A NETWORK-LEVEL PAVEMENT LIFE CYCLE ASSESSMENT FRAMEWORK FOR PROJECT SELECTION AND PRIORITIZATION IN PAVEMENT MANAGEMENT SYSTEMS

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The Road Forward

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TABLE OF CONTENTS

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1 INTRODUCTION

Transportation in the United States is the main contributor to the generation of Green-House Gases (GHGs), at around 28% of the total, and, thus, a significant driver of climate change (United States Environmental Protection Agency 2023). While many efforts are underway worldwide, and in the USA by 2050, to reach net zero emissions, personal access by driving and freight movement will continue to play a significant role in modern civilization, so reaching this goal will undoubtedly require significant changes to the vehicle fleet. However, the role of pavement condition in GHG emissions generation is often overlooked in policy and practice. This project focuses on the development of a framework that can be implemented at a state agency level, potentially within their existing Pavement Management System (PMS), that will support project selection and prioritization decisions based on GHG emissions and cost in addition to, or potentially in place of, indicators such as MAP-21[1] Good/Fair/Poor metrics or other traditional benefit measures. The framework lays out the elements needed to perform this type of network-level Life-Cycle Assessment (LCA) and provides guidelines for developing and implementing them for a particular agency.

This report also details the application of this framework to the California Department of Transportation (Caltrans) managed highway network and a portion of the Virginia DOT (VDOT) managed network. These are intended as examples of how the framework can be used, not as exhaustive studies. The origins of the framework are in the first global implementation of a pavement network-level LCA, which was for Caltrans in 2013 (Harvey, Wang, and Lea 2014; Basheer and Mafi 2021), which explains why the state was chosen as an example. This study updates some of the earlier work from California based on ten years of experience and further expands on some details. While the framework for PMS is similar across much of the world, the details can differ considerably. The implementation for Virginia is new and is intended as a test case to determine what additional components need to be developed for another agency.

Both the Infrastructure Investment and Jobs Act of 2021[2] and the Inflation Reduction Act of 2022[3] include programs incentivizing state transportation agencies to reduce transportation-related GHG emissions. Through these acts, the Federal Highway Administration (FHWA) is administering $2B in Low-Carbon Transportation Materials Grants to advance paving materials with lower embodied carbon. More than half of US states have established their own GHG reduction goals, many of which specifically include transportation-related emissions. Most of these programs and funds will likely be directed toward transit projects, pedestrian and cycle paths, micro-mobility, electric vehicle infrastructure, and potentially changes to pavements built to carry vehicles.

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[1] https://www.congress.gov/bill/112th-congress/house-bill/4348
[2] https://www.congress.gov/bill/117th-congress/house-bill/3684
[3] https://www.congress.gov/bill/117th-congress/house-bill/5376

Some proposed funding mechanisms specifically disallow highway capacity expansion for passenger vehicles. However, there are opportunities for agencies to leverage their highway maintenance programs to improve the smoothness of their existing asphalt pavement networks, thereby reducing vehicle fuel consumption and, thus, GHG emissions, while the vehicle fleet is still dependent on fossil-based transportation fuels or non-renewable electricity sources. In addition, this could reduce vehicle maintenance costs, extend vehicle life (regardless of fuel type), extend electric vehicle range (models need to be developed), and extend pavement life by maintaining pavements in a state of good repair and reducing dynamic vehicle loads, thus improving the road network's sustainability. In other words, pavement maintenance activities that improve smoothness can be considered GHG mitigation strategies for agencies, and these strategies could be incorporated into agencies' climate action plans, enabling them to qualify for federal infrastructure grants (when they become available) to fund the incremental costs of these activities where they produce beneficial results.

Examples of these strategies can include optimizing maintenance trigger levels or schedules to address roughness based on a combination of pavement smoothness and traffic levels, as has been evaluated at length by (Harvey et al. 2020) and (T. Wang, Harvey, and Kendall 2014), or using capital preventive maintenance overlays as a pavement preservation technique to reduce life cycle GHG emissions, as described by (Z. Wang and Pyle 2019). Other applications may be developing and implementing smoothness incentives or optimizing pavement maintenance schedules.

Additionally, (Robbins and Tran 2018) found that most agencies rely on pavement condition indices other than the international roughness index (IRI) as the trigger for first rehabilitation in their pavement management systems (PMS). The authors also found that asphalt pavements tend to be smoother than concrete pavements at first rehabilitation, suggesting the potential roles of pavement type selection, construction smoothness specifications, and life cycle pavement smoothness on life cycle GHG emissions. In addition, the trigger levels used for IRI in standards such as MAP-21 or in PMSs that use IRI are set based on triggering treatment at historically "unacceptable" levels rather than trigger values optimized for maximum IRI benefit or consideration of GHG emissions.

To achieve these goals requires a framework for state and local agencies to quantify the GHG emission reductions associated with changes in pavement smoothness as a result of pavement construction and maintenance activities, considering the emissions from the pavement materials, their transport, and construction activities as well as the reductions in GHG emissions from vehicles operating on the resulting smoother pavement. Since the vast majority of transportation emissions are from the vehicles, any strategies that reduce these emissions are likely to result in net savings, especially those that impact all vehicles without the need to invest in new vehicles or technologies.

2 FRAMEWORK

At the core of any strategy to reduce GHG emissions, a life cycle analysis of the system needs to be performed to give a better picture of what benefits could be achieved by making well-informed decisions. LCA is one application of a systems approach to analyzing a decision process over time. The other common application of this approach in pavement management is Life-Cycle Cost Assessment (LCCA), which is used to find a system's net cost or benefit. In both cases, the 'system' in question is a project over some lane miles, with projected future traffic, performance, and maintenance, not the highway system (which will be referred to as the 'network' here). Unlike project cost, which is aggregated automatically through contract invoicing, the GHG generated by the production, hauling, and placement of materials during initial construction and any maintenance treatments need to be accounted for and aggregated. In LCA terminology, this is referred to as extending the system boundary. Splitting the construction-related emissions from the traffic emissions (commonly called the 'use' stage) is standard in reporting GHG effects. In LCA and LCCA, the use stage system boundary always includes vehicle operation on the pavement section. In LCCA, expanding the use stage system boundary to include indirect and knock-on costs or benefits (such as road user delay costs) is common, but this is less common in LCA. Regardless, the choice of system boundary is usually left to the agency that manages the road in question and is not dictated by this framework.

Before discussing the details of the framework, it is essential to review the goals the framework is intended to address.

- **The first goal** is to allow network-level analysis to quantify network-wide GHG savings from different policies or budgets. An example of this type of analysis might be moving from seal coats, which do not significantly improve smoothness, to thin overlays as a maintenance treatment.
- **The second goal** is to allow the development of optimized triggers, such as setting different IRI triggers for different traffic levels.
- **The third goal** is to facilitate network-level LCA screening by highlighting projects with significant potential GHG savings during network-level project selection. These might be candidates for project-level LCA to optimize GHG savings through improved design alternatives.

The framework must thus attempt to merge an LCA of each potential future project with the existing pavement management framework used by most state and local road-owning agencies.

2.1 Network-level PMS Framework

Pavement management systems have been in everyday use worldwide since initial implementation by pioneer agencies in the late 1970s (Haas and Hudson 1978), and their essential components have not changed significantly in this period. These components and how they interact are shown in **Figure 1**. At the PMS's core is a 'master' table that captures information on the network being managed. Each row in this table is a 'management segment;' the list of segments should cover the network completely. The columns in the table are the data used to manage the segments.

Each segment requires some location identifier, which is often a route with a milepost begin and end but could be a GIS object identifier or another scheme—so long as the system can uniquely identify the management segment. The remaining data must capture the existing state of the management segment to the level of detail used in decision-making, which typically includes information about the last activity performed on the segment, the current condition, and traffic information.

The next major part of a PMS is the performance models, which are used to predict the future performance of each management segment. These must predict the same variables used to capture the current condition, or at least the subset used in decision-making. Using performance models to predict future condition differentiates infrastructure management from asset management, which focuses on current condition and value. The parameters of the performance models typically depend on the pavement type of the segment (as determined from the last activity), traffic, and other variables. In most modern PMSs, these performance models are deterministic and are run to predict the condition annually. With just the table of management segments and the performance models, one can run a 'do nothing' or 'freefall' scenario, which predicts how the condition of the network would change if no future maintenance activities were undertaken.

However, most realistic future scenarios involve maintenance, termed the 'work plan' or 'project list.' While these could be developed outside of the PMS, this role, as a decision support system for project selection, drives the adoption of pavement management in most agencies. The next required component is thus a list of generic construction and maintenance activities. This report will refer to these as 'treatments' since each might require multiple physical activities, such as milling followed by paving. These can be high-level activities such as 'rehabilitation' or 'routine maintenance' or more detailed descriptions, such as '2 in Mill and Overlay.' Often, a PMS will have a mix of different specificities since segments might be assigned a generic activity such as 'rehabilitation' in the future (five to ten years), and this might be refined as the project is scoped, designed, and bid. Eventually, projects under construction and past projects provide detailed information about the exact layers and materials. The case studies show examples of these treatments and the hierarchy. The high-level categories will be called 'strategies' while the detailed treatment level will be called 'structures.' Regardless of the specific treatment, the PMS needs to be able to estimate the improvement in the condition from performing the activity and, in most cases, estimate the cost. One "activity" that must always be considered is to 'Do Nothing.'

