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Realistic Traffic Condition Informed Life Cycle Assessment: Interstate 495 Maintenance and Rehabilitation Case Study

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Abstract: As construction costs continue to rise and adequate amounts of funding continues to be a challenge, the allocation of resources is of critical importance when it comes to the maintenance and rehabilitation (M&R) of highway infrastructure. A Life Cycle Assessment (LCA) methodology is presented here that integrates realistic traffic conditions in the operational phase to compare M&R scenarios over the analysis period of a 26-km stretch of Interstate-495. Pavement International Roughness Index (IRI) were determined using American Association of State Highway and Transportation Officials (AASHTO) PavementME System. Meanwhile, vehicle fuel consumption and emission factors were calculated using a combination of Google Maps®, the United States Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator, the second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study, and MassDOT's Transportation Data Management System. The evaluation of pavement performance with realistic traffic conditions, varying M&R strategies, and material characteristics was quantified in terms of Life Cycle Cost (LCC), Global Warming Potential (GWP), and Cumulative Energy Demand (CED) for both agencies and users. The inclusion of realistic traffic conditions into the use phase of the LCA resulted in a 6.4% increase in CED and GWP when compared to baseline conditions simulated for a week long operation duration. Results from this study show that optimization of M&R type, material selection, and timing may lead to a 2.72% decrease in operations cost and 47.6% decrease in construction and maintenance costs.

Keywords: pavement; LCA; LCCA; asphalt; realistic traffic conditions; rehabilitation

1. Introduction

The United States road infrastructure received a report card grade of a D from the American Society of Civil Engineers (ASCE) in 2017 [1]. ASCE reported 6.9 billion hours of delay in traffic, equating to an average of 42 h of delay per driver [1]. In addition to traffic delays, TRIP (a private nonprofit organization that researches, evaluates, and distributes economic and technical data on surface transportation issues) reported that 44% of the nation's highways were in poor or mediocre condition in 2018, causing U.S. road users $130 billion ($599 per driver) in extra vehicle repairs and operating costs [2]. In general, current practice of pavement design and maintenance and rehabilitation (M&R) plans are based on performance and economic factors, while neglecting environmental impacts. Furthermore, the majority of cost impacts of the roadway M&R decisions are driven by agency costs only, neglecting the impacts incurred by road users. There is a growing need to perform a life cycle assessment (LCA) and life cycle cost analysis (LCCA) as part of the decision process to ensure that resources, time, and money are being allocated efficiently to maintain highway infrastructure systems.

A holistic approach to pavement management should incorporate a balance of costs (both user and agency) and environmental impacts. Furthermore, the costs and environmental impacts should be assessed over the life-time of a roadway by incorporating traffic (both volumes and flow characteristics), pavement materials and their performances through lab or field measured properties, reliable pavement performance evolutions (such as changes in pavement roughness with time), and maintenance and rehabilitation treatments and their impacts on pavement performance evolutions. Often times a non-holistic approach is adopted for pavement management systems that either only focuses on life cycle costs or does not account for operational (user) costs. Moreover, the majority of these approaches do not have the necessary physical relationships to link factors such as congestions or slow-downs to impact calculations.

Incorporating an LCA-LCCA approach into the pavement design and M&R process will help to improve the pavement management of highway infrastructure systems [3–5]. It will also help to identify explicit and implicit costs incurred by both agencies and users. To date there has been an extensive amount of recent research focused on the development of LCA frameworks for pavements, which can be attested by a series of Pavement LCA symposia (2010, 2012, 2014, and 2017) and the corresponding compilation of proceedings [6–9]. Transportation agencies are also increasingly becoming aware and involved in the development of LCA tools for pavements. For example, the U.S. Department of Transportation and Federal Highway Administration (FHWA) recently released a pavement LCA framework document in an effort to aid the implementation and adoption of LCA principles in the pavement design process [10]. In addition to the LCA framework, this report also provided guidance on the overall approach, methodology, system boundaries, and identified current knowledge gaps in pavement LCA. The report also identified current research gaps in the LCA framework, including topics such as traffic delay, rolling resistance, pavement albedo, and end of life allocation.

A study in 2018 focused on the development of an integrated LCA-LCCA framework to aid in the decision making process for pavement M&R activities during the entire pavement life cycle [5]. It was concluded in the study that material, construction-related traffic congestion, and pavement surface roughness effects are three major contributors to energy consumption and greenhouse gas (GHG) emissions for pavement M&R activities [5]. When considering a high-traffic-volume highway, such as Interstate 495, which was selected as the case study location, energy and GHG savings accumulated during the use phase of the LCA due to rolling resistance can become even more significant compared to the energy use and GHG emissions from material production and construction in pavement M&R activities. Several other studies have shown the effect of pavement roughness on vehicle operation costs in terms of extra fuel consumption, vehicle repairs and maintenance, and tire wear during the use phase of the LCA [3,11–14].

The motivation of this study is to use a LCA-LCCA approach to evaluate pavement performance over the design life with the inclusion of realistic traffic conditions, different pavement M&R alternatives, and pavement material characteristics. Building upon a study performed by DeCarlo et al. in 2017, where a section of interstate highway in the New England region was selected to investigate the impact pavement structure and M&R treatment timing, the present study aims to include realistic traffic conditions in the operational phase of a pavement LCA [15]. The study presented herein has three primary objectives: (1) to perform a LCA on an interstate highway with the implementation of real time traffic data (RTTD) and M&R strategy decisions to optimize performance over a given pavement analysis life; (2) to evaluate pavement performance with realistic traffic conditions, varying M&R strategies, and material characteristics in terms of Life Cycle Cost (LCC), Global Warming Potential (GWP), and Cumulative Energy Demand (CED) for both agencies and users; and (3) to quantify the increase in fuel consumption and resulting emissions due to decrease in ride quality (as expressed by the International Roughness Index, IRI) caused by accumulated distress and pavement degradation over the analysis period. Ultimately, when an LCA-LCCA approach is utilized, pavement performance over a given analysis period can be optimized to determine a cost-effective and eco-friendly pavement M&R plan [5].

In the subsequent sections a brief summary of the materials and methods utilized in this study are presented. Information regarding the selection of the case study location, details relating to the construction, use, and M&R phase of the LCA are discussed followed by key results and a sensitivity analysis of select variables. Lastly, a discussion of the LCA results is presented and the importance of incorporating realistic traffic conditions into the LCA framework is demonstrated.

2. Materials and Methods

2.1. Case Study Location

A 26 km section of Interstate I-495 in Massachusetts was analyzed, from Chelmsford to Methuen, as shown in Figure 1. This section of interstate was selected as it consists of a high volume of commuter traffic. Temporal traffic volume data on this interstate section were collected from the Massachusetts Department of Transportation (MassDOT, Boston, MA, USA) data management system [16]. Interstate I-495 consists of 3 lanes in each direction, with a distributional factor of 50% (of 24-h peak volume). The annual average daily traffic (AADT) was approximately 121,000 vehicles. Of this volume, the business commercial vehicles (FHWA Class 4 and above) consisted of 9243 (8%) vehicles (detailed traffic distribution is provided in Appendix A.3).

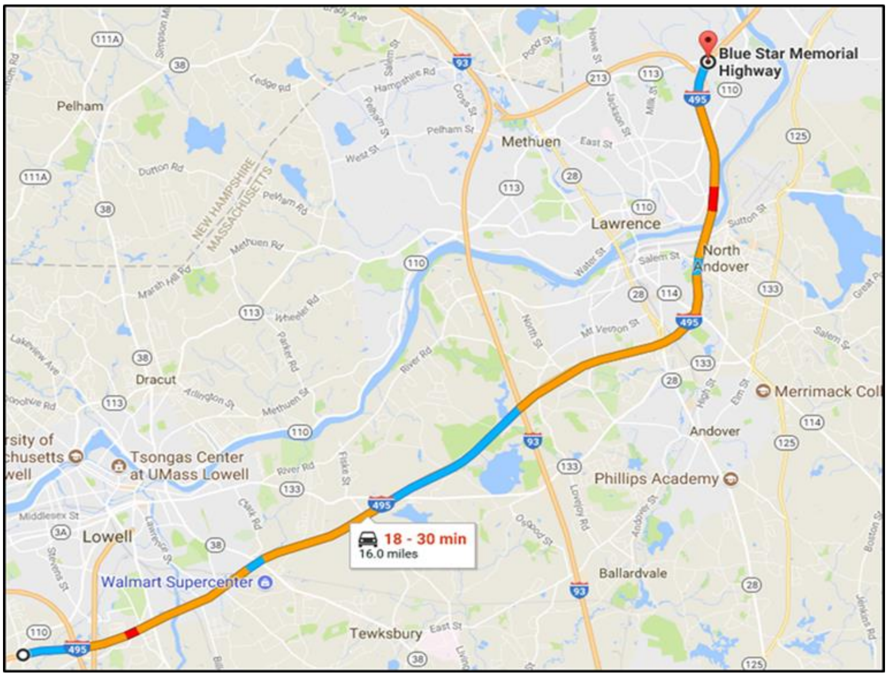

Figure 1. Map of 25.7 km roadway on I-495 from Chelmsford to Methuen, Massachusetts [17].

2.2. General Methodology

A typical pavement LCA system boundary includes raw materials and excavation, material transportation, construction, operation and maintenance, and end-of-life. In this study, a focus was placed on the initial construction, use, and maintenance phases from both an agency and user perspective. The end-of-life phase was neglected because of the challenges associated with accurately accounting for reclaimed asphalt pavement (RAP) material and its impacts beyond the analysis period of the given section of I-495 being investigated as part of this study. Three types of impacts were investigated: life cycle cost, cumulative energy demand (CED), and global warming potential (GWP). Figure 2 describes the general process of the LCA-LCCA approach that was followed. In the subsequent sections, the construction phase, use phase, and the M&R strategies are described in greater detail.

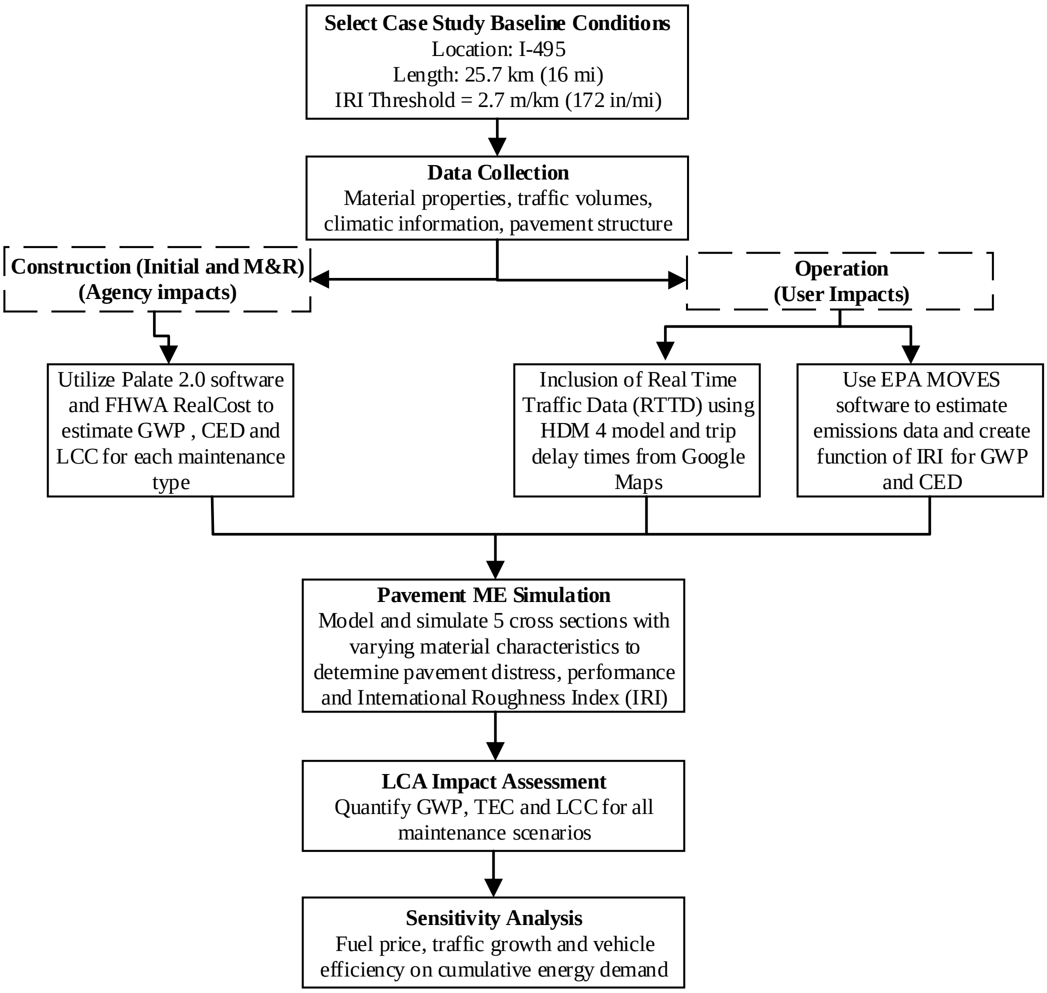

Figure 2. Flow chart of life cycle assessment (LCA) case study.

As shown in Figure 2, once the case-study location was identified the first step in the process involved collection of various spatial and temporal data that are necessary to capture various facets of the LCA process. The analysis was divided into two primary phases of activities for pavements: (1) Construction (initial, M&R), and (2) Operation. Construction activities included in the analysis are initial construction, maintenance, rehabilitation, and reconstruction. The operational phase analysis was conducted using both steady-state and realistic traffic conditions. Impacts of pavement roughness on various life time impacts and costs were included in the analysis. Lastly, a sensitivity analysis was conducted to assess effects of changing traffic volume, vehicle fuel efficiencies, and fuel prices over the course of analysis duration.

2.2.1. Construction Phase: Materials and Pavement Cross-Sections

An inventory of raw materials required to construct the 26-km stretch of road was developed based upon typical New England mixture characteristics. The various cross-sections are comprised of a combination of a wearing or surface course, binder course, base course, granular base, and subgrade. Base and subbase layer designs were held constant, while five different surface courses with varying material properties were evaluated as part of this study (Table 1). Therefore, each simulated cross-section had the same overall thickness on top of the existing subgrade (105 cm)—the factor that varied was the surface course material properties. The materials chosen for surface course represent typical asphalt mixtures and binders used in the New England region [18].

Table 1. Summary of materials used in simulated pavement cross-sections.

Mixture Name	Course Description	Layer Thickness (cm)	Asphalt Binder Type	Amount of Recycled Asphalt Pavement in the Mix (% by Total Weight of Mix)
ARGG-1	Surface	5	PG 58-28	10
ARGG-2	Surface	5	PG 58-28	0
T-1	Surface	5	PG 64-28	19.3
THS-1	Surface	5	PG 76-28	19.3
SHM-1	Surface	5	PG 70-34	0
B-1	Binder	20	PG 64-28	25
BB-1	Base	20	PG 64-28	25
GB	Granular Base	60	-	-

Each cross-section design will present its own unique degradation trajectory, which is further modeled through Pavement ME by altering the material properties of the asphalt layer. The baseline unit raw material and construction impacts and costs associated with each process were obtained from two LCA software programs, Simapro 8.3 and the Pavement Life-Cycle Assessment Tool (PaLATE 2.0) [19,20]. Further detailed information on the inventory unit impacts is provided in Appendix A.1. Transportation distances of the materials were quantified based upon the manufacturers' locations, contracted out by the Massachusetts Department of Transportation (MassDOT) for previous pavement projects. It was assumed that the transportation distance from the plant to the job site location was 10 miles.

2.2.2. Construction Phase: Maintenance and Rehabilitation

A total of 6 M&R strategies were compared in this study using a combination of Pavement ME design software and existing literature on the impacts of M&R strategies on IRI. Typical surface treatments, such as crack sealing and microsurfacing, were included as pavement preservation or pavement maintenance strategies, while common pavement rehabilitation strategies, including cold-in-place recycling and mill and overlay, were explored.

Initial and terminal IRI values were set based on Pavement ME default values of 1 m/km and 2.7 m/km, respectively. As it is commonly recommended for pavement life cycle cost analysis [21], a minimum of 3 full maintenance cycles for each type of M&R was used in the analysis prior to selecting the terminal year of the analysis period. This was done to ensure that a sufficiently long analysis period was used to make a relatively fair comparison among different M&R strategies, specifically when converting various costs to net present value (NPV) and equivalent annual costs (EAC). The analysis periods vary from 92 to 135 years depending on the type of M&R and cross-section material properties. A brief description of each M&R alternative is listed below.

- **Do nothing and reconstruct (DNR):** The first M&R scenario is simply the choice to perform no maintenance or rehabilitation and to reconstruct at the end of the pavement system's service life (reached the terminal IRI). The pavement performance curves in terms of IRI and time for this scenario are determined using Pavement ME.
- **Crack sealant (CS):** The next M&R alternative evaluated the use of a crack sealant every two years during the service life of the pavement until the terminal IRI value was reached and the pavement system was reconstructed. Crack sealant is a common preventative maintenance treatment to fill cracks at the surface of the pavement structure to prevent water from infiltrating. It was found in literature that the overall pavement service life is extended by 2 years when applying crack sealant as a pavement preservation technique [22]. For simplicity, it was assumed that the pavement continues to deteriorate at the same rate after applying the crack sealant treatment but a two-year extension of the service life was applied before reaching the terminal IRI trigger value. It should also be noted that crack sealant is a preservation treatment and does not address structural issues, as a M&R strategy does.

