by energy and toxicity potential. This is to be expected, as the quantity of raw or recycled materials required by our alternatives to fulfill the customer benefit drive the overall study results. Air and water emissions are by far the most important in the emissions category. More specifically, AP and GWP are considered the two most important air emissions. The calculation factors (Figure 31), which considers both the social weighting factors and the environmental relevance factors, indicate which environmental impact categories were having the largest affect on the final outcome. Calculation factors are utilized in converting the environmental fingerprint results (Figure 24) into the final, single environmental score as reflected in our portfolio (Figure 26). The impacts with the highest calculation factors were the same as those with the highest environmental relevance factors, with regards to the six main impact categories. The input parameters that were related to these impact categories have sufficient data quality to support a conclusion that this study has a low uncertainty. The social weighting factors (Figure 30) considered for this study did influence some minor reprioritization of the impact categories represented in the emissions and air emissions sub-categories. Water emissions increased importance relative to air emissions, and the impact of GHG received higher relative weighting for the air emissions.

![Environmental Relevance factors that are used in the sensitivity and uncertainty analyses.](image)

**Figure 29.** Environmental Relevance factors that are used in the sensitivity and uncertainty analyses.
Figure 30. Societal weighting factors that are used in the sensitivity and uncertainty analyses.

Figure 31. Calculation factors that are used in the sensitivity and uncertainty analyses.
10.2. **Critical Uncertainties:**

There were no significant critical uncertainties from this study that would limit the findings or interpretations of this study. The data quality, relevance and sensitivity of the study support the use of the input parameters and assumptions as appropriate and justified.

11 **Limitations of EEA Study Results**

11.1. **Limitations.**

These eco-efficiency analysis results and its conclusions are based on the specific comparison of the production, use, and disposal, for the described customer benefit, alternatives and system boundaries. Transfer of these results and conclusions to other production methods or products is expressly prohibited. In particular, partial results may not be communicated so as to alter the meaning, nor may arbitrary generalizations be made regarding the results and conclusions.

12 **References**


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20 “Reducing and Mitigating Impacts of Lane Occupancy During Construction and Maintenance”  A Synthesis of Highway Practice  Transportation Research Board NCHRP Synthesis 293 Table 7 page 27.


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http://www.tirerecyclingcrumbrubbershredder.com/shredder.html

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