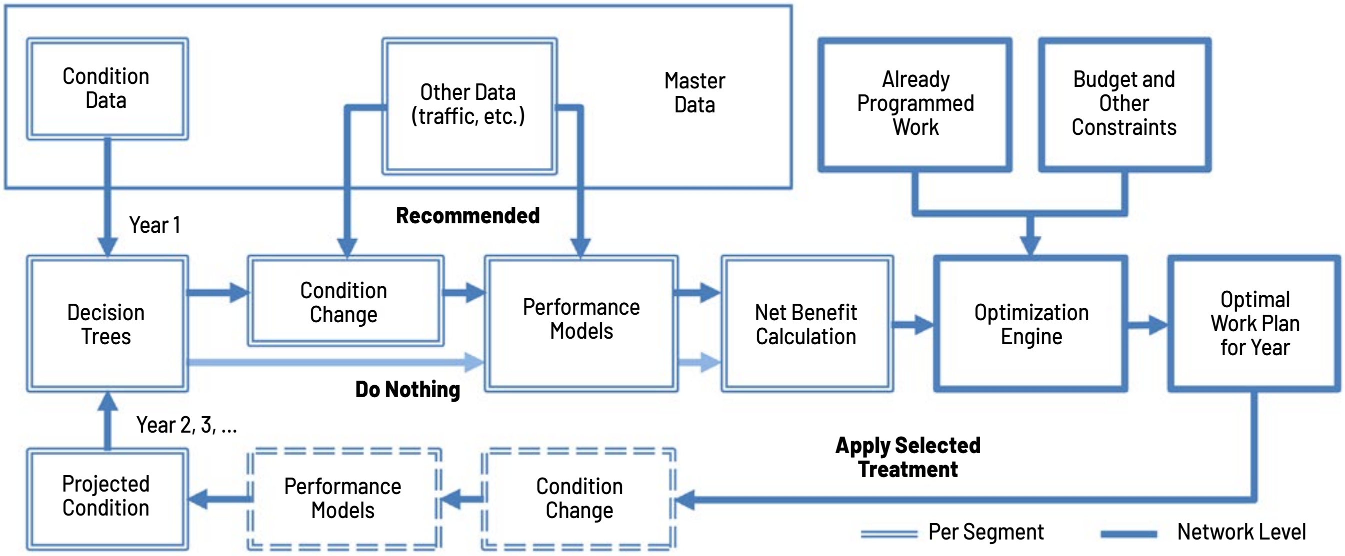


Figure 1. Classical PMS decision framework

Once a list of possible treatments is available, the PMS needs a method to select which to apply, given the current state of a particular management segment. The method most used for this task is decision trees, which allow the system to walk through a nested set of if-then-else statements based on the condition and finally come to a leaf node that decides the appropriate treatment. These decision trees are the "engineer in the box" that should mimic what treatment an experienced engineer would recommend based on observing the segment and should reflect the optimal choice given an unlimited budget. In many PMSs, these are high-level treatment categories, such as "Preventive Maintenance" or "Rehabilitation," while in others, they are more detailed, such as "Seal Coat" or "Thick Overlay." Finding a system that uses detailed treatment structures (i.e., those with specified materials and some definition of layer thickness) in the decision trees is uncommon but is present in at least some State DOT PMSs. Together with the performance models, the selection process enables a PMS to perform an 'unlimited budget' or 'now needs' type analysis at a network level. Decision trees are typically based on judgment and have not been optimized objectively for life cycle cost or any other objective goal.

The final major piece in a network-level PMS is an optimization engine, which can take the recommended treatments from the decision trees and apply constraints, especially budgets, to determine which recommended activities can be performed within the constraints while maximizing some benefit. This engine is the "manager in the box" that accepts or rejects project proposals to determine an optimal final list of proposed treatments. In most cases, PMSs only choose between the optimal activities recommended by the decision trees, not the complete set of possible activities that could be performed on a segment. Also, except for cutting-edge systems, this optimization takes place year-by-year, so multi-year optimal treatment strategies are not considered (unlike project-level LCA/LCCA, which has a multi-year maintenance strategy or schedule).

Unless the network-level optimization is performed to minimize budgets while maintaining a percentage of the lane miles better than some unacceptable state (which would be considered an asset management approach), the PMS needs some variable to optimize, typically called the benefit. There are many different ways to calculate the benefit, but one commonly used method is to compare the area between the performance curves for alternative treatments, as shown in **Figure 2**, which also captures many other components discussed above, such as performance curves and condition improvement.

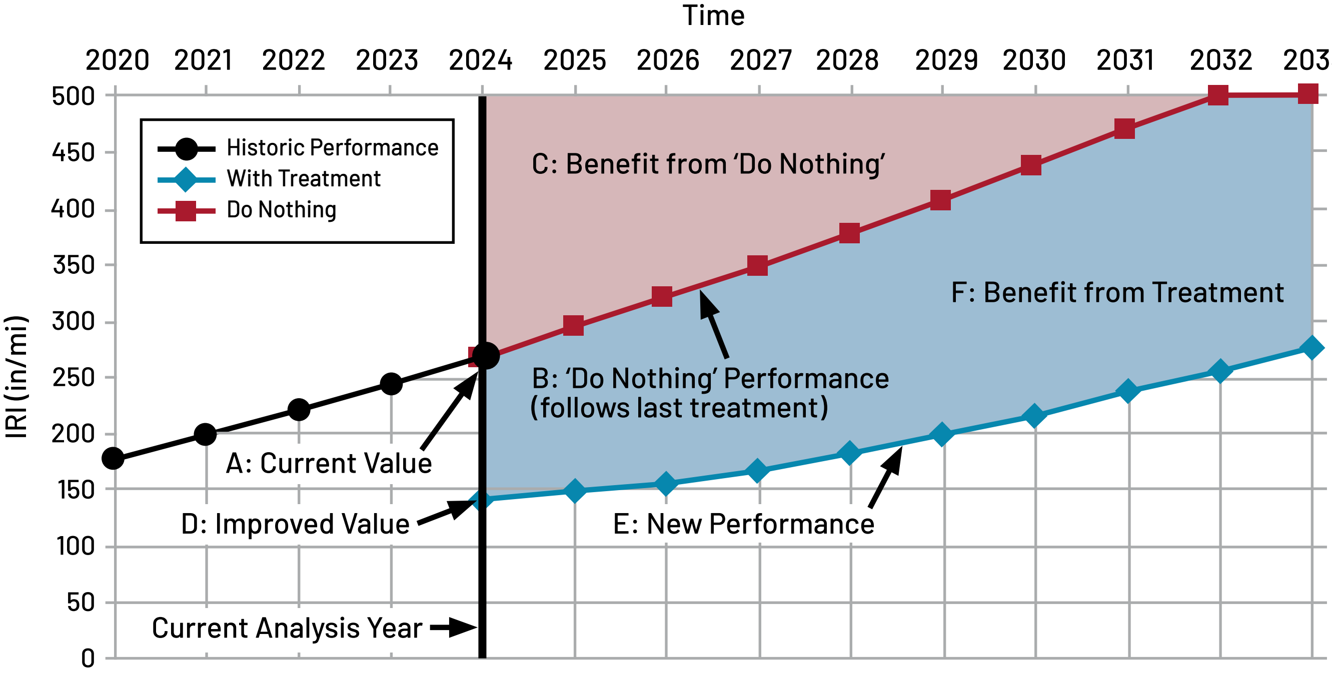


Figure 2. **Calculation of benefit using the area between performance curves approach.**

One possible benefit is to compute network-level GHG emissions using this formulation, which will be detailed later, although this is not a requirement of the framework, except if one wants to target project selection to find those projects with the lowest expected emissions. Because the optimality of the decision-making rests with the decision trees, not the benefits (and the two do not necessarily have the same definition of optimal), an alternative approach based on altering the decision trees will also be presented.

Most PMSs have many more components, including data entry and validation, reporting, and mapping. For a network-level GHG framework, the results from an LCA would be integrated directly into the core pavement management framework, so the results could thus be worked into the rest of these functions by including these new data streams alongside those used for other PMS functions.

2.2 LCA of Pavements

As mentioned above, LCA is a systems approach to determine/quantify a particular section's environmental and resource use impacts over the life cycle. Unlike LCCA, which considers direct costs, the heart of LCA is assembling a directed graph of physical processes involved in each activity required for constructing a particular project. Construction is then followed by the use stage, which might be punctuated by multiple maintenance cycles, and each construction or maintenance stage might have multiple construction activities, depending on the design, with each activity requiring a web of connected processes to produce the final result. Each physical process is driven by a 'unit output' such as "crushing one metric tonne of gravel," along with the required raw materials (e.g., mined rock), energy and other inputs, and other outputs, including co-products, waste, and emissions. Sometimes, these processes also require control variables, such as transport distance or layer thickness. These process nodes are linked together based on their inputs and outputs (e.g., "hot-mix asphalt" would require "crushed gravel," which would need "mined rock"), and the resulting network is then 'balanced,' which is the process of scaling the unit outputs to the actual quantity needed by the input to the next node, starting from the definition of the activity. These process nodes need to be manually developed based on specialist knowledge of each process, and the resulting data are known as a Life-Cycle Inventory (LCI). LCA analysis is typically performed in software, which also acts as a front-end to its internal LCI database.

Once the process nodes have been balanced, the various emissions streams from all the processes can be aggregated to find the overall emissions from each activity. These emissions are generally transformed into 'impacts,' which are then summed over all the activities in the stage to determine the final impacts from each stage. The impacts over the system's entire life cycle are then obtained by combining the impacts from all the stages. Like LCCA, emissions from short-term events like construction are tied to the service life of the treatment and the prorated impact of the construction based on the service life remaining at the end of the analysis period is subtracted from the life cycle summation, like "salvage value" in LCCA. Unlike LCCA, no discounting of future impacts is performed in most LCA. Also, while there is ongoing work on equity and other spatial impacts, the physical location of emitting these gases or otherwise incurring the impact is not considered.