- **Microsurfacing (MS 2.2 m/km):** Microsurfacing was applied when an IRI trigger value of 2.2 m/km was reached. Microsurfacing is a common M&R treatment type that applies a mixture of water, asphalt emulsion, aggregate, and chemical additives to an existing asphalt pavement surface in order to preserve the underlying pavement structure. It provides a new pavement driving surface, and according to a study by MnDOT, it resets the IRI by approximately 0.7 m/km [23]. A type III microsurface was molded in this study. It should be highlighted that microsurfacing is a pavement preservation treatment and does not address underlying structural issues.
- **Microsurfacing (MS 2.5 m/km):** Microsurfacing was applied when an IRI trigger value of 2.5 m/km was reached. Once again, IRI was reset by approximately 0.7 m/km [23].
- **Cold-In-Place (CIR) Recycling**: CIR is a pavement rehabilitation technique that involves reclaiming 50 mm to 100 mm of the existing pavement structure. It is a similar process to cold plant mix recycling, except that it is performed directly in the field, typically by a paving train of equipment. Once the terminal IRI value has been triggered, the CIR treatment is performed and the IRI decreases by approximately 1.1 m/km [24,25]. The simulated cross-section after CIR was performed, consisting of a 5-cm asphalt concrete (AC) surface course, 5-cm AC base course, 10-cm of cold recycled asphalt pulverized in place, and 60-cm granular base. CIR is generally being accepted as a pavement rehabilitation strategy that has the ability to address structural distresses. Pavement ME was used to determine the pavement performance curves when CIR was used as a M&R strategy.
- **Mill and Overlay (MO):** Mill and overlay of approximately 50 mm was performed once the terminal IRI value was reached. On average, the IRI is reset by (0.95 to 1.26 m/km), therefore this M&R alternative scenario reset the IRI to the initial value of 1 m/km and then allowed the pavement cross-section to reach the terminal IRI value of 2.7 m/km before reconstruction [26,27]. Reconstruction was performed after one MO treatment to avoid the impractical scenario of constant MO highway pavement systems. MO often falls in the gray area as a mix between a surface treatment or a rehabilitation strategy. For the purpose of this study, MO is considered as a rehabilitation treatment capable of addressing structural distresses. Pavement ME simulations were conducted for each cross-section with use of MO treatment to determine the pavement performance curves.

Figure 3 provides an example of the M&R timing sequence over the analysis period for the ARGG-1 cross-section. The terminal year of year 135 from the present time was determined when a minimum of 3 full cycles of each M&R strategy were completed. The M&R timing sequences for other pavement cross-sections are provided in Appendix A.2.

2.2.3. Use Phase

In order to incorporate realistic traffic conditions into the use phase of the LCA, hourly traffic congestion patterns over the course of a week on the target pavement segment from Google Maps® were obtained. A representative week of hourly congestion patterns was then repeated to form a year (52 weeks) of realistic traffic conditions. MassDOT's Transportation Data Management System was used to collect information regarding daily traffic volume for each vehicle type on the target pavement segment.

Next, acceleration and deceleration rates obtained from the SHRP 2 NDS databases were assigned to all vehicles based on the congestion condition and the expected vehicle speeds under each traffic congestion condition (Appendix A.3, Tables A3–A5) [28]. Note that same acceleration and deceleration rates were used for different vehicle classes, however the vehicle specific power for each of these classes differ and are accounted for in the emissions calculations. The Motor Vehicle Emission Simulator MOVES2014a software was used to convert the volume and pattern of traffic (i.e., vehicle type, speed, and acceleration) to GWP and CED estimates [29]. However, it should be noted that MOVES assumes constant pavement performance (highest smoothness), while the influence of pavement degradation on vehicle fuel consumption and emissions is neglected. To address this gap, pavement distresses over the design life were modelled using the Pavement ME design software for the 5 different pavement cross-section types [30]. The International Roughness Index (IRI) was used to assess pavement degradation and ride roughness. IRI measures the simulated transient vertical movement of a generic motor vehicle to the roughness in a single wheel path of the road surface, and is typically reported in meters per kilometer [31]. IRI correlates with vehicle fuel usage and the associated costs and emissions [12]. The approach taken in this paper is one of several approaches that researchers have proposed to link pavement condition to user costs; for example, Loprencipe et al. have developed relationships between pavement condition index (PCI) and vehicle operating costs (VOC) [32]. The approach adopted by authors in the current work was chosen to ensure that realistic traffic conditions can be incorporated within user cost estimates.

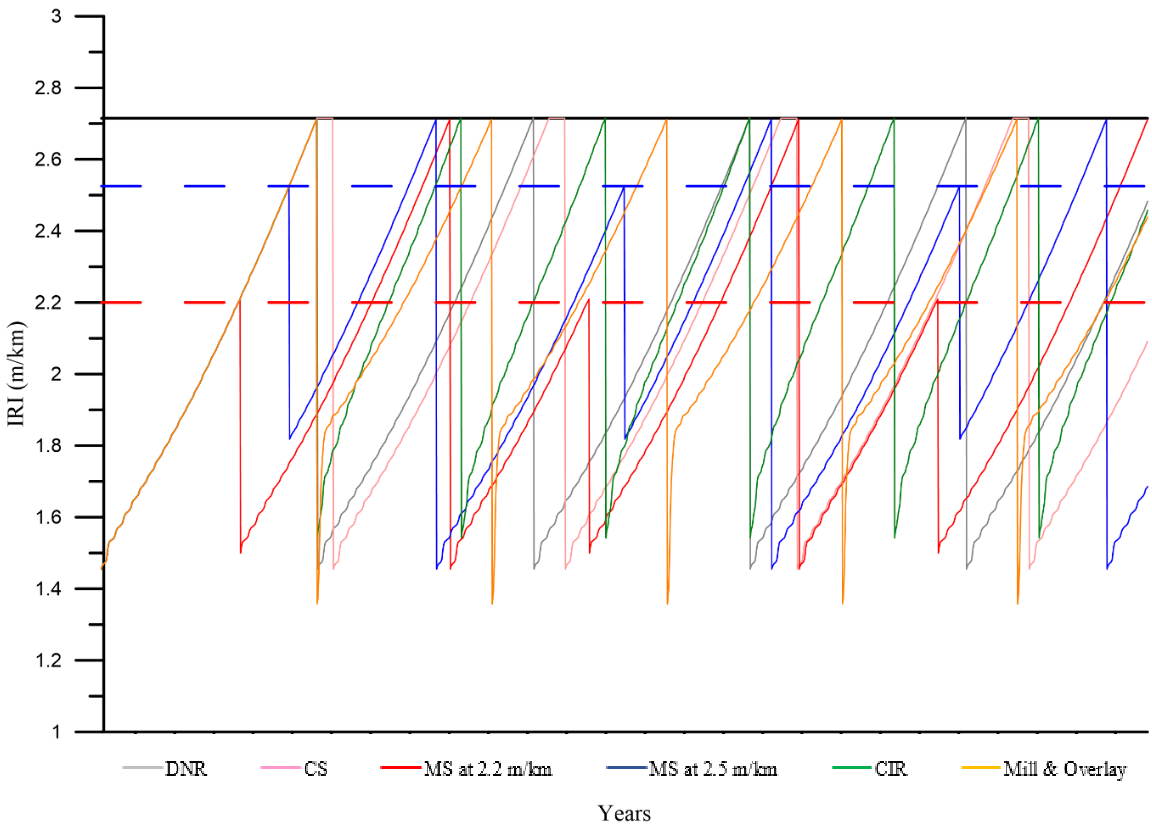

Figure 3. Example of a maintenance and rehabilitation timing sequence for ARGG-1 cross-section over the analysis period with a terminal year of 2154.

It is important to note that while M&R is being performed on the roadway it often requires lane closures. Traffic congestion may arise, resulting in an increase in emissions. These delays were not included in this study at the present time, however, the inclusion of idle time and traffic congestion from daily traffic was included. Idle time was incorporated into the results by assuming, on average, vehicles idle for 10 min per km for the 130 km of mildly congested (typically shown as red on Google Maps®) roadways per week, and for 30 min per km for the 6.6 km of highly congested (typically shown as dark red on Google Maps®) roads on I-495. By incorporating realistic traffic conditions into the use phase of the LCA, the increase in emissions due to traffic delays without consideration of lane closures was accounted for. It is recommended that the impact of lane closures be investigated further to determine the significance of M&R lane closure times associated with each strategy (i.e., lane closure time to perform crack seal versus time to perform mill and overlay) may have on the overall LCA impacts.

The inclusion of realistic traffic conditions followed a six step process. The first step used vehicle characteristics from Chatti and Zabaar [12]. Some examples of these characteristics include mass, drag coefficient, frontal area, and rolling resistance tire factors. They were then utilized in HDM-4 tractive force model equations to account for aerodynamic forces and rolling resistances [33]. The tractive forces were used to determine the vehicle specific power. Vehicle Specific Power (VSP) is a measure of a vehicle's instantaneous power per mass. VSP reveals how driving conditions affect emissions. It is a function of speed, roadway grade, acceleration, IRI, and many other variables. Since MOVES is not set-up to directly incorporate effects of IRI change on fuel usage, the results from Chatti and Zabaar were used to calibrate VSP bins for each vehicle class with respect to different pavement IRI. Once VSP bins were compiled for each variation in vehicle type, speed, and acceleration, these vehicle specific powers were used as inputs to the MOVES software.

Next, MOVES simulations were performed to obtain values of CED and GWP per length traveled. It is necessary to obtain emissions per length so they can be applied to varying traffic conditions. The MOVES outputs were then altered to allow the incorporation of the International Roughness Index (IRI). Due to the generalization of VSP Bins in MOVES software, a change in IRI does not produce a significant change in the output from MOVES for acceleration, deceleration, or idle phases. This is not unexpected, since during acceleration and deceleration the power demands associated with those activities are substantially higher than that coming directly from change in pavement roughness. Similarly, during the idle stage, there is no motion, and thus pavement surface characteristics have no impact on fuel consumption.

Lastly, the altered MOVES outputs were then combined with vehicle counts and classifications from MassDOT's Transportation Data Management System and traffic conditions from Google Maps®. This was only completed for one week of hourly traffic data because Google Maps® generalizes each week day and weekend day to have the same traffic conditions throughout the entire year. In other words, a Friday in July will have the same results as a Friday in January in terms of traffic delay estimates. Therefore, in total 168 traffic conditions were evaluated for a single week's worth of traffic on an hourly basis. The process outlined above to obtain a week's worth of traffic data was then scaled to represent the traffic conditions over the course of a year, and ultimately over the entire LCA analysis period. The implementation of RTTD was completed for both southbound and northbound directions over the 26 km stretch of roadway on I-495.

2.3. Life Cycle Cost Analysis

LCC was estimated using a discount rate of 4% and converted to net present value (NPV). A 4% discount rate was assumed in this study based on guidance from FHWA Life-Cycle Cost Analysis in the Pavement Design report that stated long-term trends for real discount rates hover around 4% and a discount rate between 3 to 5% is an acceptable range, as it is consistent with historical values in Appendix A of Office of Management and Budget (OMB) Circular A-94 [34]. Costs were converted to net present value (NPV) using Equation (1), where FV is the future value, r represents the discount rate (4%), and n is the number of years in the future the price must be brought back to present value.

$$\mathrm{NPV} = \frac{\mathrm{FV}}{(1+\mathrm{r})^{\mathrm{n}}} \tag{1}$$

2.4. Sensitivity Analysis

A sensitivity analysis on the price of fuel, traffic growth rate, and vehicle energy efficiency was performed to assess their influence on the economic performance of the LCCA. Table 2 summarizes the price of gasoline and diesel considered in the sensitivity analysis.

Traffic growth rate varied by 1%, 2%, and 3% with respect to the baseline conditions, which assumed no traffic growth. To account for the improvement in motor vehicle technology, cumulative energy demand (CED) was reduced every decade by 1%, 2%, and 3%. All pavement sections and M&R strategy combinations (24 total) were evaluated using low, current, and high fuel price values for a total of 84 scenarios.

Table 2. Gasoline and diesel prices used for three scenarios used in sensitivity analysis from U.S. Energy Information Administration (EIA) 2017 Report [35].

Scenario	Gasoline Price ($)	Diesel Price ($)
Low	1.64	1.71
Current	2.80	3.00
High	4.04	4.66

3. Results

3.1. *Effect of Realistic Traffic as Compared to Steady Speed*

First, to validate the importance of including realistic traffic conditions in the use phase of the LCA, a comparison to baseline traffic conditions was conducted. LCA results showed that using real time traffic data resulted in a 6.4% increase in CED and GWP, in comparison to baseline conditions during a given week. These percentages were based on a daily traffic count of approximately 133,000 vehicles. Therefore, the inclusion of RTTD is equivalent to accounting for the impact of an additional 8512 vehicles per day. Figure 4 highlights the difference in CED when realistic traffic conditions are included. A similar trend in GWP is observed when RTTD is included in the operations phase of the LCA.

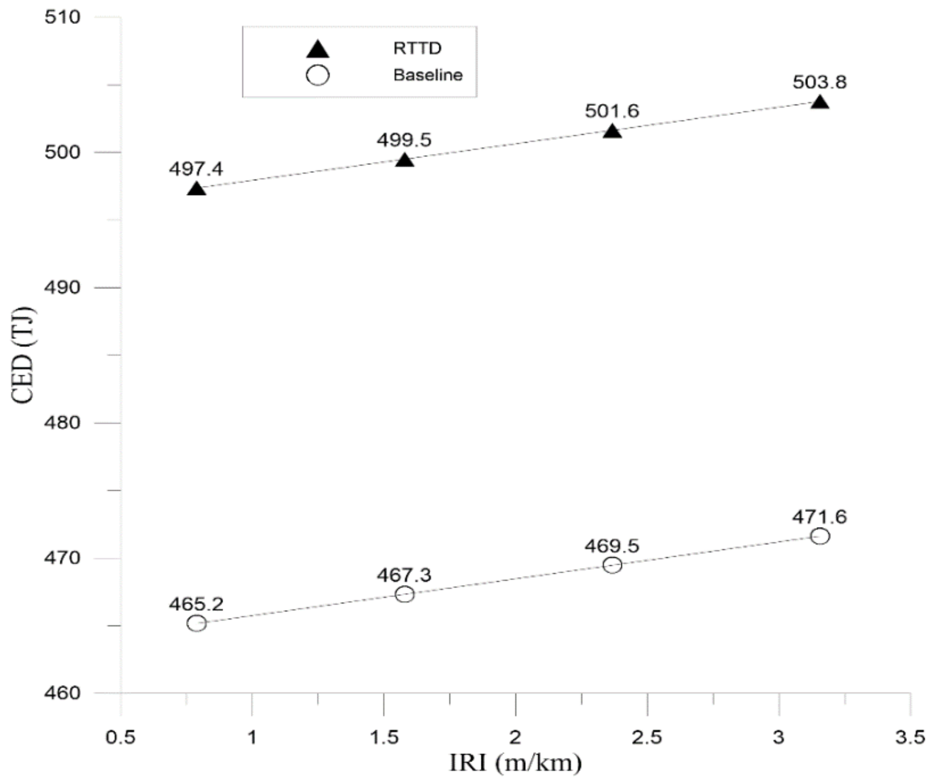

Figure 4. Comparison of baseline traffic scenario and the inclusion of realistic traffic conditions (indicated by real time traffic data).

3.2. *Overall LCA Results*

3.2.1. Global Warming Potential (GWP)

From this point on, all results are presented with the inclusion of RTTD. Figure 5a,b shows the two most contrasting cross-sections (ARGG-1 and T-1) in terms of percent difference in GWP.

User impact is represented by the solid black bars, while agency impact is shown by the grey hashed bars. Table 3 includes the results for all five cross-sections for comparison of GWP impact in terms of Gigagrams of CO_2 equivalent.

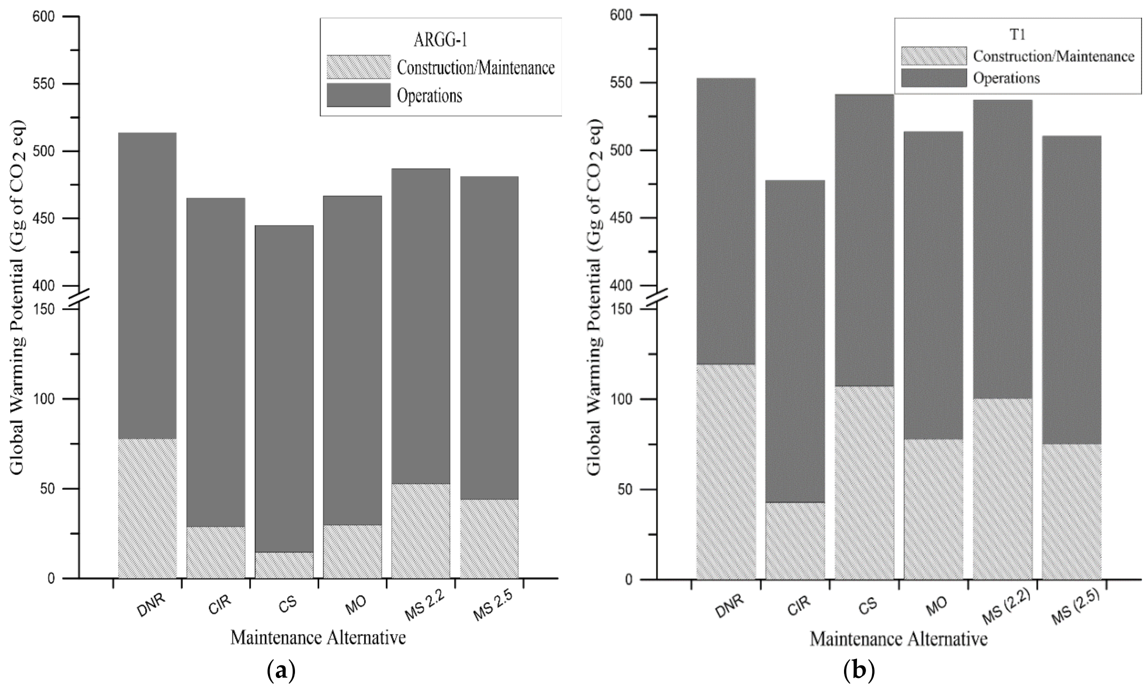

Figure 5. Global warming potential (GWP) impact broken down into construction and M&R, and operations of vehicles over LCA analysis period for (**a**) ARGG-1 and (**b**) T-1 pavement cross-sections.