In this report, the primary impact of interest is global warming—the warming or heating that occurs because of GHG emissions from human activities, the phenomenon causing climate change. These emissions are converted to "CO_2 equivalents" using characterization factors or global warming potentials (GWPs) developed within the environmental analysis community, which measure how much these emissions contribute to long-term climate change. The result is the Global Warming Impact (GWI) or GHG effect. The US Environmental Protection Agency has developed impacts for US geographic conditions called the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (Bare 2011), the favored method for converting emissions to impacts. Consistent with the United Nations Framework Convention on Climate Change guidance, TRACI uses GWPs with 100-year time horizons. However, in implementing the framework, an agency could use any set of impacts to evaluate the network; other impacts could include acidification, smog formation, or the effect on human health due to particulate matter of less than 10 or 2.5 microns.

Since this LCA balancing process is complex, it is often performed once, and the emissions and impacts are aggregated to a single process node for an activity or material, which "caches" the results, which is convenient but can mask some critical variables in the process, such as the choice of electricity mix. This can hide regional or time differences in the result, so care should be taken when using these types of results.

To determine the actual benefits or dis-benefits of applying a treatment, one needs to analyze the entire life cycle of the system, which, in this case, is the pavement. At a project level, the system boundary would include extraction of raw materials, their transportation to the manufacturing/processing plants, product manufacturing and transport to the construction site, construction, product use, maintenance/preservation/rehabilitation, transportation of removed materials to recycling facilities or landfills, and end of life (waste management which could include recycling or landfill). While this analysis might be doable at a project level if enough information/data are available and there are few unknowns, at the network level, quantification becomes difficult as it is uncertain what budget will be available to maintain the roads in the future or how they will perform, given that future traffic is also unknown; thus, what treatment needs to be applied is unknown. Similarly, the choice of materials, mix designs (job mixes), and pavement structure design decisions are also unknown.

However, while this analysis is appropriate at a project level, a pavement segment is not a product like a car that is manufactured, used, and disposed of, so assigning a "life cycle" to a pavement segment is somewhat artificial. Therefore, while typical, this choice of the system boundary is not inherently the right choice for aiding decision-making.

2.3 Network-level PMS LCA Framework

Developing a network-level GHG quantification framework would thus require performing an LCA on every possible treatment for every segment. However, as just seen, this is impossible since many variables are unknown, even if it was computationally feasible. It is thus necessary to simplify the LCA procedures, much like LCCA procedures are simplified in PMSs, while altering the system boundary to consider the network as a whole. The LCA can be simplified because different alternative treatments, at a network level, are not likely to make any difference in a variety of use-stage GHG emissions (like the traffic mix), so making assumptions about these areas will still result in the correct project selection based on expected impacts, and valid estimates of GHG savings when applied as network-level policy. The framework presented here assumes expected value decision-making, meaning that at a network level, the most likely emissions are considered for a specific scenario, not possible worse or best cases, nor considering the risk of encountering these extremes.

Like many simplifications, the framework here assumes that the expected value of GHG emissions is equal to the emissions at the expected values of the inputs. For non-linear systems, which the GHG emissions calculations are, this is known to be an invalid assumption. However, a few reasons (besides the impossibility of performing the analysis without this assumption) allow this to be justified. Firstly, as mentioned above, the absolute emissions are not of primary interest, but rather the relative emissions, and the types of non-linearities involved in the calculations are unlikely to change the ordering of alternatives. Secondly, most of the non-linear models are close to linear. For example, on the materials and construction side, most emissions scale as linear functions of thickness, transport distance, and other factors, while on the traffic side, roughness growth over short (ten-year) intervals is often close to linear. Finally, since this is a network-level framework, there are still opportunities to perform project-level LCA in the project design stage of project delivery to confirm or adjust the recommendations.

Nonetheless, the biases introduced by this assumption can be mitigated by pushing the computation of the expected values down as far as possible and performing parts of the expected value computation within the PMS, by summing over all the possible outcomes.
At a high level, this is the motivation behind the entire framework—one could take the condition of the entire network, determine some expected activity and total network traffic, and perform a single computation of

emissions (a process that has been performed in some high-level climate assessments) but this would not provide any of the insights sought in the goals outlined above. The framework thus needs to allow "pushing down" the expected value computation for network-level emissions to individual segments and then summing back up to the network results and extracting insights from the individual segment results.

With this discussion in place, it is now possible to outline the changes needed to the LCA and the PMS to develop a network-level PMS LCA framework. The LCA is changed in three ways:

- The calculations are split into a materials and construction (M&C) stage for each treatment and use stage for each segment.
- The results are computed for expected values for various inputs.
- The system boundary is changed to encompass the entire network annually.

The classic network-level PMS framework is also changed in three ways:

- Calculating impacts when performing a treatment at the point where project cost is computed.
- Computing use stage emissions for the annual traffic on each segment.
- Incorporating impacts into the decision-making.

The revised framework is shown in **Figure 3**. With these changes, a PMS can produce two quantities for each year within a particular analysis: the annual impacts from activities and the annual use stage impacts for the analyzed network.

System analysis aims to compare decisions (i.e., it is a meta-decision-making process, helping to make decisions about decisions). At a project level, LCA and LCCA are usually used to compare alternatives and make the best decision. At a network level, these treatment decisions are made within the PMS and are not what is being compared. Instead, the comparison is between different network-level results. The first framework goal (quantifying network-wide GHG savings from different policies or budgets) can be met by comparing optimization results with these different budgets or using different decision trees. The second goal (the development of optimized triggers) can be met by iterating these changes until an optimal value is found. The third goal (network-level LCA screening) can be met using a GHG benefit to select projects within a particular analysis.

This network-level LCA is referred to as a framework because many details (such as the exact treatments, traffic information, and choice of impacts) are implementation-dependent. This report only lays out the necessary components and why these are needed, so it refers to this as 'the minimal feasible LCA.'

It is essential to mention that the optimization scenario is this framework's "life cycle" boundary. The end-of-life stage is not included directly in the framework since there is no straightforward approach to including it. End-of-life is a waste management decision stage where either the material will be removed and transported to a landfill or recycled on-site/off-site for the same construction and maintenance project, or recyclable

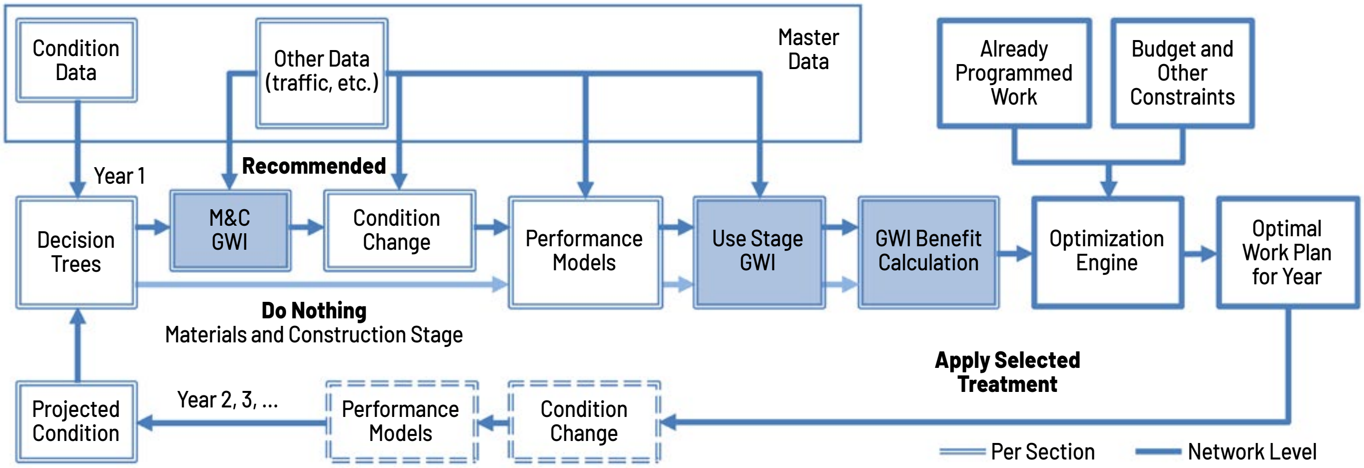


Figure 3. **Framework for network-level LCA in PMS**

material could be transported to a storage facility where it could be used for some other project. However, the network has no end-of-life and will not be removed after the analysis period. The network-level LCA framework developed in this study can include using recycled materials in the mixes, such as HMA mixes containing RAP, cold central plant recycled mixes, and in-place recycling techniques such as full-depth or partial depth recycling. The treatment definition could also include transporting materials (such as millings) to the landfill as waste or recyclable materials for storage. A residual value calculation, often used in LCCA to credit the remaining life of the last treatment at the end of the analysis period, is also not included.

The minimum feasible LCA requires a cradle-to-laid estimate of environmental impacts for each section and for each type of treatment that might be applied (which includes materials, transportation, and construction stages), along with estimates of well-to-wheel impacts (vehicle propulsion energy production and use) from the use stage based on the traffic on the section. In addition, it requires models for at least the roughness performance of each type of treatment. Without different models for each treatment, the use stage will be the same, so the obvious choice would be the treatment with the lowest initial GHG emissions. The models also need to include improvements in condition when treatments are applied.

2.4 Materials and Construction Impacts for Treatments

For the framework, the expected cradle-to-laid GWI must be estimated for each future project on the network. The actual GWI will depend on each project's design and materials, location-specific haul distances, and other factors. On the other hand, most agencies only predict project types as high-level categories, such as preservation or reconstruction (which often align with different agency budgets), which means that the projects being assigned during optimization by the PMS are not even surface-type specific, so there is not enough information to begin performing an LCA. For a minimal viable LCA, at least a reasonable estimate of GWI for each project is needed in the optimization, so any implementation of the framework will require at least some idea of what materials and design are involved in each project, which might necessitate moving an agency's PMS from categories to treatments (as defined here) within the optimization process. For example, this might entail specifying thata preservation on asphalt is a seal coat and reconstruction involves full-depth recycling, as examples of an agency's most commonly used treatments.

The first step in implementing the framework is thus to prepare a list of treatments applicable to the agency, identified from construction records or interventions being considered in the future. Examples of these treatments are shown in the case studies. Based on standard PMS practice, these treatments should be assigned to one of the preservation, rehabilitation, or reconstruction strategies. For most agencies, the staff will already know what treatments are the default choice for each strategy and have a good idea of the types of structures each treatment would involve.

Once a list of treatments has been determined, the expected cradle-to-lay GWI must be determined for each treatment. Two different approaches to this are presented in the case studies. These are determined for a nominal length (typically one lane mile) and scaled within the analysis based on actual segment length. It is to be noted that the framework being proposed in this study does not dictate how these are calculated, although the following steps are proposed that could help an agency determine the GWI per treatment type:

1. ***Identify the expected pavement layer dimensions for each treatment:*** If a state has historical data on pavement structure design, typical thicknesses could be selected for each pavement layer type (surface, base, sub-base) involved. The width of the pavement layer also needs to be defined, although, in most cases, it would be a standard 12 ft wide lane. These dimensions are needed to obtain the material quantities in the next step. If historical data are unavailable, thickness per layer type could be assumed based on expert opinions. For example, a simple treatment might be a "Thick Overlay," where the expected thickness is 10 in of Hot-Mix Asphalt (HMA), as shown in **Table 1**.
2. ***Identify and quantify materials:*** Based on results from step 1, calculate the material quantities by calculating the volume of the material based on layer dimensions (pavement length x width x layer

thickness = material volume) and multiplying it by the specific gravity/density of the same material to obtain mass, as demonstrated in **Table 1**. Based on the mix design, quantify the ingredients by multiplying the material quantity and mass percentage in the mix design. To continue the example in **Table 1**, the HMA job mix formula might be 5% asphalt binder and 95% aggregates.

3. ***Quantify impacts for each ingredient and material:*** This step first involves quantifying the impacts of manufacturing and delivering the materials to the construction site, then building up the structure. The included processes are extraction/mining of raw materials (A1 in typical LCA definitions of the life cycle stages), transportation of the materials to the processing plant (A2), product manufacturing (A3), transportation to the construction site (A4), and constructing the layer (A5). These must be calculated for each layer identified in Step 1 and ingredient/material identified in Step 2. Impacts A1 to A3, often called the materials stage, could be obtained from regional/plant-specific environmental product declarations (EPDs) for the materials, by performing a cradle-to-gate LCA for each material, or by obtaining material production impacts from the literature. For network-level analysis, where there are multiple facilities, a typical distance for hauling materials (A2) from extraction to the processing plant must be identified or assumed, as must also be done for the transportation distance from the materials processing plant to the construction site (A4). The processes/activities included in computing the impacts in the construction stage (A5) depend on the equipment type, engine power, equipment idling, operation time, and standard practices within the state. Construction impacts should be developed for each layer by performing a construction stage LCA using typical information for a given layer.
4. ***Determine $GWI_{M\&C}$:*** Summing the results of Steps 3 and 4 over all the layers identified in Step 1 would result in the total cradle-to-laid, or materials and construction (M&C) GWI for the treatment.

If an agency uses a representative structure for each treatment, this process can be seen as computing a cradle-to-laid LCA for that structure at a representative location within the network, using network-appropriate assumptions about the inputs to the LCA. There are now several LCA tools available that could be used to accomplish this task, including some listed in the case studies. Any agency planning on using this framework will also likely be considering project-level LCA, so it will be interested in developing the required LCI for the state, and these treatment GWI values would probably be a natural extension of that process.

2.5 Use Stage

The calculations for the use stage within a particular area will depend on the available traffic and other segment-specific information. For the use stage, of interest are the expected annual impacts from the vehicles traveling over each management segment as a function of the condition—primarily roughness as measured by the International Roughness Index (IRI). The minimum requirement is an equation that predicts the GWI per distance traveled for each vehicle class available in the PMS as a function of the segment's IRI.

Since, like in the construction stage, it is best if the expected value calculation is "pushed down" as far as possible to each management section, it is best to have as detailed traffic information as possible. Based on federal reporting requirements, all states should at least be able to break traffic on their networks down to cars and trucks and potentially further into federal truck classes or classes from other definitions

Table 1. Example calculation of material quantities

Volume	= 5,280 ft x 12 ft x (10/12) ft = 52,800 ft^3
Density of HMA	= 145 lbs/ft^3
Weight of HMA	= 145 x 52,800 = 7,656,000 lbs
Asphalt binder	= 5/100 x 7,656,000 = 382,800 lbs
Crushed Aggregates	= 7,656,000 - 382,800 = 7,273,200 lbs

(such as number of axles). However, there are many more aspects to traffic, such as seasonal/daily/hourly variations in volumes and speeds and differences in the drive cycles for each of the periods, not to mention that each vehicle has slightly different emissions based on maintenance, tire pressure, and other minor differences. In an ideal world, the distributions of all these variables would be known for each section in the PMS, and a section-specific model could be developed, but this is unlikely to be true in any real-world data. Besides this, the analysis is projecting into the future, so this information will likely change. As with computing impacts from materials, statistically, there are two approaches to handling these unknown variables: assuming an average value or summing over a distribution of values to obtain an expected value, which is more accurate. Traffic is a widely studied area where large datasets exist, and so many agencies already have information about the distribution of volumes and speeds, and it is preferable to use this information if possible.

The GWI needs to be expressed in terms of Well-to-Wheel (WTW) impacts to cover the cradle-to-grave life cycle of the fuel and is typically calculated by summing up the fuel's two life cycle stages: well-to-pump (WTP) and pump-to-wheel (PTW). The WTP analysis includes all the processes and related emissions from the crude oil extraction, transportation to the refinery, the refinery process, and transportation to fueling stations. In contrast, PTW analysis includes the combustion of the fuel by the vehicle during the use stage of the life cycle. For an electric vehicle (of interest in the future), the WTP analysis would encompass electricity production, and the PTW analysis would have zero emissions.

There are many studies on vehicle fuel use, but for the minimal LCA a consistent methodology that can be computed for various vehicles is needed and, for the framework, the model outputs must be credible to decision-makers within a state agency. This means relying on studies that include multiple vehicle types and where the impacts can be calculated for different regions rather than one-off studies of individual vehicles, which, in turn, implies using nationally or internationally recognized models.

One approach is to combine the WTP impacts from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) model (M. Wang et al. 2023), produced by the US Department of Energy, with PTW impacts derived from the US Environmental Protection Agency's (US EPA) MOtor Vehicle Emission Simulator (MOVES) (USEPA 2023). Both are the most common model used in their area, and their results can be compared with other studies. Wang (2013) used this approach, and this is what is currently implemented in the California PMS, although this needs some careful manipulation of the internal database used by MOVES to capture roughness effects since the MOVES does not explicitly include roughness. MOVES estimates emissions directly, rather than fuel use, and these can be converted to impacts using TRACI or any other method, as discussed above.

Another approach is to use the World Bank HDM-4 model (Bennett and Greenwood 2003; Greenwood and Bennett 1995), as calibrated in NCHRP Project 1-45 (Chatti and Zaabar 2012), which has coefficients for several vehicles that can be linked to federal truck classes. Details of this are given in Appendix A. The HDM-4 model is for PTW fuel use only, so these need to be converted into WTW GWIs by determining region-specific WTP emissions (from GREET or another source) and TRACI impacts for the fuel based on expected combustion emissions.

MOVES and HDM-4 include many vehicle-specific and section-specific parameters, and, as with the treatment impacts, these need to be handled in some way to compute an expected use stage GWI. With MOVES, distributions of these parameters are built into the software, along with a procedure to obtain the expected value, so it can be used to obtain representative emissions within a particular region, although, by default, MOVES will aggregate over all vehicle types to give just one output. Since MOVES might be using different traffic volumes or vehicle classes to the PMS, it is better to compute values for one vehicle of each vehicle class independently in MOVES and use the results to develop a use stage GWI model for the PMS. HDM-4, on the other hand, does not have any built-in distributions, so these would need to be gathered by the agency, and the expectation computed by some means.

Examples of these types of computation are shown in Appendix A, although, in many cases, these values will have to be either assumed as the model's defaults or the region's expected value.

Some parameters might have distribution information available but not at a management segment level. For example, a state might have distributions of vehicles at various times of the day or in different seasons, but these can only be assigned to urban or rural segments. In this case, two models could be developed by summing over the two hourly distributions and using the appropriate model in the PMS based on the segment, assuming the management segments were categorized as either urban or rural.

On the traffic side of an LCA, a major unresolved issue is with the determination of emissions from individual types of vehicles since detailed emissions models are only available for a small number of actual vehicle models, and these may not be representative of the fleet on a particular route, especially since many are for old models. This issue can only be solved through extensive additional research. Despite this, the models still give realistic emissions at a network level. Another consideration is the fleet transition to electric vehicles in a particular region, which has not been considered here since this would require many assumptions about the speed of this transition. However, it could be incorporated into the calculations since these are performed annually.

2.6 Roughness progression and improvement models

The last major component required by the framework is a set of roughness models for the various treatments. Because roughness is widely used in PMSs, these might already be available, so they are not listed as a new feature the framework needs. However, these would need to be developed for agencies that do not already have roughness models or where the models are generic and not linked to specific treatments. As stated previously, it is crucial for the framework that different treatments have different performance models, otherwise the treatment with the lowest materials and construction GWI will always be selected, ignoring the potential that it does not remain smooth for long.

Because the development of these models is a statistical exercise and has been widely covered in literature, their development will be left to the reader, although the Virginia case study shows how these models can be developed. The framework assumes that the models are deterministic, although it could be easily adapted to a probabilistic model (i.e., percentage of length within different IRI bins) since this type of formulation leads to a straightforward expected value calculation.