Table 3. Summary of M&R alternative scenario results in terms of GWP impact incurred by agencies and users for all 5 cross-sections.

Cross-Section	**Maintenance Alternative**											
	DNR		**CIR**		**CS**		**MO**		**MS 2.2 m/km**		**MS 2.5 m/km**	
	C/M	**O**	**C/M**	**O**	**C/M**	**O**	**C/M**	**O**	**C/M**	**O**	**C/M**	**O**
	Gg CO_2 eq											
ARGG-1	78	436	29	436	15	430	30	437	53	434	44	437
ARGG-2	77	435	26	435	72	436	29	435	52	435	55	438
SHM-1	73	430	27	436	52	435	-	-	54	436	26	437
T-1	119	434	43	435	107	434	78	436	101	436	75	435
THS-1	83	435	34	437	91	435	-	-	75	436	61	435

Note: C/M = Construction and maintenance (agencies); O = Operations (users); DNR = Do nothing reconstruct; CIR = Cold in-place recycling; MO = Mill and overlay; MS = Microsurface.

It can be inferred from both Figure 5 and Table 3 that while the type of pavement cross-section and the use of different asphalt mixtures have an impact of the life cycle costs and impacts, this is not as significant as the type and timing of M&R performed over the design life of a pavement structure. All GWP user impacts are relatively similar, ranging from 430 to 438 Gg of CO_2 equivalent. In contrast, the agency impact ranges from 15 to 119 Gg of CO_2 equivalent depending on the type and timing of M&R.

The cross-section and M&R alternative that had the lowest operational impact in terms of GWP for both users and agencies is associated with the ARGG-1 cross-section combined with CS. By simply maintaining the pavement system using crack sealant to prevent water infiltration and rapid degradation of the pavement surface, it benefits not only the users of the roadway but the agency in which it is responsible for maintaining the pavement infrastructure. In terms of policy or practical implications, these findings support the need for implementing pavement preservation treatments, whereby if a highway network is routinely treated with preventative maintenance using a preservation treatment such as CS, the need for pavement reconstruction could be avoided, resulting in a lower operational costs for users and agencies. Furthermore, the asphalt rubber gap-graded mixture without inclusion of recycled asphalt pavement appears to have better performance and lower life cycle impacts.

In comparison, the highest user (operational) GWP impact is associated with the ARGG-2 cross-section using MS 2.5. The highest construction and M&R GWP impact resulted from the combination of the using SHM-1 cross-section and the DNR alternative. For all cross-sections the M&R alternative to do nothing and reconstruct (DNR) had the highest total impact, including both agency and user impacts, with T-1 cross-section performing the worst with 553 Gg of CO_2 equivalent.

3.2.2. Life Cycle Cost (LCC)

The last comparison of cross-section and M&R alternatives considered in this study was in terms of LCC. All LCC presented below are in terms of NPV. Figure 6a,b shows results for cross-section ARGG-1 and T-1 to be consistent with GWP comparison in Section 3.2.1. However, Table 4 may be referenced for further comparison of all 5 cross-sections, broken into user and agency LCC impacts.

LCC impact is not constant among the five cross-sections and depends on material properties, M&R treatment, and the application timing over the service life. For example, comparing Figure 6a (ARRG-1) and Figure 6b (T-1), crack sealant every two years followed by reconstruction once terminal IRI is reached resulted in the overall highest total LCC for ARGG-1 cross-section, but for the T-1 cross-section it was from the DNR scenario. It is important to note that while total LCC is highest for this case, depending on the cross-section, the distributions of user and agency LCC are different. In other words, the total bar height is comprised of different user (black portion) and agency (gray portion) costs.

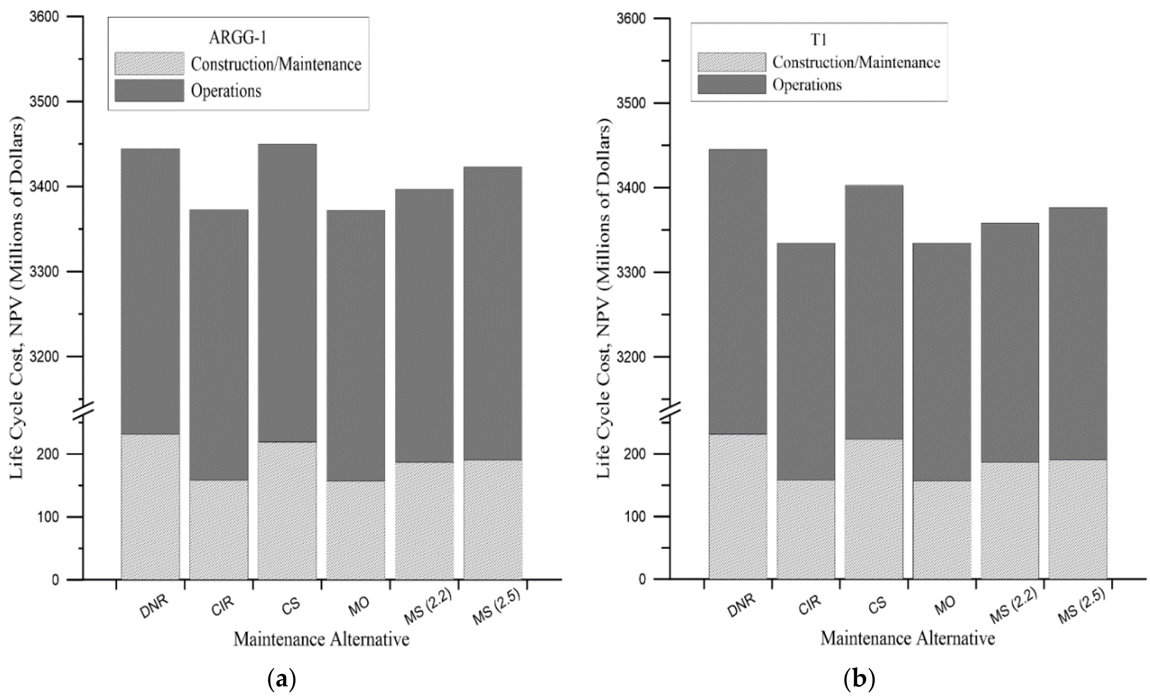

Figure 6. LCC impact broken down into construction and maintenance, and operations of vehicles over LCA analysis period for (**a**) ARGG-1 and (**b**) T-1 pavement cross-section.

Table 4. Summary of M&R alternative scenario results in terms of LCC impact incurred by agencies and users for all 5 cross-sections.

Cross-Section	Maintenance Alternative											
	DNR		CIR		CS		MO		MS 2.2 m/km		MS 2.5 m/km	
	C/M	O	C/M	O	C/M	O	C/M	O	C/M	O	C/M	O
	Millions of Dollars											
ARGG-1	232	3213	158	3214	219	3231	157	3215	187	3209	191	3232
ARGG-2	231	3213	158	3215	219	3219	157	3216	187	3210	156	3224
SHM-1	299	3145	160	3147	277	3146	-	-	253	3144	215	3145
T-1	232	3213	158	3177	224	3179	157	3178	187	3171	191	3186
THS-1	267	3209	159	3203	252	3196	-	-	219	3200	199	3193

Note: C/M = Construction and maintenance (agencies); O = Operations (users); DNR = Do nothing reconstruct; CIR = Cold in-place recycling; MO = Mill and overlay; MS = Microsurface.

The overall lowest total LCC impact between these two cross-sections was the MO scenario. The lowering of LCC with mill and overlay is resulting from greater structural contribution from an overlay and having the IRI of the pavement return to new pavement condition with each application of overlay. It should be highlighted again that these results are made with realistic traffic conditions without consideration to lane closure time associated with the varying M&R strategies during the use phase. With the realistic traffic conditions and assumptions made in this study, it can be concluded that by optimizing M&R type, material selection, and timing of treatment, decision makers can achieve a 2.72% difference in operations costs (users) and 47.6% difference in construction and maintenance costs (agency).

The varied LCC from agencies' and users' perspectives may lead to substantial economic and environmental tradeoffs for agencies and users. In comparing the GWP results to the LCC results, the most environmentally conscious decision may not appear as the most economical decision, assuming that economics is only assessed in terms of the construction and operational costs. Depending on whether decisions are being made from a user's perspective, agency perspective, or an overall combination of the two, the most economical and environmental alternative varies. Furthermore, future studies necessitate inclusion of GWP and LCC in a combined manner to optimize the costs, as well as financial impacts associated with unit GWP. Implementing a LCA-LCCA approach can help to identify those tradeoffs and identify both a cost-effective and eco-friendly pavement M&R plan.

3.3. Sensitivity Analysis

A comparison for all M&R options was performed as part of the sensitivity analysis, however, only results for the ARGG-1 cross-section are included for demonstration purposes. Figure 7 shows the percent different from baseline conditions (0% traffic growth and current fuel price) in terms of NPV when assuming low versus high fuel price scenario, as defined in Table 2.

There is minimal difference in terms of NPV over the analysis period when using either low or high fuel prices, as seen in Figure 7, with respect to baseline conditions. In general, this trend was consistent among all cross-sections considered in this case study. However, it should be noted that as traffic growth rate increases from 1 to 3 percent, the timing of microsurfacing becomes more critical as the impact on NPV increases.

The SHM-1 cross-section, which consisted of a surface course that was a highly polymer modified mixture, had the same fuel consumption cost regardless of the M&R treatment alternative, while holding all other parameters constant. In comparison, results for the other four cross-sections showed that microsurfacing at a trigger value of 2.5 m/km consistently had a higher cost of fuel consumption as the traffic growth rate increased.

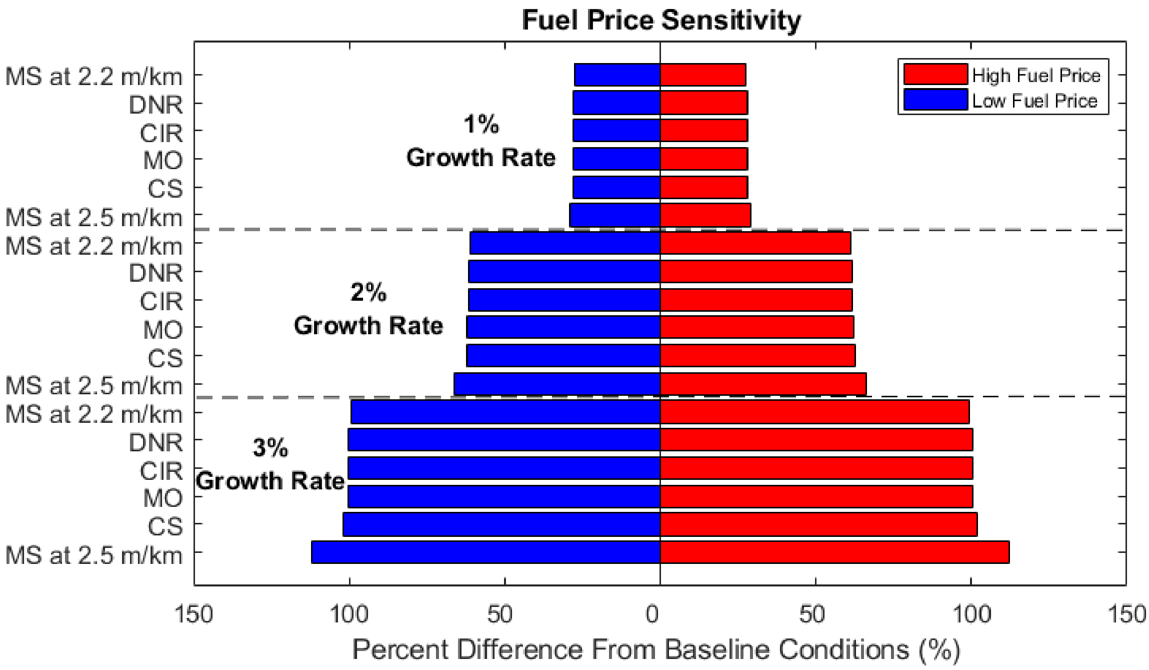

Figure 7. Fuel price sensitivity analysis example for ARGG-1 cross-section showing comparison of low fuel price scenario (**blue**) and high fuel price scenario (**red**) at three levels of traffic growth (1%, 2%, and 3%).

The cost of fuel consumption was not only dependent on traffic growth rate, but with the combination of traffic growth and CED reduction with the improvement of vehicle efficiency each decade. As the percentage of CED improvement and traffic growth rate increased, greater distinction in fuel consumption costs between the different M&R alternatives was observed. Overall, the MS at 2.5 m/km M&R alternative was the most sensitive to variations in traffic growth and CED improvement.

4. Discussion

Results from this study emphasize the importance of utilizing a holistic approach to decision and policy making regarding the M&R of highway infrastructure systems. Economic and environmental tradeoffs for agencies and users exist and vary depending on the stakeholders considered or prioritized during the decision process. It is recommended that life cycle LCC, GWP, and CED be considered in the decision process. This recommendation is supported by the results presented in this paper, where use of only construction or only use phase LCA impacts may not yield optimal results.

The inclusion of realistic traffic conditions was shown to have an impact on the use phase of the LCA. This finding agreed with the literature review from other studies that have shown pavement surface roughness to affect vehicle fuel consumption and emissions during the use phase of the LCA. The framework presented in this study is unique in providing guidance on how to consider realistic traffic conditions using publicly available data sources. This contribution helps bridge the gap of moving from traditional pavement management to an LCA-LCCA informed approach. It also provided a method to consider not only agency cost but also user costs in the decision process.

From a user's perspective, the results from this study indicated that the most economical decision overall was to perform a microsurface when 2.2 m/km IRI was reached (SHM-1 cross-section). The most carbon and energy efficient alternative was to perform crack sealant treatment every two years, followed by reconstruction once the terminal IRI was reached (ARRGG-1 cross-section). Similarly, from an agency-based perspective, the results showed that the most economical decision was microsurfacing at 2.5 m/km scenario (ARGG-2 cross-section) and the lowest environmental impact was achieved by the crack sealant M&R scenario (ARGG-1 cross-section). While this study only considered two different trigger values on when to apply the MS treatment, it is recommended that other IRI trigger times be evaluated to truly optimize the proper timing of M&R strategies. It has been shown by Ogwang et al. in 2019 that agency-wide cracking-threshold policies affect the magnitude of future emissions and costs significantly [36]. It is an essential step to developing a cost-effective and environmentally friendly M&R plan to determine not only the correct type of M&R strategy to apply but the optimal timing of that treatment for a given pavement condition.

This study also showed that material characteristics matter, and what may be optimal for one highway will vary for a different highway. As an example, when considering ARGG-1 cross-section only, the optimal M&R strategy selection is different. The M&R alternative to perform microsurfacing at 2.5 m/km trigger value results in the highest user cost, while allowing the road to degrade and reconstruct after reaching the terminal IRI value (DNR scenario) is the most expensive for agencies. When comparing all cross-sections together, SHM-1 is the worst overall from an agency's perspective and ARGG-1 is the worst overall from a user's perspective.

Meanwhile, from an environmental impact perspective, the highest agency impact for the ARGG-1 cross-section is observed for the DNR M&R scenario and the highest environmental impact from users is seen with the MO M&R scenario. Comparing all cross-sections reveals the highest environmental impacts for agencies with the T-1 cross-section following the DNR M&R scenario, and from user's perspective the ARGG-2 cross-section following the MS 2.5 M&R scenario. Therefore, it can be concluded that decision makers must give attention to the pavement structure and its material characteristics, the type of M&R options that are available within an agency, budget constraints, and potential environmental impacts that are associated with each when developing a long term M&R plan for highway pavement infrastructure systems. This paper provides a methodology to develop that M&R plan with the inclusion of realistic traffic conditions to evaluate LCA and LCCA impacts that can be applied to other highways and be implemented within infrastructure asset management systems with varying material properties, traffic conditions, and available M&R strategies.

5. Conclusions and Recommendations

This study highlighted the importance of including realistic traffic conditions into the operations phase of a pavement LCA. A 6.4% difference in CED and GWP was observed with the inclusion of realistic traffic compared to steady state constant speed conditions. Results from this study also provided valuable insight into the trade-off between GWP, CED, and LCC impacts resulting from performing an LCA on varying pavement cross-sections and M&R alternatives for both agencies and users. Cross-section type, in addition to the timing and type of M&R strategy, has an impact on IRI, which translates into changes in GWP, CED, and LCC. In terms of NPV, the mill and overlay M&R strategy had the lowest LCC for agencies and users. Results from this study also showed that optimization of M&R type, material selection, and timing may lead to a 2.72% difference in operations costs (users) and a 47.6% difference in construction and maintenance costs (agency). Lastly, a sensitivity analysis was performed to assess the robustness of input assumptions, such as traffic growth, fuel price, and vehicle efficiency over the analysis period. Fuel price had minimal impact on LCA results, however traffic growth and CED improvements had an impact on results depending on type of pavement cross-section and the M&R strategy applied.

It is recommended that further analysis be performed to investigate the effect the number of cycles performed for each M&R alternative during the analysis period has on the overall LCA results. Since fuel consumption is directly related to CED and ultimately the IRI performance curve, a greater understanding of the effect each M&R alternative has on the IRI performance is critical. For example, when applying a microsurface treatment at 2.2 m/km IRI or 2.5 m/km IRI, is it an accurate estimation to reset both IRI values by 0.7 m/km, or does it vary depending on the IRI value at the time of treatment? It is also recommended that a similar analysis be conducted on other M&R alternatives, such as chip seal, fog seal, or full depth reclamation, to evaluate other practical M&R techniques that may be used over the pavement design life. The M&R scenarios presented in this study were held constant throughout the analysis period. However, in reality a combination of M&R alternatives would be performed on a given cross-section during its service life. A third recommendation would be to include lane closure and traffic delays related to the time to perform each M&R strategy during the use phase of the LCA. All analysis and results presented in this paper focus on pavement management for a specific highway, however, there is a need to adapt the proposed framework for network level pavement management system implementation. Approaches similar to those discussed by Pantuso et al. could provide a pathway for such implementation [37].

The framework presented in this study may be applied to perform an LCA on a combination of M&R techniques over the design life of a given pavement section. It is critical to include RTTD in the operation phase of a pavement LCA and to carefully consider the impacts of both users and agencies when making management decisions in order to optimize social, environmental, and economic impacts. The adoption of an LCA and LCCA approach in the pavement design and M&R decision process can help to identify the most cost effective and environmentally friendly option benefiting all stakeholders.

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Appendix A

Appendix A.1. Life Cycle Inventory

Table A1 provides a summary of the life cycle inventory and the corresponding sources used in this study [38].

Table A1. Life cycle inventory unit impact.

Impact Unit	Units	Value	Source
Production			
Asphalt Concrete	MJ/ton	641	SimaPro
Asphalt Concrete	kg CO_2 eq/ton	84.7	SimaPro
Gravel	MJ/ton	265	SimaPro
Gravel	kg CO_2 eq/ton	14.1	SimaPro
Sand	MJ/ton	61.8	SimaPro
Sand	kg CO_2 eq/ton	4.25	SimaPro
Transportation			
Dump Truck transportation	MJ/ton·mile	5.134	SimaPro
Dump Truck transportation	kg CO_2 eq/ton·mile	0.321	SimaPro
Construction			
Asphalt Paver (Productivity)	ton/h	10	PaLATE
Asphalt Rolling—TandemIngersol Rand DD90HF (productivity)	ton/h	395	PaLATE
Asphlat Roller—Pheumatic Dynapac CP134	ton/h	884	PaLATE
Unbound Material Placement—Caterpillar 120H	ton/h	300	PaLATE
Unbound Material Compaction (productivity)	ton/h	1832	PaLATE
Construction Machine Operation	MJ/ton	10816	SimaPro
Construction Machine Operation	kg CO_2 eq/hr	72	SimaPro
Maintenance			
Asphalt Milling	ton/h	6.23	SimaPro
Asphalt Milling	kg CO_2 eq/yd^3	0.409	SimaPro
CIR Recycler 800 hp (Productivity)	ton/h	1713	PaLATE

Table A1. *Cont.*

Impact Unit	Units	Value	Source
CIR Recycler 800 hp (Productivity)	kg CO_2 eq/yd^3	0.99	PaLATE
Crack Seal Treatment	MJ/ft^2	0.92	Chehovits et al., 2010
Crack Seal Treatment	kg CO_2 eq/ft^2	0.000067	Chehovits et al., 2010
Operation			
Gasoline	MJ/gal	132	EPA
Gasoline	lb CO_2 eq/gal	19.6	EPA
Diesel	MJ/gal	137.7	EPA
Diesel	lb CO_2 eq/gal	22.4	EPA

Appendix A.2. Life Cycle Analysis Period

Table A2 summarize how many cycles of each M&R type were completed during the analysis period by cross-section type. In Table A2, highlighted values in bold denote the M&R type that controlled the terminal year (i.e., complete 3 full cycles in the longest period of time).

Table A2. Summary of M&R cycles by cross-section over the course of the analysis period, where numbers in bold represent controlling (longest) maintenance and rehabilitation treatment to complete 3 full cycles.

M&R Alternative	Cross-Section				
	ARGG-1	ARGG-2	SHM-1	T-1	THS-1
Do Nothing Reconstruct	5	5	6	5	6
Crack Sealant	5	5	5	5	5
Microsurface @ 2.2 m/km	**3**	**3**	4	**3**	4
Microsurface @ 2.5 m/km	4	4	**3**	4	**3**
Cold-In-Place Recycling	7	6	9	6	9
Mill and Overlay	6	6		6	

Figures A1–A5 show the M&R timing sequences for all cross-sections considered in this study.

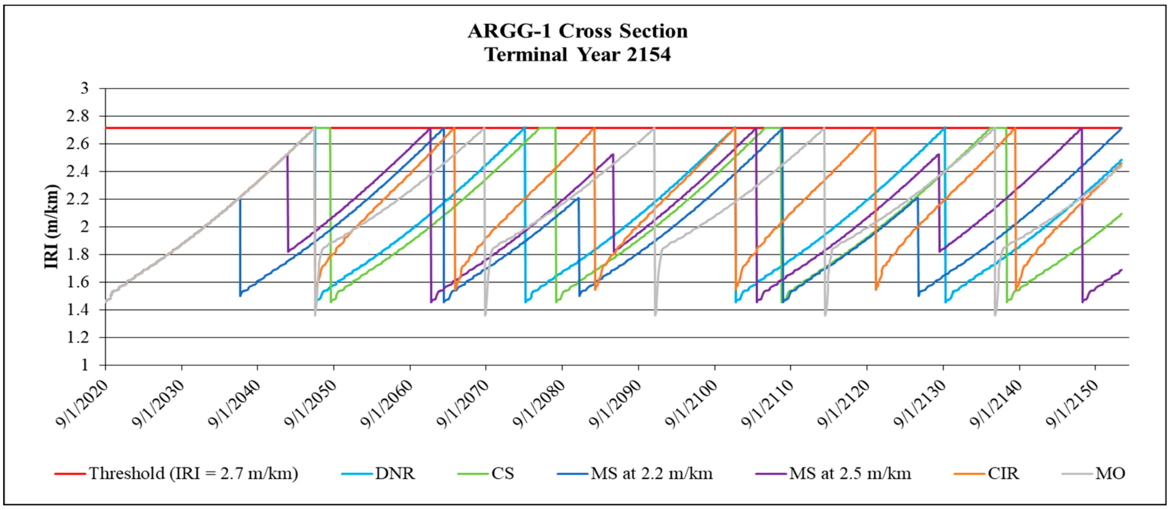

Figure A1. ARGG-1 cross-section M&R activity timing.

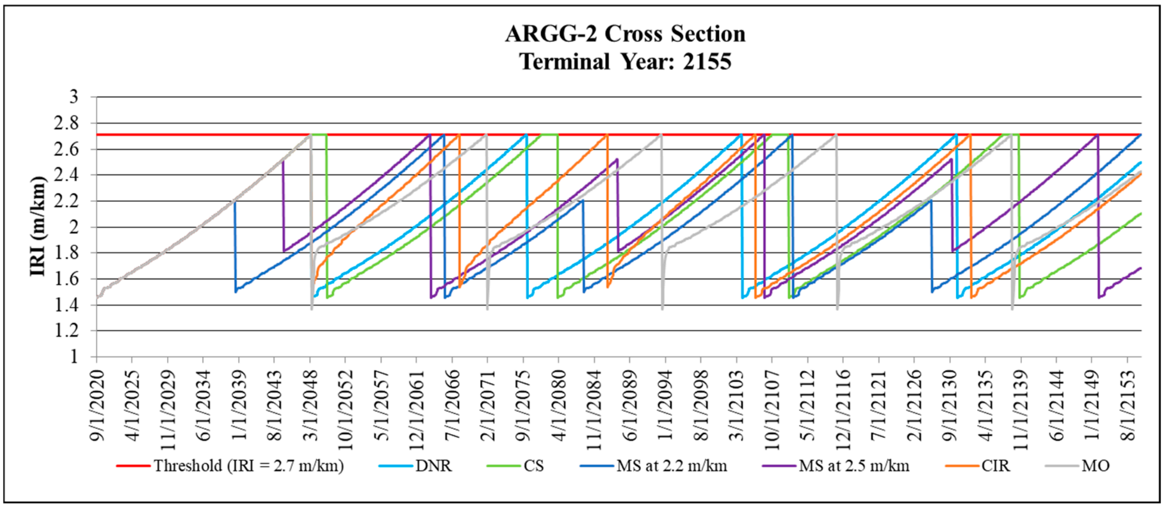

Figure A2. ARGG-2 cross-section of M&R activity timing.

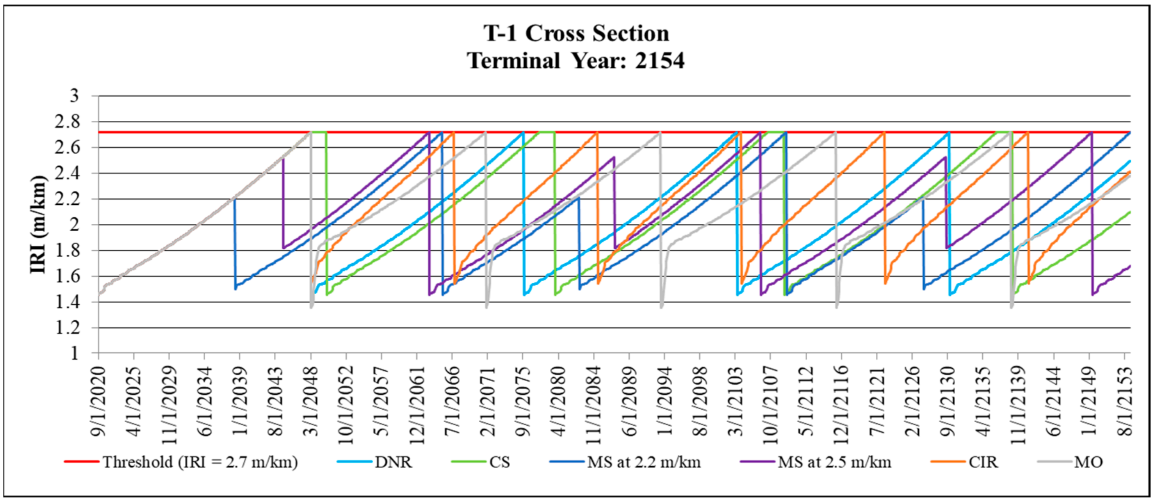

Figure A3. T-1 cross-section of M&R activity timing.

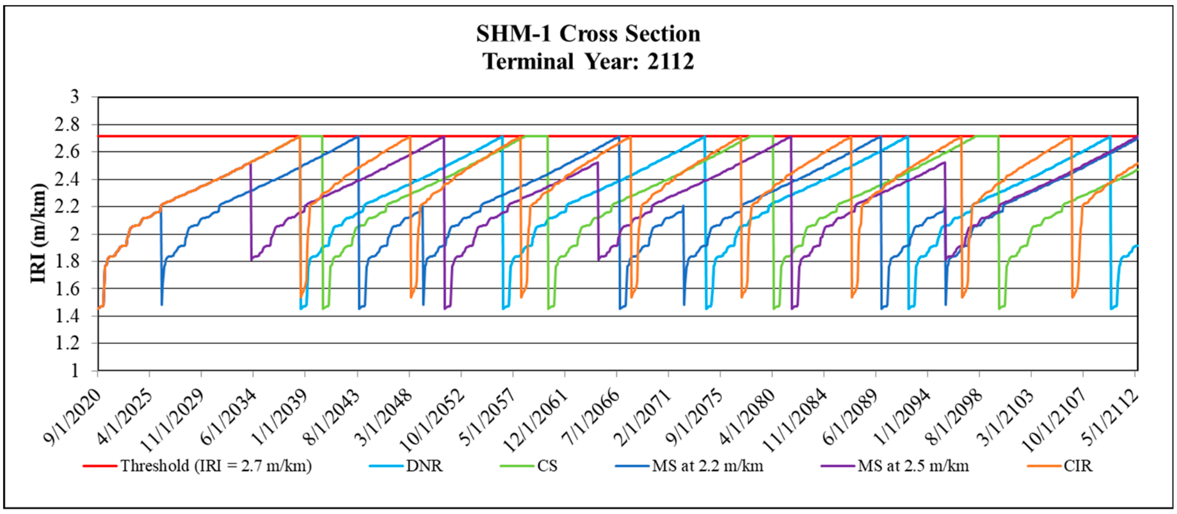

Figure A4. SHM-1 cross-section of M&R activity timing.

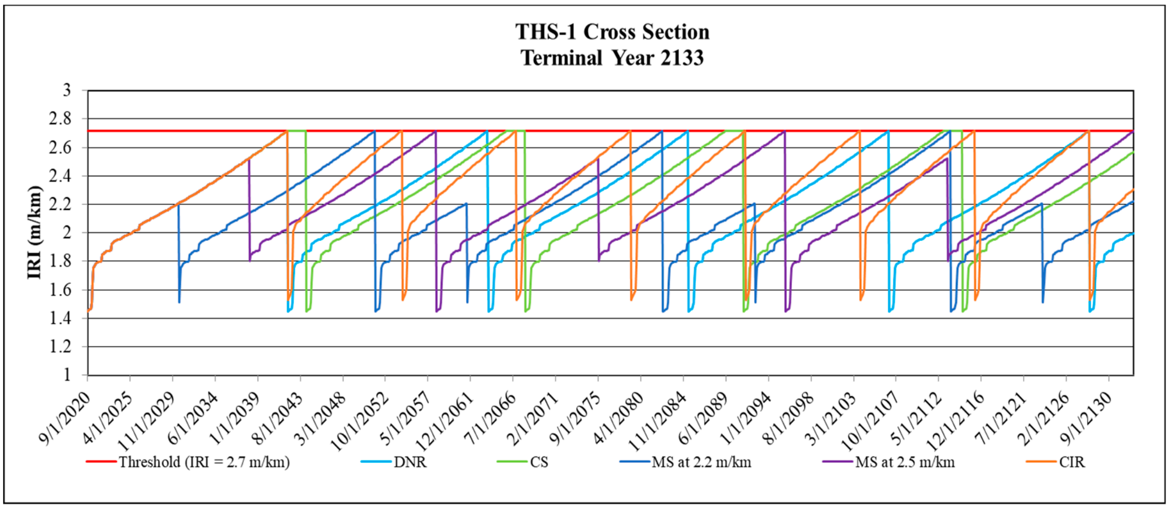

Figure A5. THS-1 cross-section of M&R activity timing.

Appendix A.3. Implementation of RTTD

Included in Appendix A.3 is a summary of the information used in this study to implement the 6-step process to incorporate realistic traffic conditions in the use phase of an LCA.

Step 1

Table A3. Step 1, NCHRP-720 default vehicle and tire characteristics [12].

Vehicle Class	Number of Axles	N*w*	M (tons)	*Kcr2*	CD	AF (m^2)	WD	Tire Type	CR1	*b11*	*b12*	*b13*	C_{0lc} (dm^3/MNm)	C_{tcle} (dm^3/MNm)	VOL (dm^3)	VEHF AC
Small car	2	4	1.9	0.5	0.42	1.9	0.62	Radial	1	22.2	0.11	0.13	0.01747	0.001	1.4	2
Medium car	2	4	1.9	0.5	0.42	1.9	0.62	Radial	1	22.2	0.11	0.13	0.01747	0.001	1.4	2
Large car	2	4	1.9	0.5	0.42	1.9	0.62	Radial	1	22.2	0.11	0.13	0.01747	0.001	1.4	2
Van	2	4	2.54	0.67	0.5	2.9	0.7	Radial	1	25.9	0.09	0.1	0.01602	0.00092	1.6	2
Four-wheel drive	2	4	2.5	0.58	0.5	2.8	0.7	Radial	11	25.9	0.09	0.1	0.01602	0.00092	1.6	2
Light truck	2	4	4.5	0.99	0.6	5	0.8	Radial	1	29.6	0.08	0.08	0.01602	0.00092	1.6	2
Medium truck	2	6	6.5	0.99	0.6	5	0.8	Bias	1.3	29.6	0.08	0.11	0.02999	0.00099	6	1
Heavy truck	3	10	13	1.1	0.7	8.5	1.05	Bias	1.3	38.85	0.06	0.11	0.03829	0.00135	8	1
Articulated truck	5	18	15.6	1.1	0.8	9	1.05	Bias	1.3	38.85	0.06	0.2	0.04328	0.00153	8	1
Mni bus	2	4	2.16	0.67	0.5	2.9	0.7	Radial	1	25.9	0.09	0.1	0.01747	0.00092	1.6	2
Light bus	2	4	2.5	0.99	0.5	4	0.8	Radial	1	29.6	0.08	0.08	0.01747	0.00092	1.6	2
Medium bus	2	6	4.5	0.99	0.6	5	1.05	Bias	1.3	38.85	0.06	0.06	0.02999	0.00099	6	1
Heavy bus	3	10	13	1.1	0.7	6.5	1.05	Bias	1.3	38.85	0.06	0.06	0.03829	0.00135	8	1
Coach	3	10	13.6	1.1	0.7	6.5	1.05	Bias	1.3	38.85	0.06	0.06	0.03829	0.00135	8	1

Table A4. Step 1, NCHRP-720, HDM 4 tractive force model vehicle characteristic formulas [12].