The IRI improvement models are equally important and can be more challenging to develop since most states do not record IRI before and after a project. However, one of the primary tools that a state could use this framework to investigate is the adoption or strengthening of IRI-based construction smoothness specifications. In this case, changing the IRI improvement model to reflect anticipated smoothness on future projects would be one of the main ways to validate such a policy shift.

2.7 Distribution across lanes

Astute readers will have noticed that all the discussion above involving the interaction between vehicles and roughness only physically applies to a single lane, while many roads have multiple lanes with different traffic. This issue can be ignored by assuming that the IRI is the same in all lanes (often the implicit assumption in network-level PMS) or handled by splitting the traffic across the lanes if IRI is available or estimated in each lane. The process California uses for lane-based traffic assignment is simple: assume a set of lane distribution factors for the truck traffic (based on the number of lanes) and then assign car equivalents for these trucks to the respective lanes. The car traffic is then assigned to the lanes to make the car equivalent flow in all lanes equal. This process is documented in (Kim et al. 2023). The various truck classes are assumed to have the same distribution in each lane as in the whole segment.

Most states only measure condition in the outside lane since it is assumed to carry the most load and deteriorate the fastest. Given this, it could be assumed that the inside lanes deteriorate more slowly and thus have a lower roughness. If traffic data are available for all lanes from measurements or assigned using the procedure above, then the IRI on the inner lanes must also be determined. Analysis of California IRI data, where all lanes are collected, shows a stable relationship, shown in Equation (1), between the measured IRI on a lane (the 'outer lane') compared to the lane immediately inside (the 'inner lane'), although with a relatively large residual. The formulation implies an exponential decay towards an IRI of 60 from one lane to the next. This relationship does not seem to depend strongly on age or treatment, although the data range changes as the pavement deteriorates. It also does not seem to depend on whether the outer one or two lanes are designated as "truck lanes," probably because lighter, faster-moving trucks use the inner lane. There are 157,833 observations in the data over eight years of data collection using only flexible pavements. The data are all paired, such that the inner and outer lanes have the same age and treatment and were measured within seven days of one another in the same survey. The data and model are shown in **Figure 4**, and an example across four lanes with different outside lane IRIs is shown in **Figure 5**. This figure can also be used visually to estimate values for two or three-lane roads since the decrease from each pair depends only on the outer value (the left side value), not on the lane number or number of lanes.

$$\frac{IRI_{in}}{60} = \left(\frac{IRI_{out}}{60}\right)^{0.795 \pm 0.263} \qquad (1)$$

Where:

IRI_{in} = the roughness on the inner lane of the pair (in/mi)

IRI_{out} = the roughness on the outer lane of the pair (in/mi)

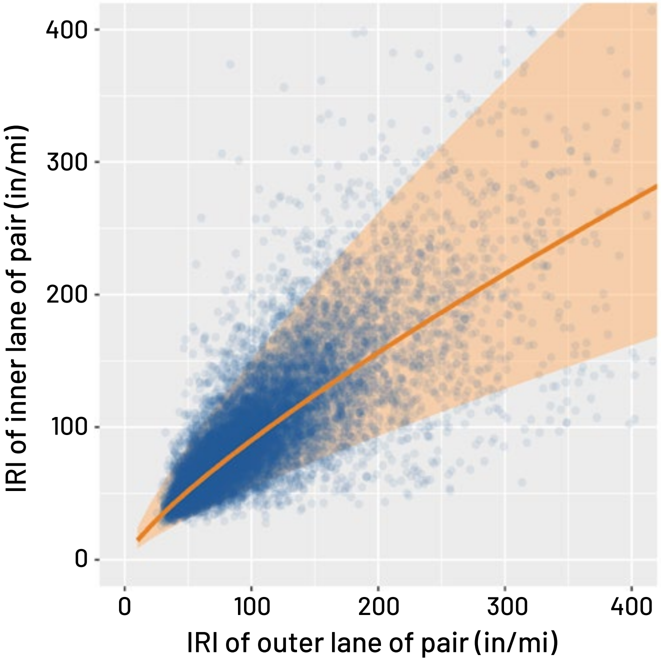


Figure 4. IRI relationship between inner and outer lane based on California data

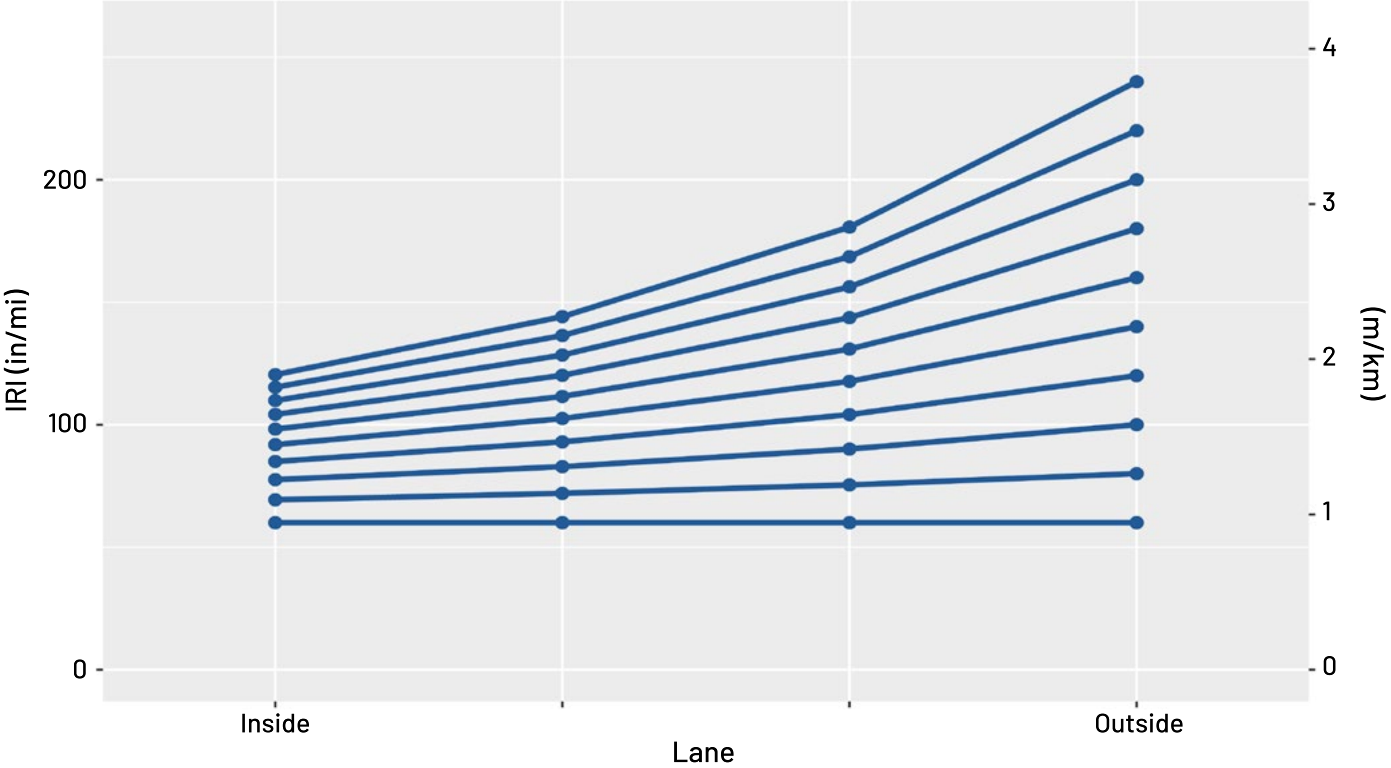


Figure 5. Example of IRI interpolation on inside lanes for a four-lane facility with different outside lane roughness

2.8 Calculation of GWI benefit

Although not strictly required by the framework, extending the annual GWI use stage values to compute a GWI benefit is straightforward. Assuming that the PMS software already calculates a benefit of some type and that this is likely performed at the same point that the GWI needs to be computed (see **Figure 3**), then an "area under the curve" type benefit (see **Figure 2**) can be computed by merely looping over some future time horizon to establish both the 'Do Nothing' GWI and that of the particular treatment being considered. The difference between these can then be used as a benefit, although it must be negated if the PMS can only maximize benefit since the objective is to minimize GWI. The ranking of projects from using GWI benefits is often similar to an IRI benefit (as depicted in **Figure 2**) that is weighted by traffic, so if it is not possible to change the benefit calculations in the PMS, it might be possible to use this as an alternative.

This type of "area under the curve" benefit is common in PMSs but does not include the influence of future maintenance decisions—it only compares the performance of two treatments over some time horizon, so the results should not be confused with a true LCA comparison, or reported as "potential savings." In reality, both treatment alternatives would have different maintenance paths in the future, so determining the incremental GWI difference between taking these two paths must be assessed by a project-level LCA that includes realistic future maintenance strategies. Since the PMS is a decision-support system, not a decision-making system, most agencies will evaluate PMS treatment recommendations in any case at a project level to determine the best strategy or design. So, project-level LCA can be added to the existing project planning and development cycle to evaluate those with significant GWI benefits, balanced with other agency priorities, such as safety. Nonetheless, a GWI benefit calculation of this type can help highlight good candidate projects for more detailed study. This benefit calculation could also be paired with a new or modified decision tree, such as one that recommended an overlay purely to address smoothness, and if the results were ranked by this benefit, this would highlight where this new treatment strategy would be most effective.

2.9 Interpreting the framework results

In a project-level LCA, multiple design alternatives are evaluated, seeking the one with the least impact. However, the network-level analysis is not between different alternatives but between two or more optimization scenarios that reflect different approaches to managing the network, as discussed above. These approaches might take the form of different budgets (i.e., a high and low budget comparison), different policies (such as using overlays rather than seal coats), or different configurations (for example, lowering the IRI trigger thresholds). For each scenario, the results from the framework are per year and are in two parts: materials and construction GWI and use stage GWI. As a first step, these can be added together and summed over the planning horizon, and the final sums compared to determine which has the least impact. Care must be taken to ensure that the compared scenarios are comparable (for example, they have the same planning horizon). However, the results from each year can also be compared to consider why one scenario might have lower impacts and when these would be expected to accrue.