Name	Description	Unit
Aerodynamic forces (*Fa*)	$Fa = 0.5 * \rho * CD * AF * \upsilon^2$	N
CD	Drag coefficient (Table 4-12)	dimensionless
AF	Frontal area (Table 4-12)	m^2
ρ	Mass density of the air (default = 1.2)	kg/m^3
υ	Vehicle speed	m/s
Gradient forces (*Fg*)	$Fg = M * GR * g$	N
M	Vehicle weight (Table 4-12)	kg
GR	Gradient	radians
g	Gravity	m/s^2
Curvature forces (*Fc*)	$Fc = \max\left(0, \frac{\left(\frac{M * \upsilon^2}{R} - M * g * e\right)^2}{Nw * Cs} * 10^{-3}\right)$	N
R	Curvature radius (Default = 3000)	m
Superelevation (*e*)	$e = \max(, 0.045 - 0.68 * Ln(R))$	m/m
Nw	Number of wheels (Table 4-12)	dimensionless
Tire stiffness (*Cs*)	$Cs = a0 + a1 * \frac{M}{Nw} + a2 * \left(\frac{M}{Nw}\right)^2$	kN/rad
*a*0 to *a*2	Model parameter (Table 4-10)	dimensionless
Rolling resistance (F_r)	$Fr = CR2*(b11 * Nw + CR1*(b12*M + b13*\upsilon^2))$	N
*CR*1	Rolling resistance tire factor (Table 4-12)	factor
Rolling resistance parameters (*b*11, *b*12, *b*13)	$\begin{cases} b11 = 37 * Dw \\ b12 = 0.064 / Dw \\ b13 = 0.012 * Nw / Dw^2 \end{cases}$	factors
Dw	Diameter of wheel	
Rolling resistance surface factor (*CR*2)	$= Kcr2[a0 + a1 * Tdsp + a2 * IRI + a3 * DEF]$	factor
*Kcr*2	Calibration factor (Table 4-12)	factor
*a*0 to *a*3	Model coefficient (Table 4-11)	dimensionless
Texture depth using sand patch method (*Tdsp*)	$Tdsp = 1.02 * MPD + 0.28$	mm
MPD	Mean Profile Depth	mm
IRI	International roughness index	m/km
DEF	Benkelman Beam rebound deflection	mm

Table A5. Acceleration rates corresponding to Google Maps predicted congestion level orange, red, and dark red using Strategic Highway Research Program 2 (SHRP2) Naturalistic Driving Study databases.

	Car Acceleration (m/s^2)	Truck Acceleration (m/s^2)
Orange	2.94	1.47
Red	2.94	1.47
Dark Red	2.9	1.45

Step 2

$$\mathrm{VSP} = \frac{\mathrm{Power}}{\mathrm{Mass}} = \frac{\frac{d}{dt}(E_{Kinetic} + E_{Potential}) + F_{Rolling} \cdot v + F_{Aerodynamic} \cdot v + F_{internal\ friction} \cdot v}{m} =$$

$$\approx v \cdot a \cdot (1 + \varepsilon_i) + g \cdot grade \cdot v + g \cdot C_R \cdot v + \frac{1}{2} \rho_a C_D \frac{A}{m} (v + v_w)^2 \cdot v + C_{if} \cdot v$$

Figure A6. Step 2, vehicle specific power formula [29].

where v = vehicle speed, m = vehicle mass, a = vehicle acceleration, ε_i = Mass factor, C_D = drag coefficient, C_R = coefficient of rolling resistance, A = frontal area of the vehicle, ρ_a = ambient air density, v_w = headwind into the vehicle.

Step 3

VSP Bin	Characteristics
0	Braking
1	Idling
11	Low Speed Coasting; VSP< 0; 1<=Speed<25
12	Cruise/Acceleration; 0<=VSP< 3; 1<= Speed<25
13	Cruise/Acceleration; 3<=VSP< 6; 1<=Speed<25
14	Cruise/Acceleration; 6<=VSP< 9; 1<=Speed<25
15	Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25
16	Cruise/Acceleration; 12<=VSP; 1<=Speed<25
21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50
22	Cruise/Acceleration; 0<=VSP< 3; 25<=Speed<50
23	Cruise/Acceleration; 3<=VSP< 6; 25<=Speed<50
24	Cruise/Acceleration; 6<=VSP< 9; 25<=Speed<50
25	Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50
26	Cruise/Acceleration; 12<=VSP; 25<=Speed<50
27	Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50
28	Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50
29	Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50
30	Cruise/Acceleration; 30<=VSP; 25<=Speed<50
33	Cruise/Acceleration; VSP< 6; 50<=Speed
35	Cruise/Acceleration; 6<=VSP<12; 50<=Speed
36	Cruise/Acceleration; 12 <= VSP; 50<=Speed
37	Cruise/Acceleration; 12<=VSP<18; 50<=Speed
38	Cruise/Acceleration; 18<=VSP<24; 50<=Speed
39	Cruise/Acceleration; 24<=VSP<30; 50<=Speed
40	Cruise/Acceleration; 30<=VSP; 50<=Speed

Figure A7. Step 3, MOVES vehicle specific power (VSP) Bins examples.

Step 4

Run	Header Item:	Item Value
	Report Description:	Summary Report
	Report Date/Time:	2017-10-30 17:47:0
	MOVES Output Database:	VehicleClass_Out
	Emission Process:	All
33	Run Date/Time:	2017-10-26 01:09:46.0
33	Run Specification:	C:\Users\Shane Majenski\Documents\Fall 2017\Senior Project\Vehicle Cl
33	Run Spec File Date/Time:	2017-10-26 01:09:18.0
33	Run Spec Description:	Vehicle Classification Run
33	Mass Units:	g
33	Energy Units:	KJ
33	Distance Units:	mi
33	Time Units:	hour

Figure A8. Step 4, MOVES Run Specification output information.

Run	TotalEnergy	CO2_Equiv
33	82416	6072

Figure A9. Step 4, MOVES output.

Step 5

Table A6. Step 5, MOVES interpolation—no change in MOVES output from 0 m/km International Roughness Index (IRI) to 19.1 m/km IRI.

MOTORCYCLE (NCHRP 720 Classification: Car, MOVES: Motorcycle) Gas														
Length (Miles)	Grade (%)	v(mph)	v (m/s)	a(m/s^2)	IRI (m/km)	Faero (kW/ton)	Froll (kW/ton)	VSP (kW/Tonne)	VSP Bin	Condition	SourceTypeID	Run	Total Energy Consumption (MJ)	GWP Unit (kg CO2 eq)
1	0	60	26.8224	0	0	0.000252	0.059	6.448402596	35	Good	11	3	2.689	0.194
1	0	60	26.8224	0	0.25	0.000252	0.062	6.520946694	35	Good	11	3	2.689	0.194
1	0	60	26.8224	0	0.5	0.000252	0.065	6.593490792	35	Good	11	3	2.689	0.194
1	0	60	26.8224	0	0.75	0.000252	0.067	6.66603489	35	Good	11	3	2.689	0.194
1	0	60	26.8224	0	1	0.000252	0.070	6.738578987	35	Good	11	3	2.689	0.194
1	0	60	26.8224	0	1.25	0.000252	0.073	6.811123085	35	Good	11	3	2.689	0.194
1	0	60	26.8224	0	1.5	0.000252	0.075	6.883667183	35	Good	11	3	2.689	0.194
1	0	60	26.8224	0	1.75	0.000252	0.078	6.956211281	35	Acceptable	11	3	2.689	0.194
1	0	60	26.8224	0	2	0.000252	0.081	7.028755378	35	Acceptable	11	3	2.689	0.194
1	0	60	26.8224	0	2.25	0.000252	0.083	7.101299476	35	Acceptable	11	3	2.689	0.194
1	0	60	26.8224	0	2.5	0.000252	0.086	7.173843574	35	Acceptable	11	3	2.689	0.194
1	0	60	26.8224	0	2.75	0.000252	0.089	7.246387672	35	Bad	11	3	2.689	0.194
1	0	60	26.8224	0	3	0.000252	0.092	7.318931769	35	Bad	11	3	2.689	0.194
1	0	60	26.8224	0	3.25	0.000252	0.094	7.391475867	35	Bad	11	3	2.689	0.194
1	0	60	26.8224	0	3.5	0.000252	0.097	7.464019965	35	Bad	11	3	2.689	0.194
1	0	60	26.8224	0	19.1	0.000252	0.266	11.99077166	35	Bad	11	3	2.689	0.194
1	0	60	26.8224	0	19.2	0.000252	0.267	12.0197893	37	Bad	11	35	3.44	0.248

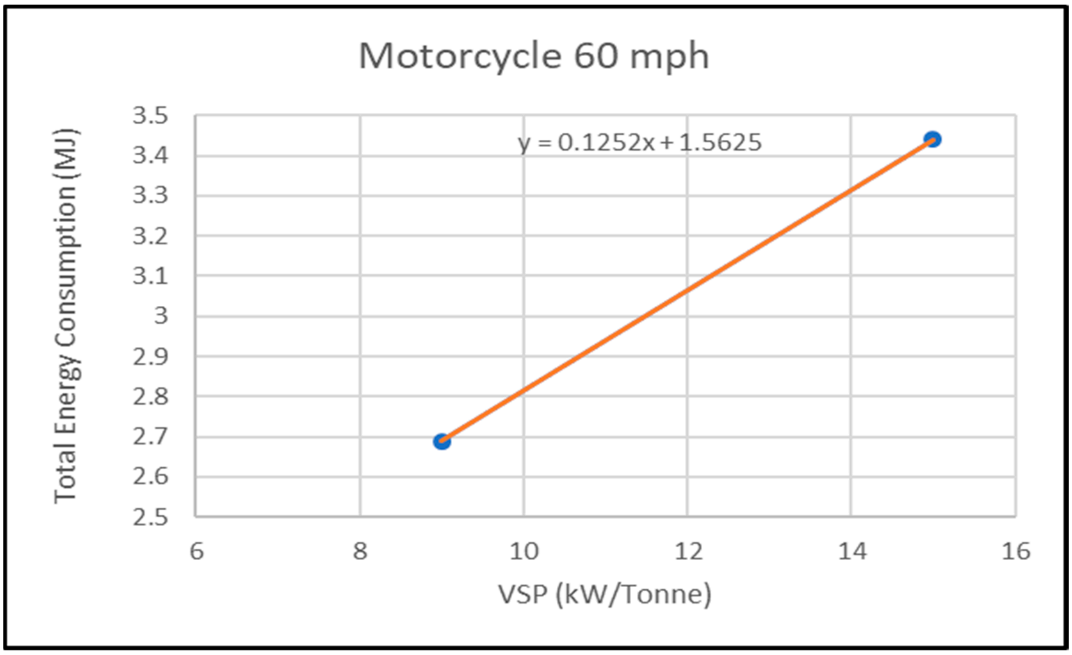

Figure A10. Step 5, MOVES interpolation for total energy consumption.

Step 6

Table A7. Step 6, MOVES interpolation output for varying vehicle classifications and traffic conditions. Colors represent traffic congestion and resulting speeds where green is free flow at posted speed limit of 60 mph, orange is 40 mph, red is 20 mph and dark red is 10 mph.

			Total Energy Consumption (MJ)/ 1 Mile												
Color	Acceleration/Deceleration	Speed (mph)	Motorcycle	Car	Light Truck	Bus	2A SU	3A SU	>3A SU	<5A 2U	5A 2U	>5A 2U	<6A >2A	6A >2A	>6A >2A
Green	None	60	2.370	2.823	3.483	55.351	32.963	45.902	34.629	82.416	82.416	82.552	82.552	82.552	82.552
Green	Deceleration	60	2.689	2.023	2.374	24.605	5.269	20.848	6.615	82.416	82.416	82.552	82.552	82.552	82.552
Orange	None	40	3.011	2.600	2.824	46.748	26.751	44.902	30.535	123.787	123.787	123.992	123.992	123.992	123.992
Orange	Deceleration	40	2.590	2.101	2.436	19.818	6.310	17.810	2.406	157.131	157.131	157.389	157.389	157.389	157.389
Orange	Acceleration	40	4.339	7.671	8.930	104.757	72.103	99.465	66.715	123.787	123.787	123.992	123.992	123.992	123.992
Red	None	20	3.229	3.829	4.126	42.795	24.344	42.045	28.862	95.475	95.475	95.633	95.633	95.633	95.633
Red	Deceleration	20	3.446	3.123	3.674	20.755	3.083	19.807	5.965	95.475	95.475	95.633	95.633	95.633	95.633
Red	Acceleration	20	4.846	8.287	9.300	79.295	76.308	79.466	72.208	95.475	95.475	95.633	95.633	95.633	95.633
Dark Red	None	10	6.117	7.172	7.567	50.880	31.609	50.384	38.325	145.543	145.543	145.782	145.782	145.782	145.782
Dark Red	Deceleration	10	6.542	6.246	7.349	29.312	5.941	28.622	11.928	118.315	118.315	118.511	118.511	118.511	118.511
Dark Red	Acceleration	10	7.986	11.849	13.149	89.985	66.780	87.226	74.648	190.950	190.950	191.265	191.265	191.265	191.265

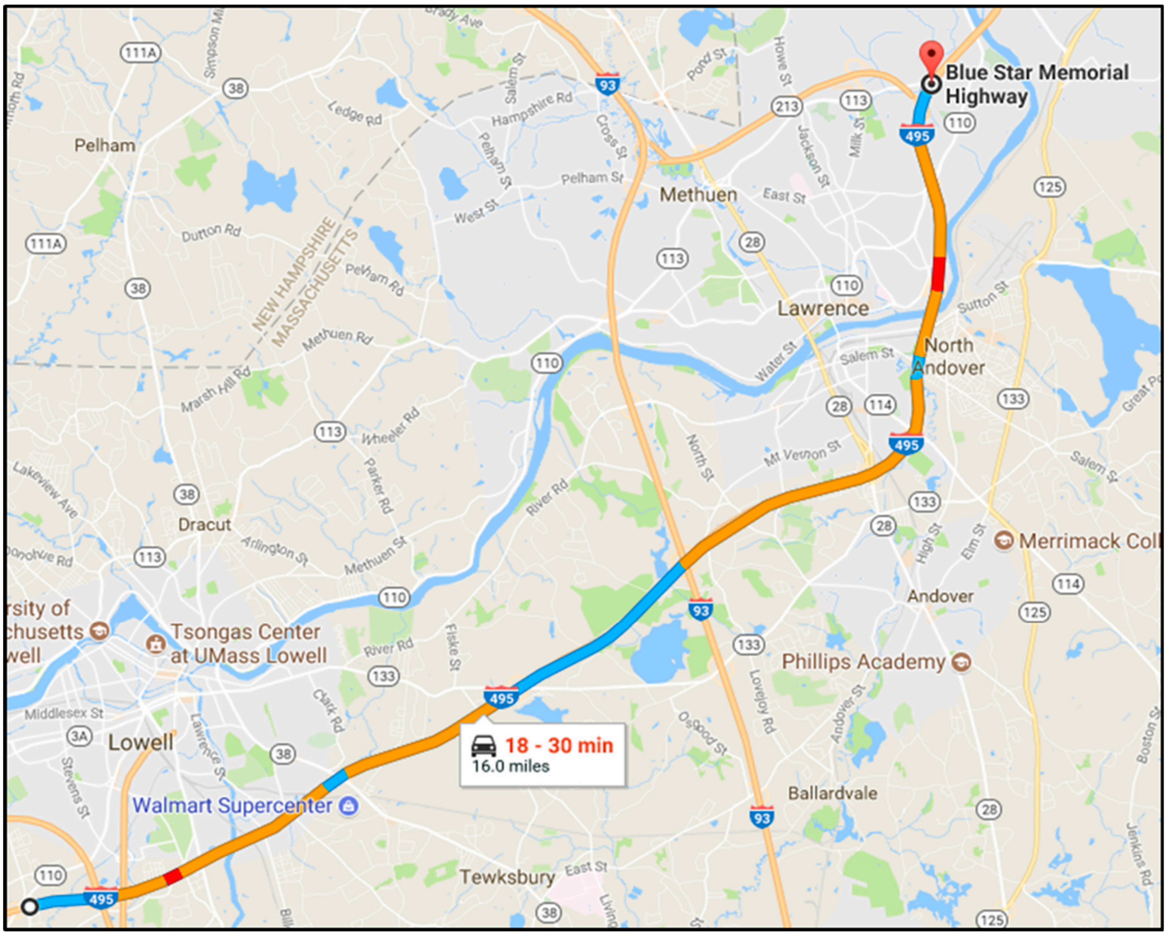

Figure A11. Step 6, Google Maps®traffic conditions for Interstate I-495 [17].

Table A8. Step 6, example of Massachusetts Department of Transportation Data Management System information database on vehicle classification [16].

FHWA-Scheme F Classification

Start Time	Motor cycle	Car	Pick up	Bus	2A SU	3A SU	>3A SU	<5A 2U	5A 2U	>5A 2U	<6A >2U	6A >2U	>6A >2U	14	15	TOTAL
12:00 AM	3	474	119	5	11	8	0	12	133	6	8	10	3	0	0	792
1:00 AM	6	317	87	3	10	4	0	10	142	5	10	3	2	0	0	599
2:00 AM	6	269	70	5	11	9	0	9	136	6	8	3	5	0	0	537
3:00 AM	3	300	101	1	24	11	0	21	169	5	8	4	2	0	0	649
4:00 AM	7	751	238	4	32	17	0	23	222	21	14	4	5	0	0	1338
5:00 AM	16	3056	1003	10	88	42	6	45	299	31	20	5	14	0	0	4635
6:00 AM	15	6284	1640	24	140	88	9	71	372	49	14	9	19	0	0	8734
7:00 AM	24	8821	1486	18	152	55	16	56	351	25	16	6	22	0	0	11048
8:00 AM	71	6286	1028	28	117	109	15	60	283	33	12	11	25	0	0	8078
9:00 AM	38	5798	1288	25	180	73	19	68	527	45	14	13	20	0	0	8108
10:00 AM	16	4297	1166	20	147	68	15	69	451	45	2	4	14	0	0	6314
11:00 AM	13	3847	1098	12	139	101	14	65	402	27	6	4	21	0	0	5749
12:00 PM	16	4572	1302	19	144	79	12	62	484	29	3	3	20	0	0	6745
1:00 PM	17	4451	1250	24	132	81	6	55	461	38	4	2	30	0	0	6551
2:00 PM	34	6077	1512	22	153	68	6	59	449	32	5	3	18	0	0	8438
3:00 PM	21	7313	1626	13	130	59	4	59	351	26	4	3	23	0	0	9632
4:00 PM	17	7925	1376	13	94	40	1	46	329	14	2	2	21	0	0	9880
5:00 PM	24	7711	1163	12	69	21	3	48	267	10	2	2	22	0	0	9354
6:00 PM	5	5982	895	14	47	12	1	45	233	4	4	3	11	0	0	7256
7:00 PM	6	3796	667	9	52	9	0	35	197	9	7	3	11	0	0	4801
8:00 PM	6	2416	423	8	38	4	0	28	148	10	10	4	7	0	0	3102
9:00 PM	10	1903	339	7	19	6	0	32	202	7	23	6	7	0	0	2561
10:00 PM	5	1307	230	4	16	3	0	23	195	6	12	6	2	0	0	1809
11:00 PM	13	1030	191	3	14	6	2	17	148	5	6	11	2	0	0	1448
TOTAL	392	94983	20298	303	1959	973	129	1018	6951	488	214	124	326	0	0	128158

Vehicle Classifications

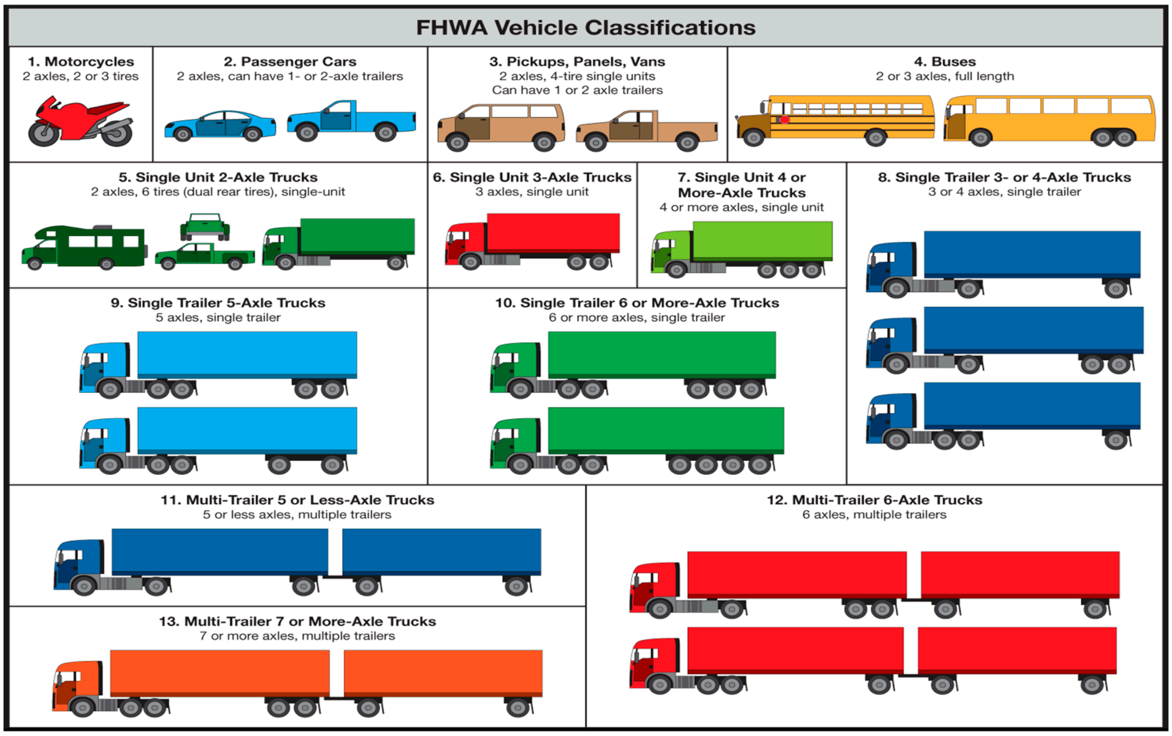

Figure A12. MassDOT's Transportation Data Management System information vehicle classification chart [16].

Combination Long-haul Truck
Combination Short-haul Truck
Intercity Bus
Light Commercial Truck
Motor Home
Motorcycle
Passenger Car
Passenger Truck
Refuse Truck
School Bus
Single Unit Long-haul Truck
Single Unit Short-haul Truck
Transit Bus

Figure A13. MOVES vehicle classifications.

Trips by Maximum Acceleration and % Rur Frwy < 4 Lns

% Rur Frwy < 4 Lns

	0.0 - 20.0	20.0 - 40.0	40.0 - 60.0	60.0 - 80.0	80.0 - 100.0	>= 100.0	NULL (no value)	Total
< 0.0	0	0	0	0	0	0	0	0
0.0 - 0.1	0	0	0	0	7.6	0	0	7.6
0.1 - 0.2	0	0	0	0	22.5	0	0	22.5
0.2 - 0.3	0	0	0	0	40.7	0	0	40.7
0.3 - 0.4	0	0	0	0	25.1	0	0	25.1
0.4 - 0.5	0	0	0	0	3.5	0	0	3.5
0.5 - 0.6	0	0	0	0	0.2	0	0	0.2
0.6 - 0.7	0	0	0	0	0	0	0	0
>= 0.7	0	0	0	0	0.2	0	0	0.2
NULL (no value)	0	0	0	0	0.3	0	0	0.3
Total	0	0	0	0	100.0	0	0	100.0

Figure A14. SHRP 2 NDS acceleration data [16].

Table A9. NCHRP-720 HDM4 vehicle and tire classifications [12].

Vehicle Class	Number of Axles	*Nw*	M (tons)	*Kcr2*	CD	AF (m^2)	WD	Tire Type	CR1	*b11*	*b12*	*b13*	C_{0lc} (dm^3/MNm)	C_{tcle} (dm^3/MNm)	VOL (dm^3)	VEHF AC
Small car	2	4	1.9	0.5	0.42	1.9	0.62	Radial	1	22.2	0.11	0.13	0.01747	0.001	1.4	2
Medium car	2	4	1.9	0.5	0.42	1.9	0.62	Radial	1	22.2	0.11	0.13	0.01747	0.001	1.4	2
Large car	2	4	1.9	0.5	0.42	1.9	0.62	Radial	1	22.2	0.11	0.13	0.01747	0.001	1.4	2
Van	2	4	2.54	0.67	0.5	2.9	0.7	Radial	1	25.9	0.09	0.1	0.01602	0.00092	1.6	2
Four-wheel drive	2	4	2.5	0.58	0.5	2.8	0.7	Radial	11	25.9	0.09	0.1	0.01602	0.00092	1.6	2
Light truck	2	4	4.5	0.99	0.6	5	0.8	Radial	1	29.6	0.08	0.08	0.01602	0.00092	1.6	2
Medium truck	2	6	6.5	0.99	0.6	5	0.8	Bias	1.3	29.6	0.08	0.11	0.02999	0.00099	6	1
Heavy truck	3	10	13	1.1	0.7	8.5	1.05	Bias	1.3	38.85	0.06	0.11	0.03829	0.00135	8	1
Articulated truck	5	18	15.6	1.1	0.8	9	1.05	Bias	1.3	38.85	0.06	0.2	0.04328	0.00153	8	1
Mni bus	2	4	2.16	0.67	0.5	2.9	0.7	Radial	1	25.9	0.09	0.1	0.01747	0.00092	1.6	2
Light bus	2	4	2.5	0.99	0.5	4	0.8	Radial	1	29.6	0.08	0.08	0.01747	0.00092	1.6	2
Medium bus	2	6	4.5	0.99	0.6	5	1.05	Bias	1.3	38.85	0.06	0.06	0.02999	0.00099	6	1
Heavy bus	3	10	13	1.1	0.7	6.5	1.05	Bias	1.3	38.85	0.06	0.06	0.03829	0.00135	8	1
Coach	3	10	13.6	1.1	0.7	6.5	1.05	Bias	1.3	38.85	0.06	0.06	0.03829	0.00135	8	1

Table A10. Vehicle classification combinations and distributions.

Vehicle Classifications			
FHWA Traffic Count	**NCHRP 720**	**MOVES**	**Distribution (%)**
Car	Car	Car	100
Motorcycle	Motorcycle	Motorcycle	100
Pick Up	Four-wheel Drive	Passenger Truck	100
	Light Bus	School Bus	15
Bus	Medium Bus	Transit Bus	80
	Coach	Intercity Bus	5
2A SU	Light Truck	Single-Unit Long Haul Truck	100
3A SU	Medium Truck	Single-Unit Long Haul Truck	100
>3A SU	Heavy Truck	Single-Unit Long Haul Truck	90
		Refuse Truck	10
<5A SU and 5A SU	Articulated Truck	Combination Short Haul Truck	100
>5A 2U and higher	Articulated Truck	Combination Long Haul Truck	100

Appendix A.4. Pavement ME Inputs

Appendix A.4.1. Material Characteristic Inputs

Table A11. Pavement ME material characteristics for each layer.

Asphalt Material Properties		Mixture Name						
		ARGG-1	ARGG-2	T-1	THS-1	SHM-1	B-1	BB-1
Aggregate gradation	Cum % rt. 3/4 in sieve	100	100	100	100	100	99	88
	Cum % rt. 3/8 in sieve	84	85	81	84	86	74	56
	Cum % rt. #4 sieve	40	37	57	57	59	46	36
	% Passing #200 sieve	3.5	3.5	3.8	4	3.7	3.5	3.5
Asphalt Binder	Superpave (PG)	58-28	58-28	64-28	76-28	70-34 PMA	64-28	64-28
Asphalt General	Reference temp (F)	70	70	70	70	70	70	70
	Poisson's ratio	0.36	0.35	0.36	0.36	0.35	0.36	0.36
	Effective binder %	6.68	6.32	4.9	4.9		4.39	4.35
	Air voids %	5.36	3.01	3.5	6.21	4	5.18	4.38
	Total Unit weight (pcf)	144.8	146.9	158.7	155.6	151.5	149.5	151.3
	Thermal conductivity AC	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	Heat capacity asphalt	0.23	0.23	0.23	0.23	0.23	0.23	0.23

Appendix A.4.2. Dynamic Modulus (E*) Pavement ME Input

Table A12. Dynamic modulus input for ARGG-1 cross-section.

ARGG-1				
Temp (F)	Frequency (Hz)			
	0.1	1	10	25
10	1,688,550.19	1,966,960.96	2,175,448.5	2,240,515.8
40	687,552.7197	979,985.536	1,331,318.2	1,476,540
70	169,907.9615	304,180.895	522,202.28	636,736.3
100	56,526.39519	96,813.0315	179,173.21	231,341.41
130	29,662.06475	43,677.4749	71,655.429	89,572.235

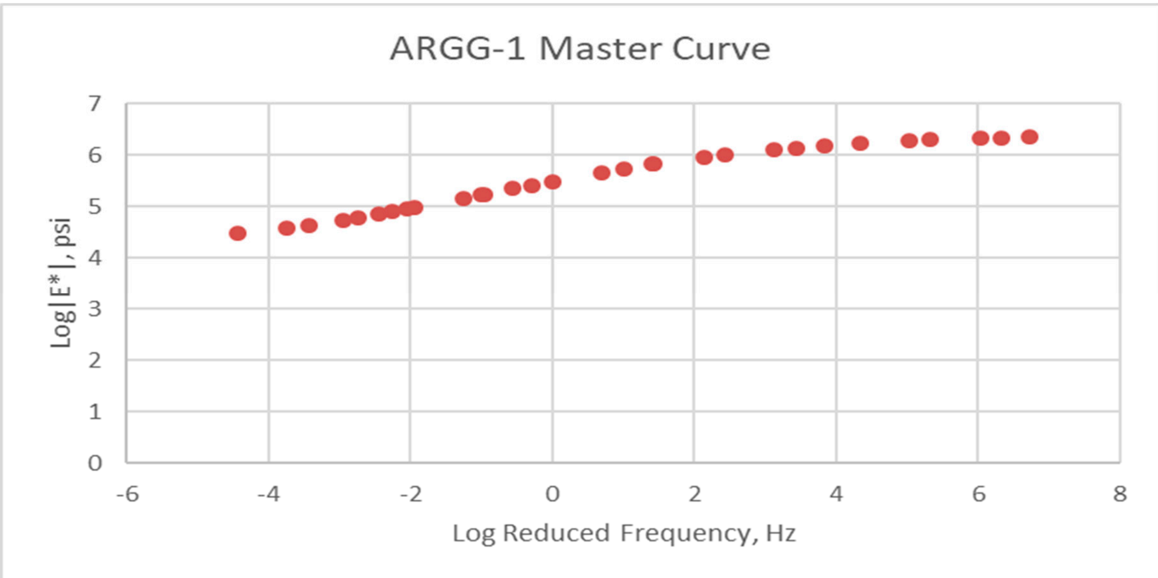

Figure A15. ARGG-1 cross-section master curve.

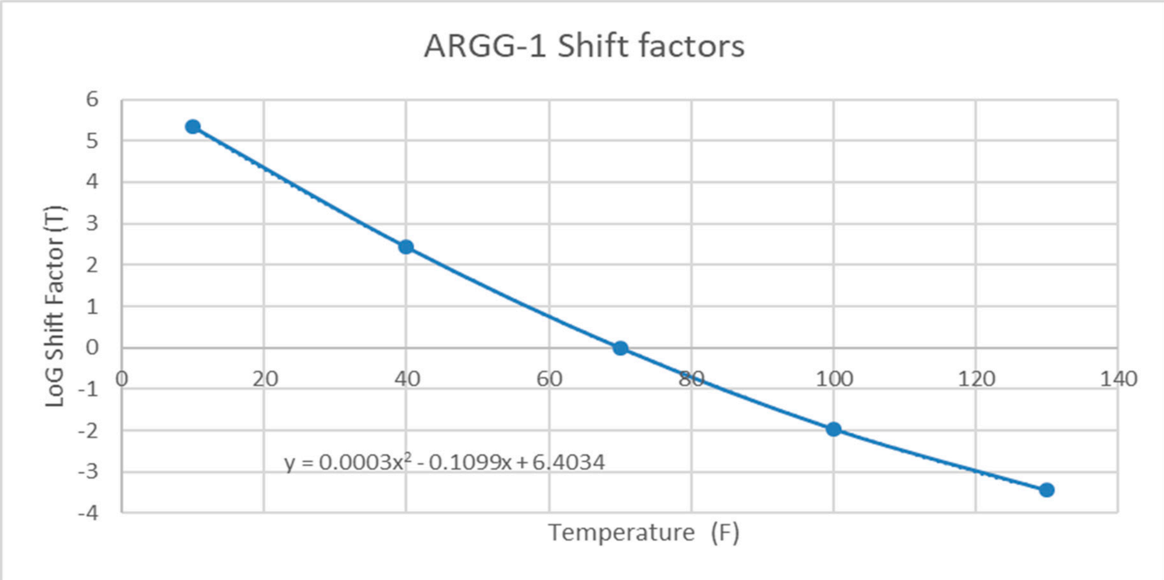

Figure A16. ARGG-1 cross-section shift factors.

Table A13. Dynamic modulus input for ARGG-2 cross-section.