Notably, the use stage results will always include fuel consumption and thus impacts from air resistance and vehicle losses unrelated to the pavement, which would be present even if the IRI was zero. Obviously, no technology exists today to build roads with no roughness, but this is a convenient benchmark for determining the lower limit of what can be achieved through pavement changes alone. Within the GWI calculations, it is thus helpful to compute the use stage GWI for an IRI of zero and store this result as GWI_0, which can also be aggregated within the results for each scenario. If computing GWI_0 directly is not possible, it can also be achieved by temporarily setting the IRI of all management segments to zero and computing the annual use stage GWI. Depending on how traffic growth or fleet changes are modeled, GWI_0 will differ from year to year, but if it differs between scenarios, it is a good indicator that they are incompatible and should not be compared (at least from a pavement impact perspective).

GWI$_0$ will differ for different states due to fuel quality, speeds, state topography, technology levels, and other factors. It will also depend on the size of the network being analyzed and the current mix of vehicles on that network. A good calibration check for the overall implementation of the framework will be to determine the annual use stage GWI for the network as a whole, with current IRI results, and compare this to statewide GHG emissions estimates or impacts based on network vehicle miles of travel and fuel sales. These results are often available from air-quality agencies within the state if they are not widely published. Similarly, a single-year work plan reflecting current and recently completed projects can provide an M&C GWI that can be compared to impact estimates based on total material quantities from agency invoicing for the same period to determine if the treatment quantities were truly representative.

Figure 6 shows an example of the expected total GWI outcome from using the proposed framework for three scenarios, along with the baseline GWI$_0$. The vertical axis has been compressed because the GWI$_0$ values are typically much larger than the construction and excess use stage impacts due to roughness. Because of this, it makes sense to show results relative to GWI$_0$ rather than absolute results, although it is still essential to consider the absolute results when reporting network impacts.

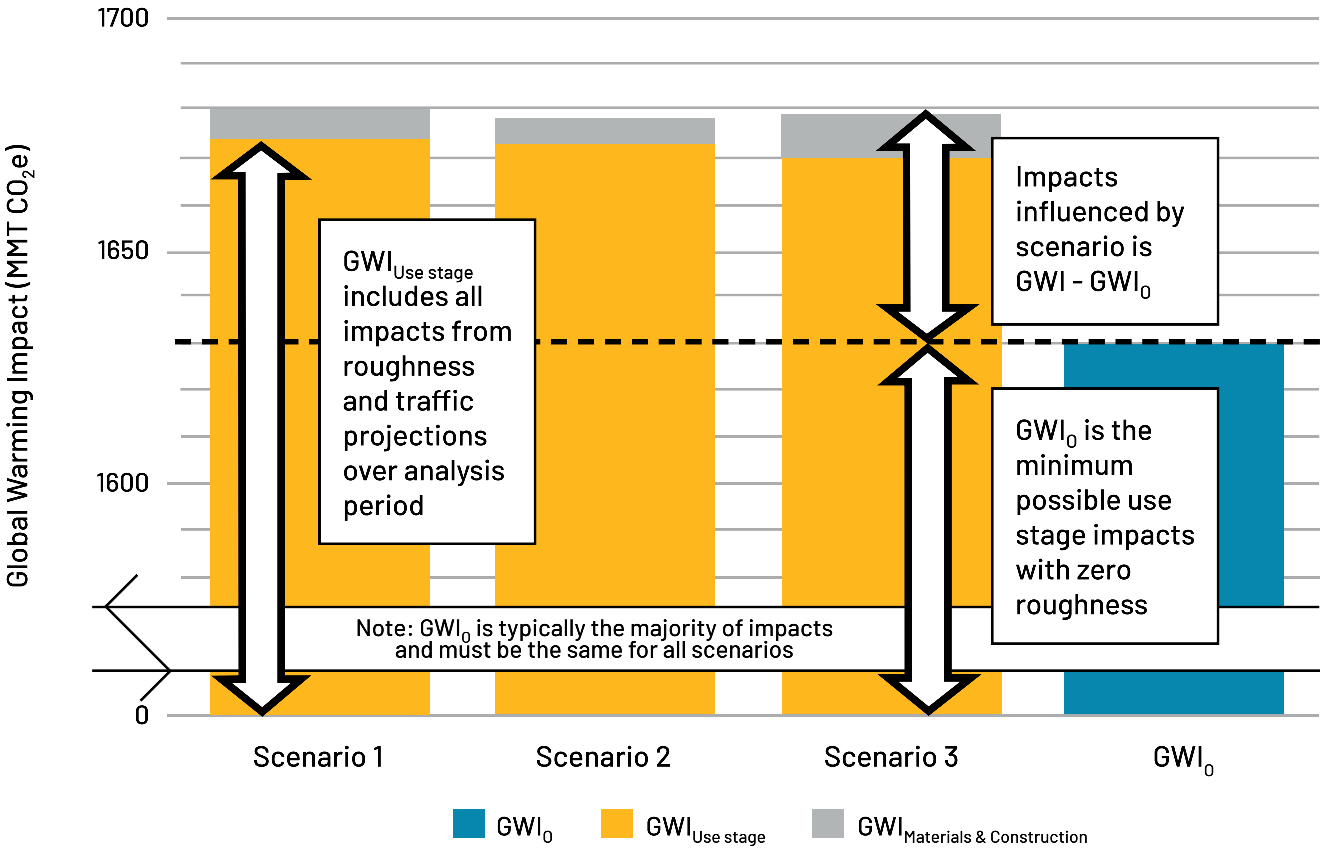


Figure 6. **Example of expected GWI from different scenarios**

3 CALIFORNIA CASE STUDY

3.1 Background

In 2010, Caltrans initiated a project to completely overhaul its pavement management process, including a new pavement condition methodology, new software, and a complete reimplementation of the "engineering configuration" of the system. As part of that process, it was realized that it was possible to implement a GHG calculation procedure in the PMS in parallel with other traditional measures (T. Wang 2013). This new system, known as PaveM, was implemented in 2013, making Caltrans the first agency worldwide to be able to manage pavements based on GWI (Basheer and Mafi 2021).

The framework presented in this report is a formalization of the Caltrans implementation, and this case study reflects various updates to the procedures used by Caltrans, some of which are still being merged into their production PMS. As such, this report's contents reflect the authors' views and do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not represent any standard, specification, or regulation.

Several unique features of PaveM aided the initial implementation. Because of the complexity of the Caltrans network, a decision was made to collect condition data on all lanes of the network and to perform all management based on primary condition measures (IRI and cracking) rather than a composite index such as Pavement Condition Index (PCI). As a result, roughness and cracking models were available for all lanes, and a procedure for assigning traffic to each lane was also developed. Although Caltrans uses different funding pools for maintenance and rehabilitation and manages the routes in the network using a three-level class hierarchy, the configuration used lower-level (more prescriptive) treatments than categories such as 'preventive maintenance' or 'reconstruction.' Because of this, assigning a generic structure to each treatment and using early LCA results to determine GWI for these treatments was possible, and the treatments all had IRI models developed that did not depend on the budget category or class.

Another unique feature of PaveM is that it supports multiple different 'master' tables or network segmentations. It is standard practice in PaveM to develop work plans using a 'coarse' segmentation that covers all lanes and directions (when possible), with an average segment size of around 25 ln-mi. Once a work plan has been established, using the appropriate budget and constraints, it is re-run using a lane-based 'fine' segmentation, with a one ln-mi average length, allowing for more accurate prediction of the future network condition. The results shown in this case study use this procedure, and more details on this segmentation process can be found in (J. D. Lea 2015).

3.2 Updated treatment GWIs from eLCAP

When the first implementation was developed for Caltrans, the LCA of pavements was still in its infancy. LCA information was available for only a few materials, and much had not been reviewed. As such, the materials and construction GWIs for the treatments implemented in the Caltrans PMS in 2012 are some of the earliest pavement LCA results and needed to be updated for this case study. The original 2012 GWI emission factors for flexible treatments used in PaveM are shown in **Table 2**, along with the new GWI emission factors updated in 2023 for this case study.

The procedure used for the 2012 GWI calculations was to determine a representative structure for each treatment used in the PMS and then perform an LCA for each of these structures, which is assumed to provide a representative GWI emission factor for that treatment, as outlined in the framework above. A downside of this approach is that if the definitions of the treatments are altered (same name but what is done in the treatment changes), then the representative structure might no longer be applicable, so the LCA needs to be redone. A new approach was implemented for the updated GWI values presented here, based in part on procedures used for the performance modeling of the treatments. Caltrans has built an extensive database of past construction activities, which is used within the PMS to determine past treatments and develop performance models. This database captures the layer information for each construction location on the network, where a project might have many construction locations for different routes or with different structures. The data are captured as a list of removed and added layers with some thickness and material for each layer. This information is then used to decide the appropriate treatment name to assign within the PMS, meaning that if the treatment definitions are changed or expanded, the as-built treatments can be altered to meet the new criteria.

As a reminder, the interest is in the expected $GWI_{M\&C}$ from a particular treatment for the framework. With the as-built information, this can be defined as the construction length weighted mean of the current impacts associated with each structure defined as falling within a treatment type category. While this would appear to require an LCA for each structure, it can be simplified to two components: the GWI associated with manufacturing the materials and transporting them to the site (cradle-to-site or A1–A4) and the GWI associated with the construction of one lift or layer of that material (site-to-laid or A5). With this information, the thickness and material are known for a particular as-built structure, so only the required number of lifts needs to be computed from the thickness. Based on the Caltrans Highway Design Manual rules for different layer types and standard lift thicknesses, it is possible to determine a maximum thickness for one lift of each material in the as-built database. An LCA can then be performed for a project consisting of a single lift with this maximum lift thickness, and the results captured for the two components (cradle-to-site and site-to-laid). These results can then be combined with the lane-miles and structures of projects from the construction history to obtain expected materials and construction impacts. The complete calculation is shown in Equation (2).

$$GWI_{M\&C}(T) = \frac{\sum_{t \in T} m_t \left(\sum_{l=1}^{L_t} \left(\frac{h_{tl}}{s_{M_{lt}}} GWI_{cs}(M_{tl}) + \left\lceil \frac{h_{tl}}{s_{M_{lt}}} \right\rceil GWI_{SL}(M_{tl}) \right) \right)}{\sum_{t \in T} m_t} \quad (2)$$

Where

$GWI_{M\&C}(T)$	is the GWI for treatment type T,
m_t	is the constructed length of location t, where t is a treatment of type T,
L_t	is the number of removed or added layers in project t,
M_{tl} and h_{lt}	are the material and thickness of layer l in project t,
$s_{M_{lt}}$	is the height for one lift of material M_{lt}
$\lceil \bullet \rceil$	is the ceiling operator (rounds up to the nearest integer),
GWI_{CS} and GWI_{SL}	are the Cradle-to-Site and Site-to-Laid GWIs.

The UCPRC recently developed a pavement LCA web-based tool called the environmental life cycle assessment for pavements (eLCAP), which is currently data license limited to use only by Caltrans and for university teaching and research (J. Lea et al. 2022; J. Lea and Harvey 2021). eLCAP includes all the life cycle stages: materials, construction, use, and end of life of a pavement, with data and model developed to follow California-specific conditions and reflect Caltrans construction practices. The LCI data on material production, construction equipment use, transportation, assumptions, and calculation methods can be found in (Saboori et al. 2022), which covers data collection methods and model development in detail. Using the process detailed above, eLCAP was used to find the materials and construction GWIs for each of the materials used within the PaveM treatments from **Table 2**, for a single lift, and the results are shown in **Table 3**. In combination with the full construction history, these results were then used to determine representative GWIs for a lane mile for each treatment to obtain the new values shown in **Table 2**.

It is to be noted that the impacts of different treatment types shown in **Table 2** are not meant to be compared against each other, in the same way that treatment cost per lane mile cannot be directly compared, because the different treatments are intended for different purposes for pavements in different condition and they have different design lives. In other words, full-depth recycling cannot be compared to a chip seal shown in the table—to compare them would require a complete LCA. As can be seen, many computed values have changed for this case study compared to the 2012 values, reflecting the updated information used in eLCAP. In particular, the GWI for recycling treatments has decreased significantly because some of the assumptions used in the original coefficient development were invalid.

3.3 Well-to-Wheel Impacts

The traffic within PaveM follows the standard traffic process used within Caltrans, which has cars and four classes of trucks based on their number of axles. The process for obtaining traffic on each lane is outlined above and is detailed in (Kim et al. 2023). For this case study, it was decided to continue to use the original GWIs calculated using GREET and MOVES, as described in (T. Wang 2013) and also outlined in the framework. These coefficients, shown in **Table 4**, are close to those obtained in Appendix A from HDM-4, but it was not clear how best to map the HDM-4 calibration vehicles to the Caltrans vehicle classification breakdown. In MOVES, the energy consumption is reported, which must be converted to the quantity of fuel (in gallons) to complete the analysis (WTW) since the GREET values are for a unit fuel volume. Converting energy to fuel use requires values for instantaneous/total consumed energy, energy density of fuel, and fuel density. For example, an energy density of 43.5 kJ/g and a fuel density of 2,839 g/gal would give an energy fuel conversion factor of 123.5 MJ/gal for gasoline.

Table 2. **Original and new treatment GWIs for PaveM**

PaveM Treatment	GWI (kg CO_2-e/ln-mi)	
	Original	New
Fog Seal	21.14	1.6
Slurry Seal	21.14	4.5
Seal Coat (Generic)	21.14	6.8
Chip Seal	21.14	7.1
Microsurfacing	21.14	9.9
Partial Depth Recycling	156.44	54.
Thin Overlay (<=0.1 ft)	42.28	32.
Mill and Fill (<= 0.1 ft)	42.28	37.
Medium Overlay (0.1 ft to 0.25 ft)	84.56	69.
Digouts (Wheel path patching)	-	% Area Patched x 110.
Thick Overlay (>0.25 ft)	169.12	130.
Full Depth Recycling	241.00	150.
HMA Lane Replacement/New HMA Lane	169.12	260.

Table 3. **GWI per layer type for materials and construction per lane mile of a road section.**

Layer Type	Thickness (inch)[a]	GWI in kg $CO_{2\text{-eq}}$ per lane mile	
		Cradle-to-Site (GWI_{CS})	Cradle-to-Laid ($GWI_{M\&C}$)
Aggregate Base	6	2.20E+04	2.23E+04
Aggregate Sub-base	6	2.10E+04	2.13E+04
Asphalt Treated Permeable Base	6	4.55E+04	4.60E+04
Cold Central Plant Recycling (with 4% Engineered Emulsion)	per inch	9.57E+03	9.83E+03
Cement Treated Base - Class A	6	1.15E+05	1.16E+05
Cement Treated Base - Class B	6	8.08E+04	8.15E+04
Cement Treated Permeable Base	6	1.40E+05	1.40E+05
Full Depth Recycling-1% Portland cement (PC) & 2.5% foam asphalt (FA)	per inch	6.35E+03	6.72E+03
Full Depth Recycling - No Stabilizer	per inch	0	1.65E+02
Full Depth Recycling - 3% PC	per inch	8.11E+03	8.35E+03
Hot Mix Asphalt (HMA)	3	6.74E+04	6.82E+04
HMA-Gap Graded (Polymer Modified)	3	1.15E+05	1.16E+05
HMA-Polymer Modified	3	1.15E+05	1.16E+05
Open Graded Friction Coarse	3	1.02E+05	1.03E+05
Open Graded Friction Coarse (Polymer Modified)	3	1.15E+05	1.16E+05
Rubberized Hot Mix Asphalt (RHMA) - Gap Graded	3	8.87E+04	8.96E+04
RHMA-Open Graded	3	1.00E+05	1.01E+05
Lime Treated Base (Reclaimed Asphalt Pavement with 3% Lime)	6	1.38E+05	1.38E+05
Lime Treated Subgrade (with 3% Lime)	6	9.10E+04	9.14E+04
Chip Seal	-	6.08E+03	6.38E+03
Fog Seal	-	1.59E+03	1.64E+03
Slurry Seal	-	2.33E+03	2.39E+03
Flush Coat	-	2.81E+03	2.86E+03
Cold In-Place Recycling (Partial Depth Recycling-Foam Asphalt)	per inch	7.18E+03	7.82E+03
Milling Asphalt Layer	per inch	1.06E+03	1.35E+03
Geosynthetic Pavement Interlayer[b]	-	1.10E+03	1.26E+03

[a] Layer thicknesses are maximum for one lift per Caltrans Highway Design Manual rules. Values are per inch where GWI scales by thickness, not lift. Null values are layers where thickness is not relevant.

[b] EPD: Woven geotextile from Beaulieu Technical Textiles 2022-2027 (1 lane-mile = 5886 m^2)

Table 4. PaveM use stage GWIs based on MOVES

Vehicle	GWI (kgCO$_2$e/mi/year)	
	Intercept	IRI Slope (per in/mi)
Car	133.5	0.056
2-Axle	400.9	0.057
3-Axle	657.5	0.115
4-Axle	957.2	0.191
5-Axle	1046.1	0.202

3.4 IRI Models

The IRI models within the Caltrans PMS have also been recently updated and are now based on an exponential curve rather than a linear model. The system's current configuration uses a decision tree-like approach to select the model based on the treatment type, the climate (Mild or Severe), and the traffic level (Low: <60,000 ESALs/year, Medium: <3000,000 ESALs/year, or High). Soon, the implementation will be changed to use a continuous traffic variable. The IRI performance models are shown in **Figure 7**. The Unknown-AC models are followed for segments where the initial treatment is unknown. This treatment is not shown in the tables above since it cannot appear in the decision trees, and thus, a GWI$_{M\&C}$ does not need to be computed.