ARGG-2				
Temp (F)	**Frequency (Hz)**			
	0.1	**1**	**10**	**25**
10	2,014,657.96	2,300,848	2,516,240	2,584,199
40	804,896.3419	1,132,508	1,517,460	1,673,494
70	191,077.648	350,222.3	596,736.8	723,122.5
100	58,660.58927	106,064	203,032.5	261,578.6
130	28,301.08178	46,310.03	83,084.46	106,713.7

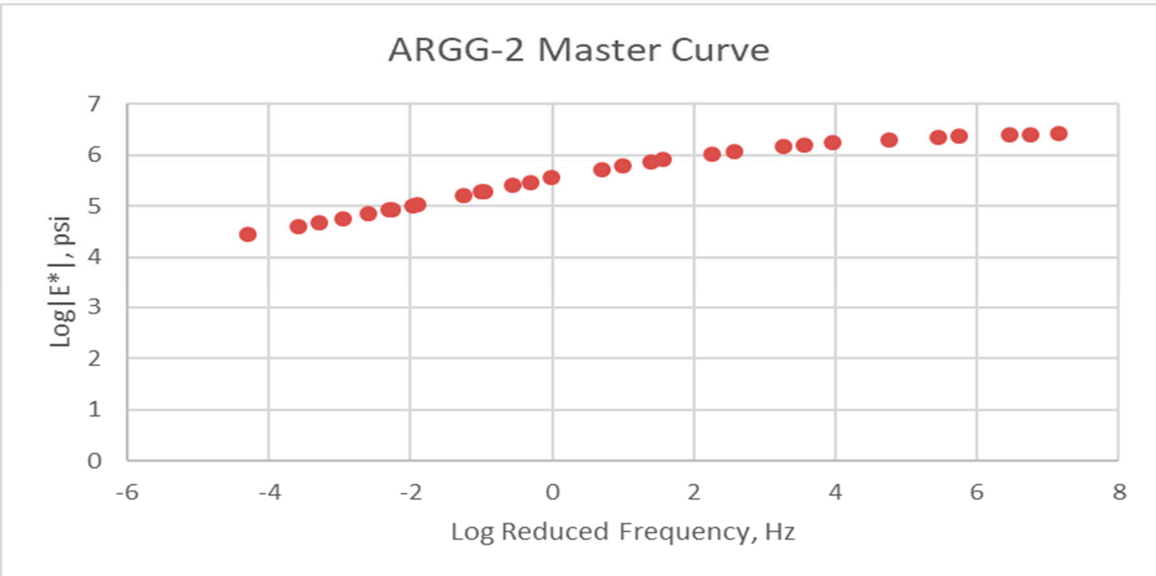

Figure A17. ARGG-2 cross-section master curve.

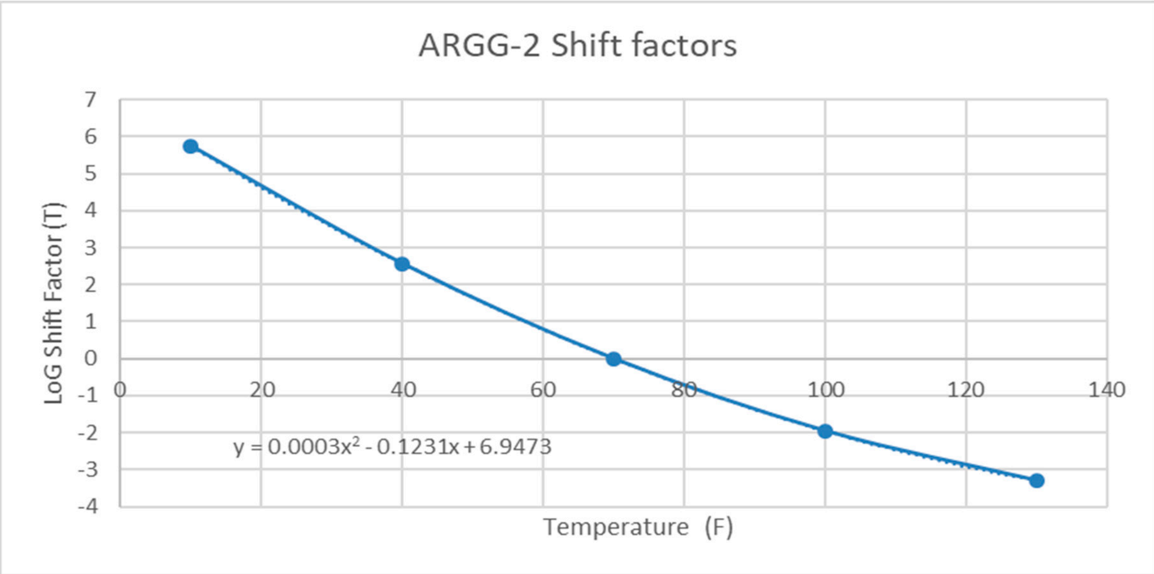

Figure A18. ARGG-2 cross-section shift factors.

Table A14. Dynamic modulus input for T-1 cross-section.

T-1				
Temp (F)	**Frequency (Hz)**			
	0.1	**1**	**10**	**25**
10	1,671,717.47	2,057,179	2,315,221	2,387,669
40	655,208.6218	1,081,775	1,568,820	1,770,225
70	111,555.0371	262,359.1	558,316.2	716,218.8
100	32,156.70826	57,201.74	131,883.5	188,498.1
130	14,663.03545	19,164.5	29,545.46	37,104.88

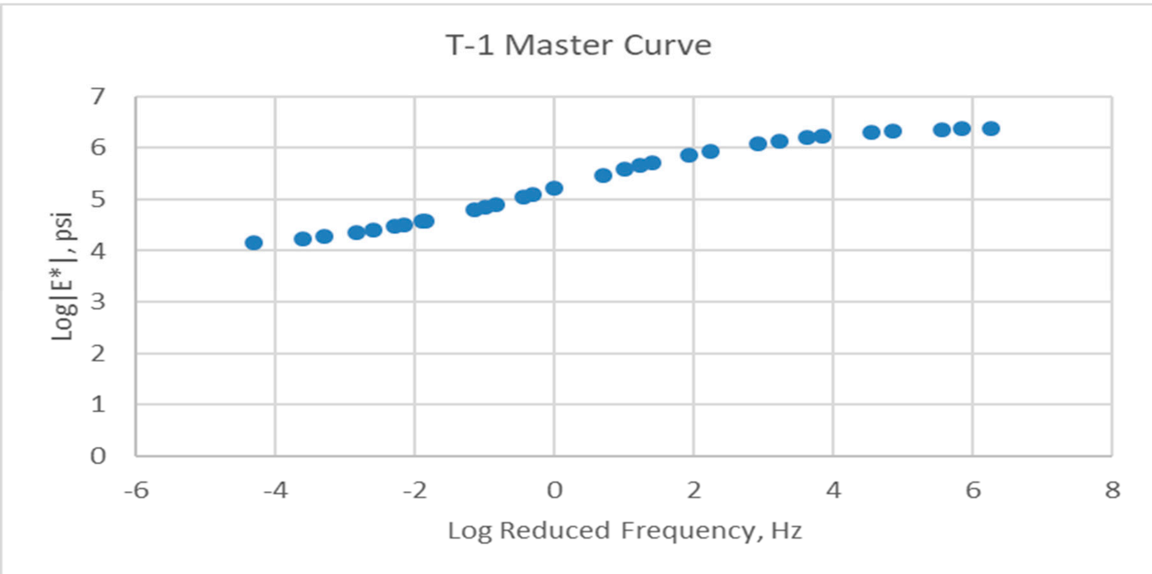

Figure A19. T-1 cross-section master curve.

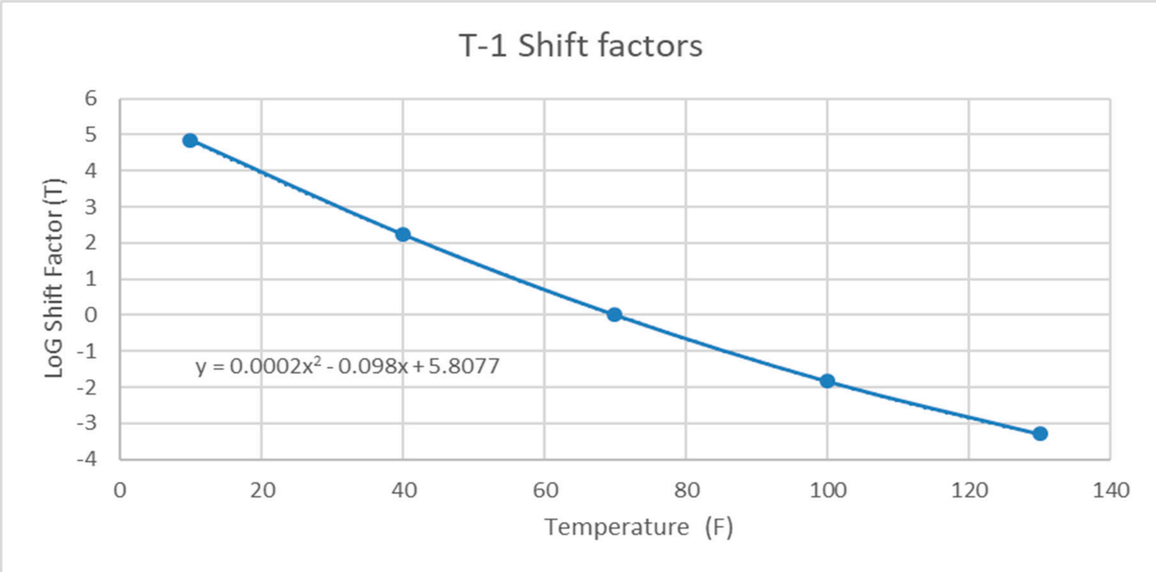

Figure A20. T-1 cross-section shift factors.

Table A15. Dynamic modulus input for THS-1 cross-section.

THS-1				
Temp (F)	**Frequency (Hz)**			
	0.1	**1**	**10**	**25**
10	2,468,122.901	2,773,966	2,962,146	3,013,166
40	1,060,744.307	1,530,931	2,067,423	2,278,389
70	198,413.424	427,556.5	820,621.8	1,016,861
100	55,629.35472	102,580.4	233,180.4	324,235.4
130	27,789.83053	41,829.18	75,808.53	100,861

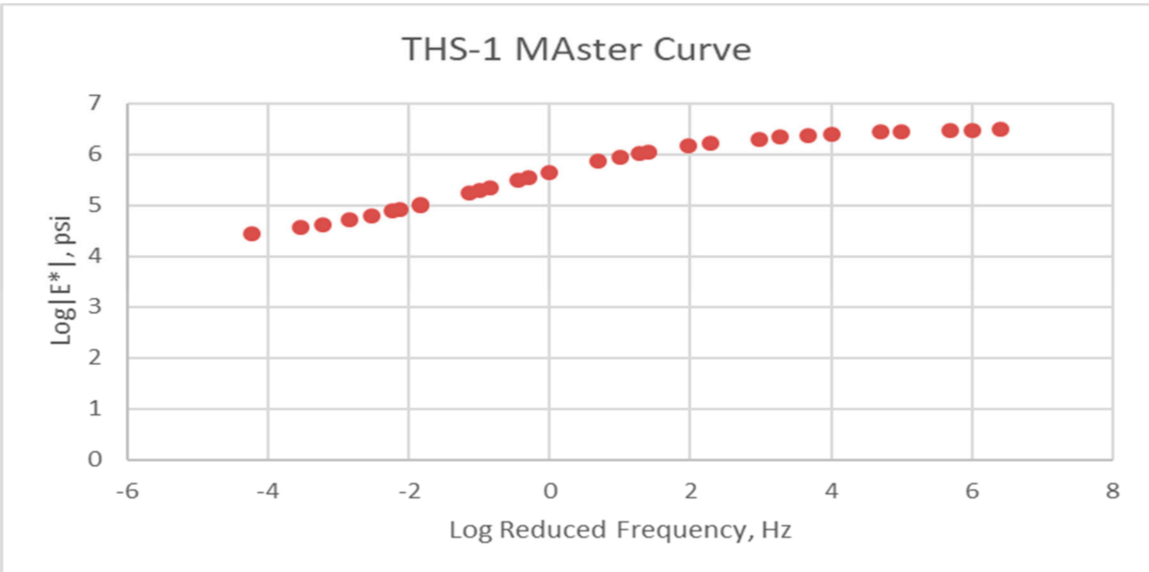

Figure A21. THS-1 cross-section master curve.

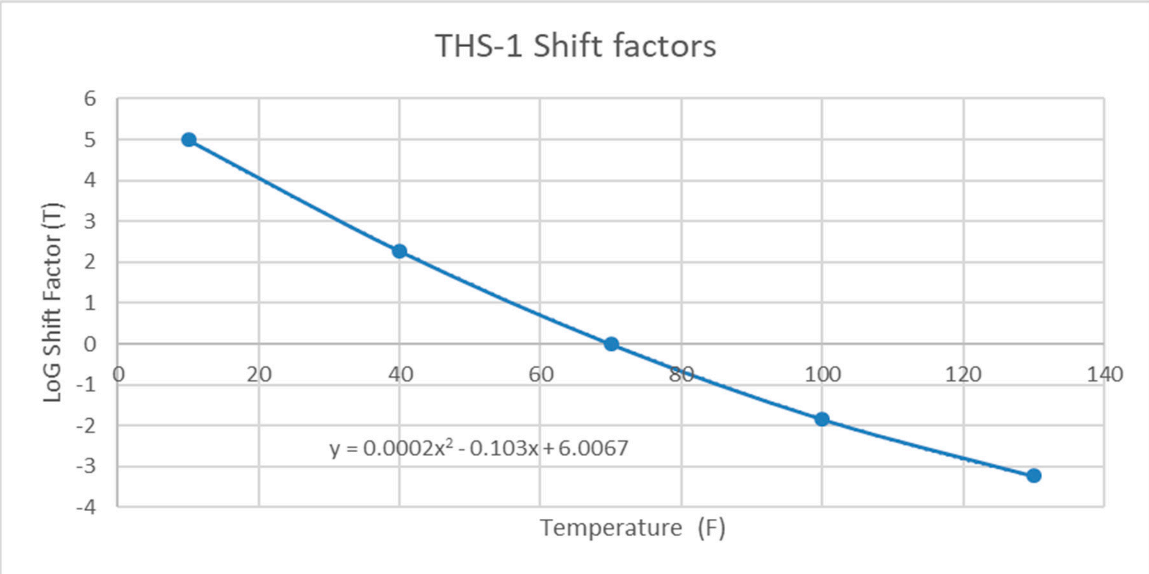

Figure A22. THS-1 cross-section shift factors.

Table A16. Dynamic modulus input for SHM-1 cross-section.

SHM-1				
Temp (F)	**Frequency (Hz)**			
	0.1	**1**	**10**	**25**
10	1,334,184.018	1,721,320	1,987,313	2,061,850
40	323,538.2494	648,593.7	1,092,120	1,273,953
70	70,265.07206	135,411.7	289,778.7	390,499.8
100	34,666.43581	48,370.83	81,156.58	105,082.9
130	27,227.06839	31,853	41,968.07	48,997.99

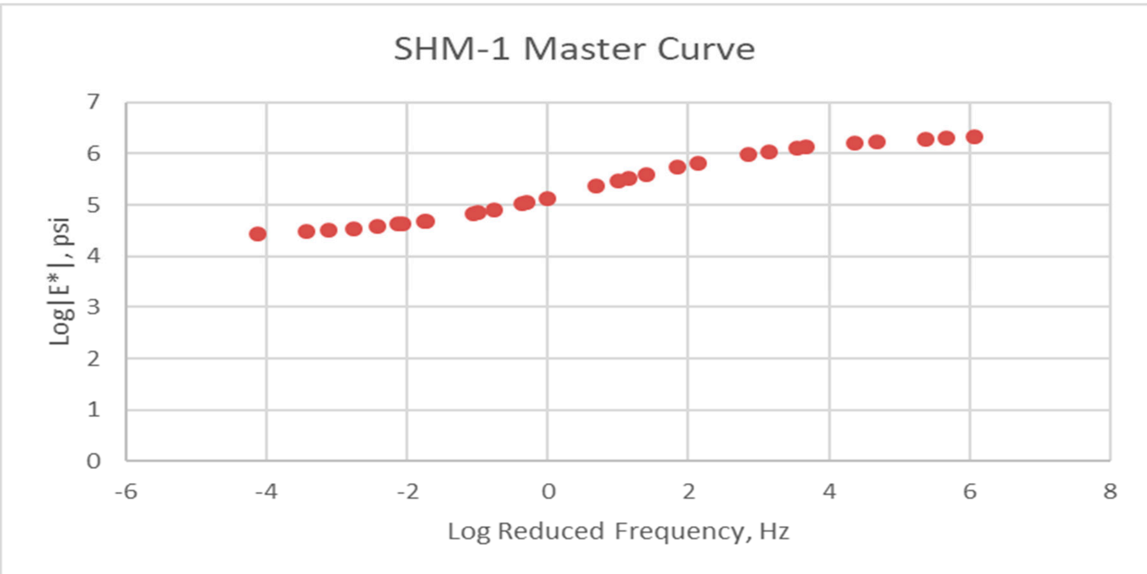

Figure A23. SHM-1 cross-section master curve.

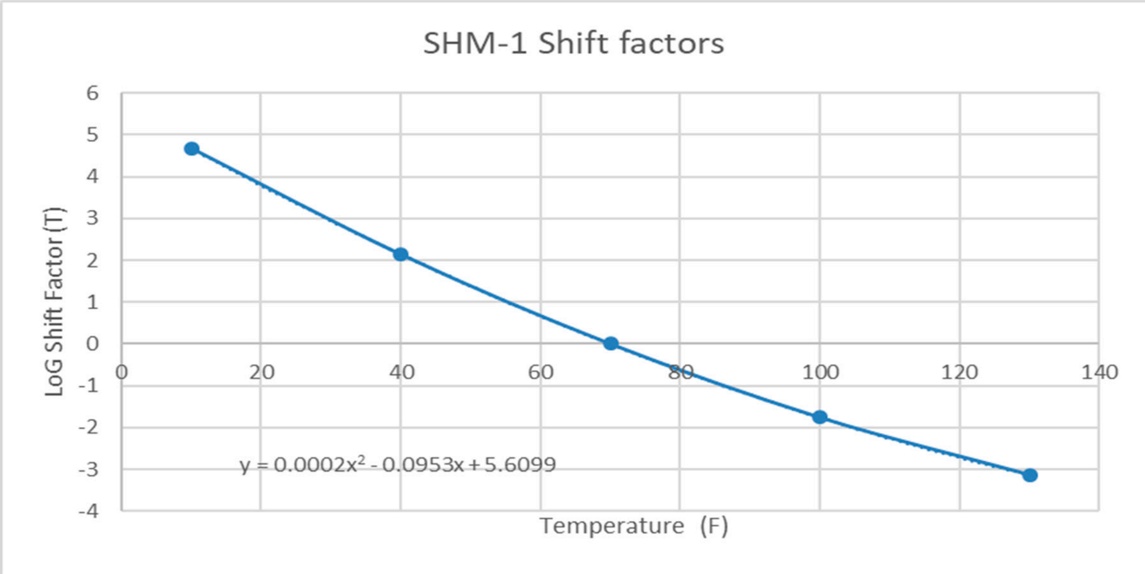

Figure A24. SHM-1 cross-section shift factors.

Table A17. Dynamic modulus input for B-1 cross-section.

B-1				
Temp (F)	**Frequency (Hz)**			
	0.1	**1**	**10**	**25**
10	2,389,826	2,739,077	2,977,744	3,047,586
40	1,022,230	1,482,512	1,986,847	2,187,285
70	222,885.2	461,931.6	853,728.2	1,047,307
100	53,774.47	112,214.4	255,679	350,569.3
130	21,303.35	37,603.73	77,110.14	105,669.7

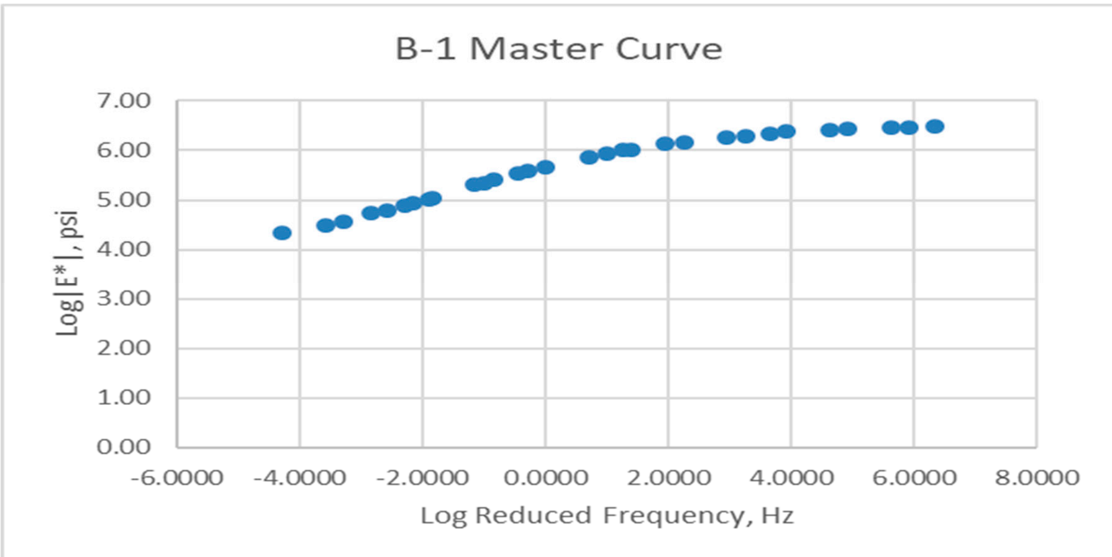

Figure A25. B-1 cross-section master curve.

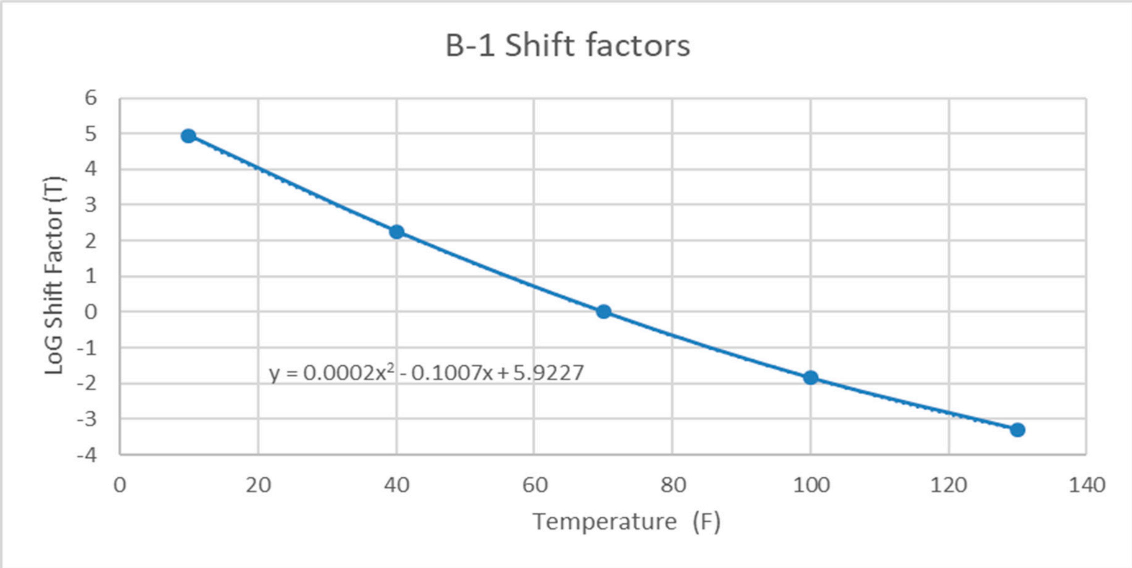

Figure A26. B-1 cross-section shift factors.

Table A18. Dynamic modulus input for BB-1 cross-section.

BB-1				
Temp (F)	**Frequency (Hz)**			
	0.1	**1**	**10**	**25**
10	2,442,356.456	2,576,548	2,662,972	2,687,742
40	948,857.5471	1,360,029	1,820,795	2,000,413
70	159,373.9746	363,308.6	678,359	835,859.2
100	41,299.4409	81,029.95	185,399.2	256,839.6
130	23,343.24016	46,724.3	102,701.4	141,528.8

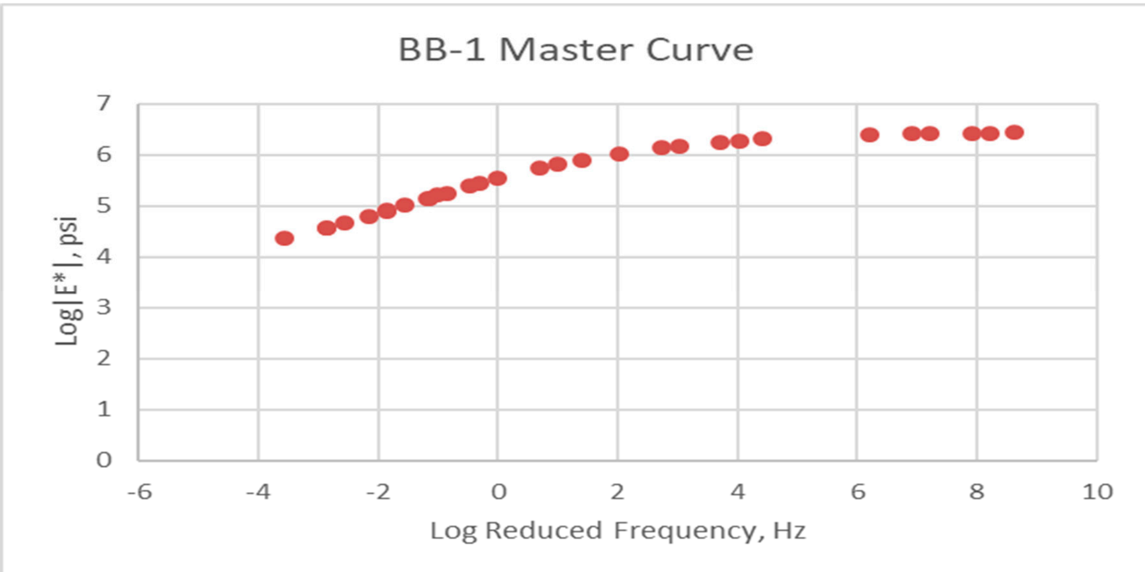

Figure A27. BB-1 cross-section master curve.

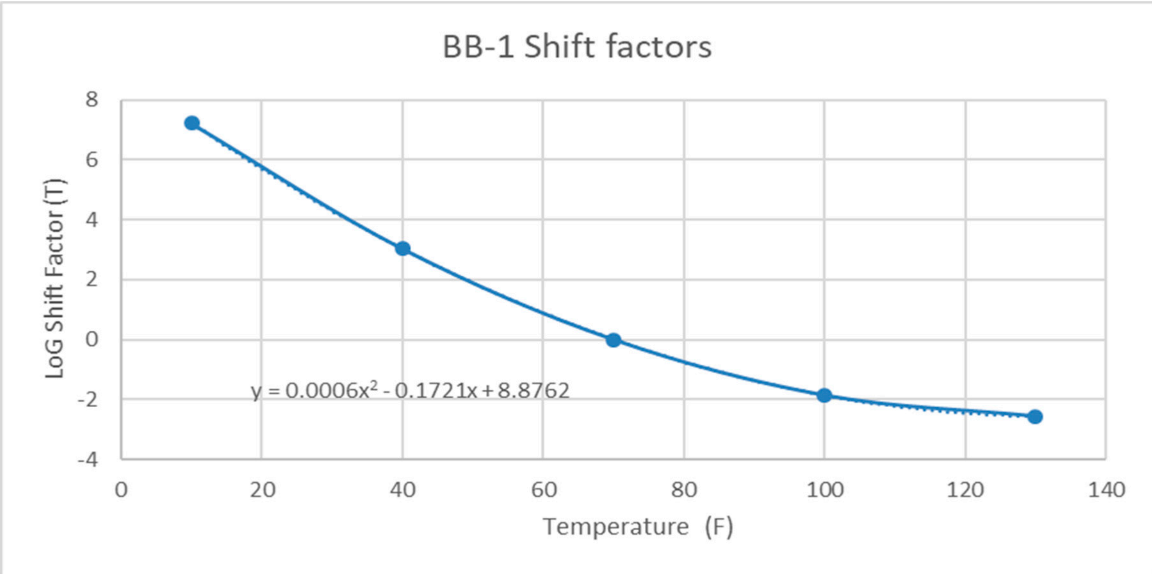

Figure A28. BB-1 cross-section shift factors.

Appendix A.4.3. Complex Shear Modulus (G*) Pavement ME Binder Input

Table A19. Summary of Superpave performance grade (PG) information for each mixture.

B-1	Temp (C)	Temp (F)	G* (Pa)	Phase Angle
PG 64-28	64	147.2	1193	86
	70	158	300	87.5
	76	168.8	250	89
BB-1	Temp (C)	Temp (F)	G* (Pa)	Phase Angle
PG 64-28	64	147.2	1107	82.93
	70	158	300	85.97
	76	168.8	250	89
ARGG-1	Temp (C)	Temp (F)	G* (Pa)	Phase Angle
PG 58-28	58	136.4	1505	85.93
	64	147.2	700	87.47
	70	158	300	89
ARGG-2	Temp (C)	Temp (F)	G* (Pa)	Phase Angle
PG 58-28	58	136.4	1479	86.18
	64	147.2	700	87.59
	70	158	300	89
T-1	Temp (C)	Temp (F)	G* (Pa)	Phase Angle
PG 64-28	64	147.2	1100	82.76
	70	158	300	85.88
	76	168.8	250	89
THS-1	Temp (C)	Temp (F)	G* (Pa)	Phase Angle
PG 76-28	76	168.8	1301	67.83
	82	179.6	200	78.42
	88	190.4	100	89
SHM-1	Temp (C)	Temp (F)	G* (Pa)	Phase Angle
PG 70-34	70	158	1245	54.21
	76	168.8	250	71.61
	82	179.6	200	89

Appendix A.5. Maintenance and Rehabilitation Alternative Emission Results

Table A20. ARGG-1 M&R alternative emissions from Palate 2.0 software.

ARGG-1 Cross Section			
Baseline		Energy [MJ]	CO_2 [Mg] = GWP
Initial Construction	Materials Production	37,972,888,683	2,004,224
	Materials Transportation	2,003,300,632	149,765
	Processes (Equipment)	193,655,431	14,535
	SUM	40,169,844,745	2,168,524
Mill and Fill		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	6,865,339,512	368,288
	Materials Transportation	405,995,727	30,352
	Processes (Equipment)	54,425,489	4,085
	SUM	7,325,760,728	402,725
CIR		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	5,149,004,634	276,216
	Materials Transportation	340,644,743	25,466
	Processes (Equipment)	49,098,146	3,685
	SUM	5,538,747,523	305,368
Microsurface		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	3,432,669,756	184,144
	Materials Transportation	275,293,760	20,581
	Processes (Equipment)	41,779,821	3,136
	SUM	3,749,743,337	207,861

Table A21. ARGG-1 M&R alternative emissions from Palate 2.0 software.

ARGG-2 Cross Section			
Baseline		Energy [MJ]	CO_2 [Mg] = GWP
Initial Construction	Materials Production	37,972,888,683	2,004,224
	Materials Transportation	2,003,300,632	149,765
	Processes (Equipment)	193,655,431	14,535
	SUM	40,169,844,745	2,168,524
Mill and Fill		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	6,795,577,992	363,862
	Materials Transportation	412,709,701	30,854
	Processes (Equipment)	55,053,496	4,132
	SUM	7,263,341,189	398,848
CIR		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	5,096,683,494	272,897
	Materials Transportation	345,680,224	25,843
	Processes (Equipment)	49,569,152	3,720
	SUM	5,491,932,870	302,460
Microsurface		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	3,397,788,996	181,931
	Materials Transportation	278,650,747	20,832
	Processes (Equipment)	42,093,825	3,159
	SUM	3,718,533,568	205,922

Table A22. THS-1 M&R alternative emissions from Palate 2.0.

THS-1 Cross Section			
Baseline		Energy [MJ]	CO_2 [Mg] = GWP
Initial Construction	Materials Production	37,972,888,683	2,004,224
	Materials Transportation	2,003,300,632	149,765
	Processes (Equipment)	193,655,431	14,535
	SUM	40,169,844,745	2,168,524
Mill and Fill		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	5,381,887,465	284,662
	Materials Transportation	404,968,158	30,275
	Processes (Equipment)	54,198,337	4,068
	SUM	5,841,053,960	319,005
CIR		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	4,036,415,599	213,497
	Materials Transportation	339,874,066	25,409
	Processes (Equipment)	48,927,782	3,672
	SUM	4,425,217,448	242,578
Microsurface		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	2,690,943,733	142,331
	Materials Transportation	274,779,975	20,542
	Processes (Equipment)	41,666,245	3,127
	SUM	3,007,389,953	166,001

Table A23. T-1 M&R alternative emissions from Palate 2.0 software.

T-1 Cross Section			
Baseline		Energy [MJ]	CO_2 [Mg] = GWP
Initial Construction	Materials Production	37,972,888,683	2,004,224
	Materials Transportation	2,003,300,632	149,765
	Processes (Equipment)	193,655,431	14,535
	SUM	40,169,844,745	2,168,524
Mill and Fill		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	5,442,180,423	287,509
	Materials Transportation	412,579,971	30,844
	Processes (Equipment)	54,922,550	4,122
	SUM	5,909,682,943	322,475
CIR		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	4,081,635,317	215,631
	Materials Transportation	345,582,926	25,835
	Processes (Equipment)	49,470,942	3,713
	SUM	4,476,689,185	245,180
Microsurface		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	2,721,090,211	143,754
	Materials Transportation	278,585,882	20,827
	Processes (Equipment)	42,028,352	3,154
	SUM	3,041,704,445	167,736

Table A24. SHM-1 M&R alternative emissions from Palate 2.0 software.

SHM-1 Cross Section			
Baseline		Energy [MJ]	CO_2 [Mg] = GWP
Initial Construction	Materials Production	37,972,888,683	2,004,224
	Materials Transportation	2,003,300,632	149,765
	Processes (Equipment)	193,655,431	14,535
	SUM	40,169,844,745	2,168,524
Mill and Fill		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	5,492,078,801	290,431
	Materials Transportation	411,118,915	30,735
	Processes (Equipment)	54,788,931	4,112
	SUM	5,957,986,647	325,278
CIR		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	4,119,059,101	217,823
	Materials Transportation	344,487,134	25,754
	Processes (Equipment)	49,370,728	3,706
	SUM	4,512,916,963	247,282
Microsurface		Energy [MJ]	CO_2 [Mg] = GWP
Maintenance	Materials Production	2,746,039,401	145,215
	Materials Transportation	277,855,354	20,772
	Processes (Equipment)	41,961,542	3,149
	SUM	3,065,856,297	169,137

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