3.5 Results

3.5.1 Investigation of the influence of benefit selection

Caltrans typically runs two scenarios with each new annual condition survey data set. The first is a "do nothing" or 'Freefall' scenario, where no maintenance is performed (even excluding work currently under construction)—the goal of this is to establish a "worst case" baseline for performance. The second is an 'Unlimited Budget' scenario, which captures a "best

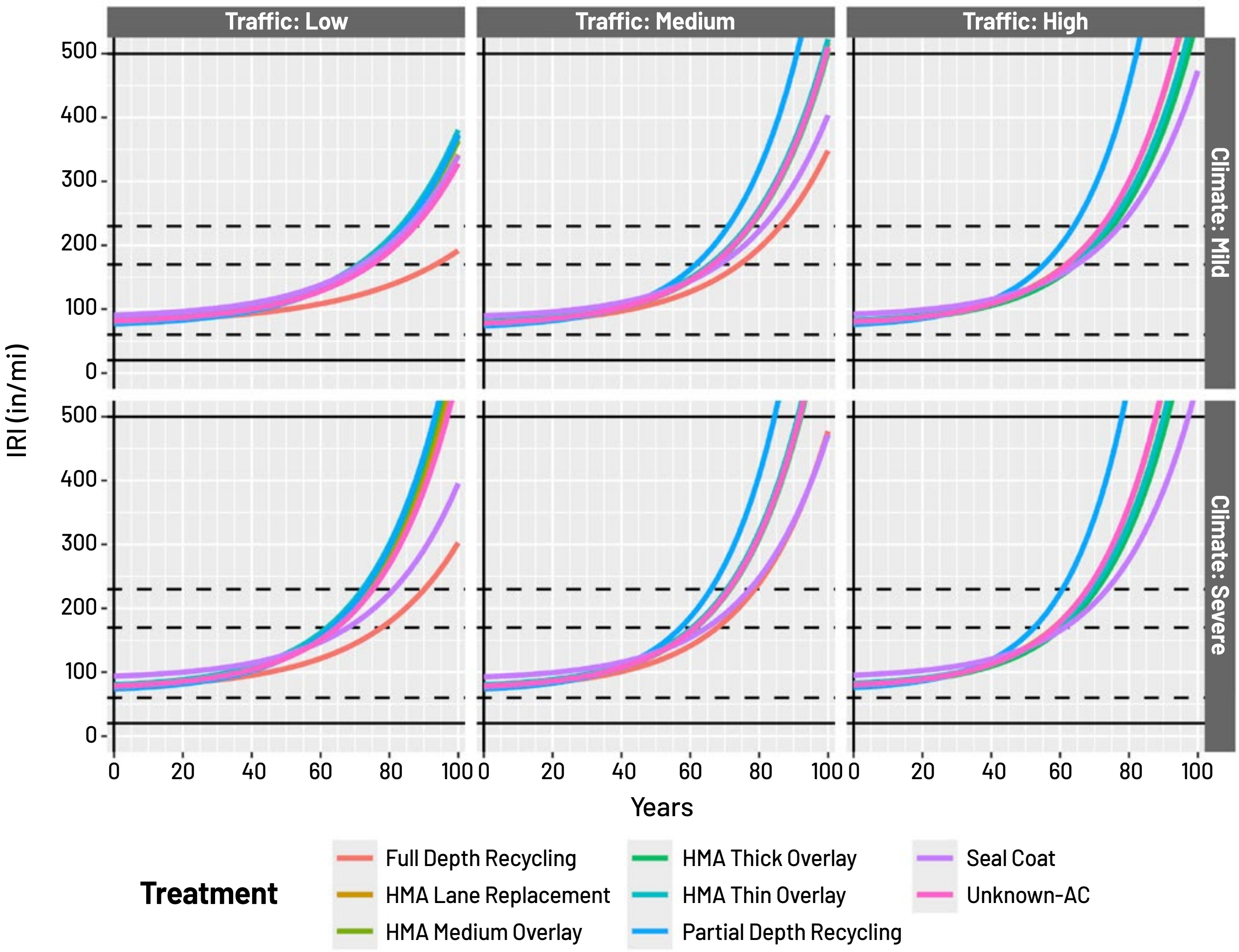


Figure 7. California IRI models

case" baseline for performance if all the decision tree recommendations were to be followed. Between these two cases fall any realistic budget scenarios. Caltrans then continues the project development cycle, following what most other state agencies do in pavement management, by running scenarios with the existing approved work plan and giving additional funding in the out years to find candidate projects. Following their long-standing practice of prioritizing sections with structural distress as measured by cracking, this process typically optimizes on a cracking benefit, which follows a process like **Figure 2** but uses the cracking performance curves. A straightforward change to realize GHG reduction is prioritizing smoothness improvements during project selection.

Thus, the following four cases were run for this case study, and the results are presented below:

- A worst case, with no budget (freefall),
- A best case with an unlimited budget,
- A case optimizing the Cracking benefit within a realistic constrained budget and
- A case optimizing the IRI benefit within the same constrained budget.

It should be noted that the fine segmentation and GWI results for this case study were computed outside of PaveM using a Matlab® script that mimics the PaveM computations because the updated treatment GWIs had not yet been implemented in PaveM. Other than the freefall case, which has no projects, the projects were all selected within PaveM using the coarse segmentation. In the Cracking and IRI cases, the budgets used are the current projected budgets for the first few years, followed by a budget of $1.5 billion annually, with $300 million of that allocated to preservation treatments. Year zero in the analysis is the current condition of the network (evaluated using the fine network segments), and only asphalt pavements are shown, which cover ~35,000 ln-mi.

Figure 8 shows what happens to the average roughness of the network under these four scenarios. As expected, the average increases according to an exponential curve if no maintenance is undertaken since the performance models follow an exponential curve. The roughness changes for the other three scenarios are similar, with a decrease in the initial years and a slow increase as the network transitions to a steady state of repeated preventive maintenance.

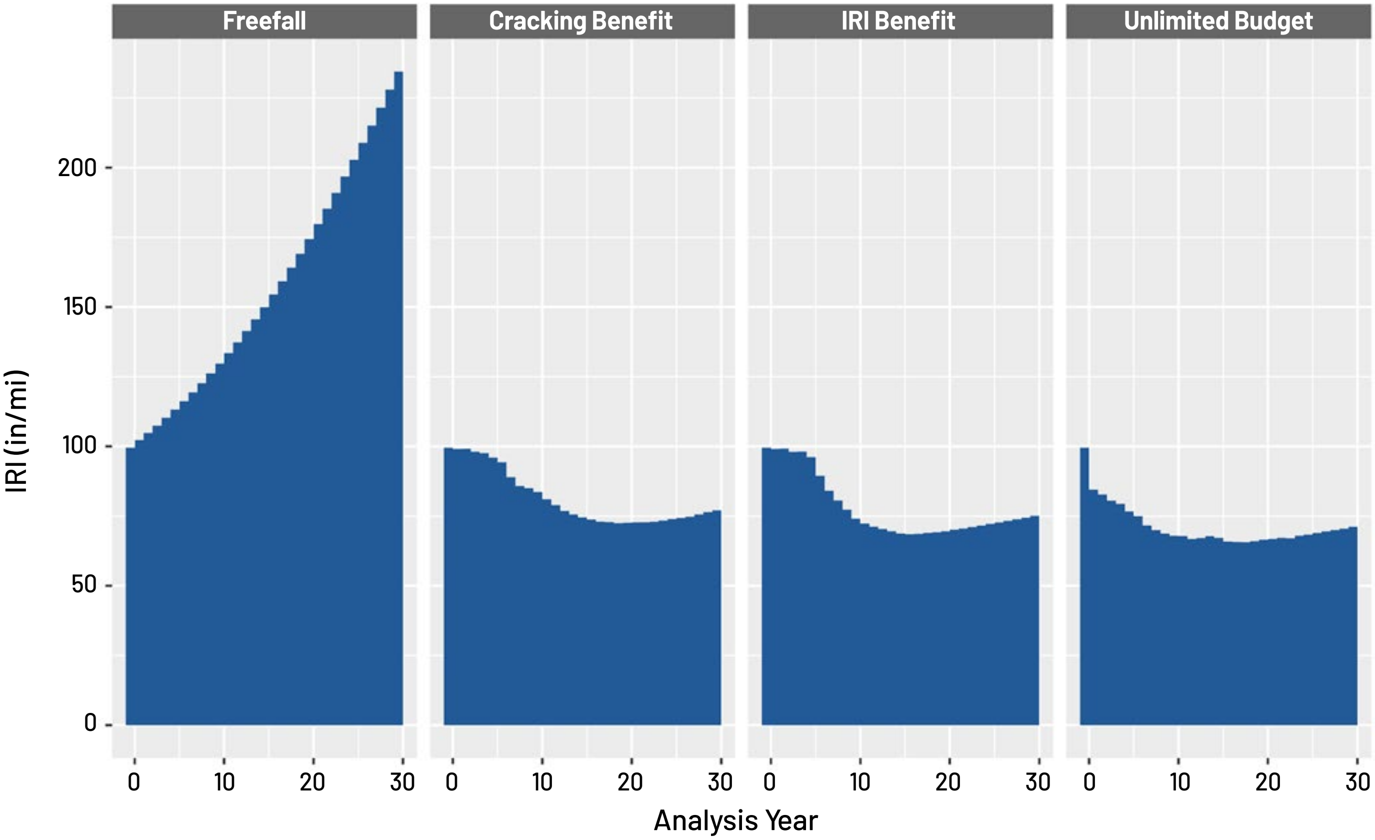


Figure 8. **Average roughness for different California scenarios**

The unlimited budget scenario is the most aggressive since it can fix all of the poor pavement segments immediately. Since the IRI benefit scenario tries to minimize roughness, it is not surprising that the network roughness after thirty years is slightly lower than when using the cracking benefit.

The reasons for some of these changes become apparent when the treatments are considered, as shown in **Figure 9**. PaveM is configured so that only one treatment is considered for each condition state in the decision trees, and even if the system has budget available, it will not perform that treatment if it determines that doing so would have a "negative benefit." Thus, even though the roughness is configured to always improve after treatment, if the IRI deterioration curve for the new treatment has a steeper increase in future IRI than the current treatment, it will surpass the Do Nothing alternative and result in a negative area between the curves. This happens frequently for seal coats since the performance model is not dependent on the underlying structure. Also, looking at **Figure 7**, it can be seen that the Partial Depth Recycling (PDR) treatment currently has a performance model with a steep IRI increase with time, while Full-Depth Recycling (FDR) has the lowest slope (partly due to these models being based on limited data).

The result of these differences is that the IRI benefit scenario does not spend all of the available budget in the first few years and then transitions to spending on FDR rather than PDR in the later years. Even though the two constrained budget scenarios perform similarly to the unlimited budget scenarios in terms of average IRI, it can be seen that they treat significantly less pavement.

Figure 10 shows the annual GWI for each scenario, and **Figure 11** shows the same information but is presented as a cumulative result. As explained above, there is a minimum baseline GWI for any network that comes from energy use by the vehicles traveling on the network that is not devoted to overcoming pavement roughness (Basheer and Mafi 2021), which has been subtracted from the GWIs reported in these results, resulting in plotting of what is sometimes called

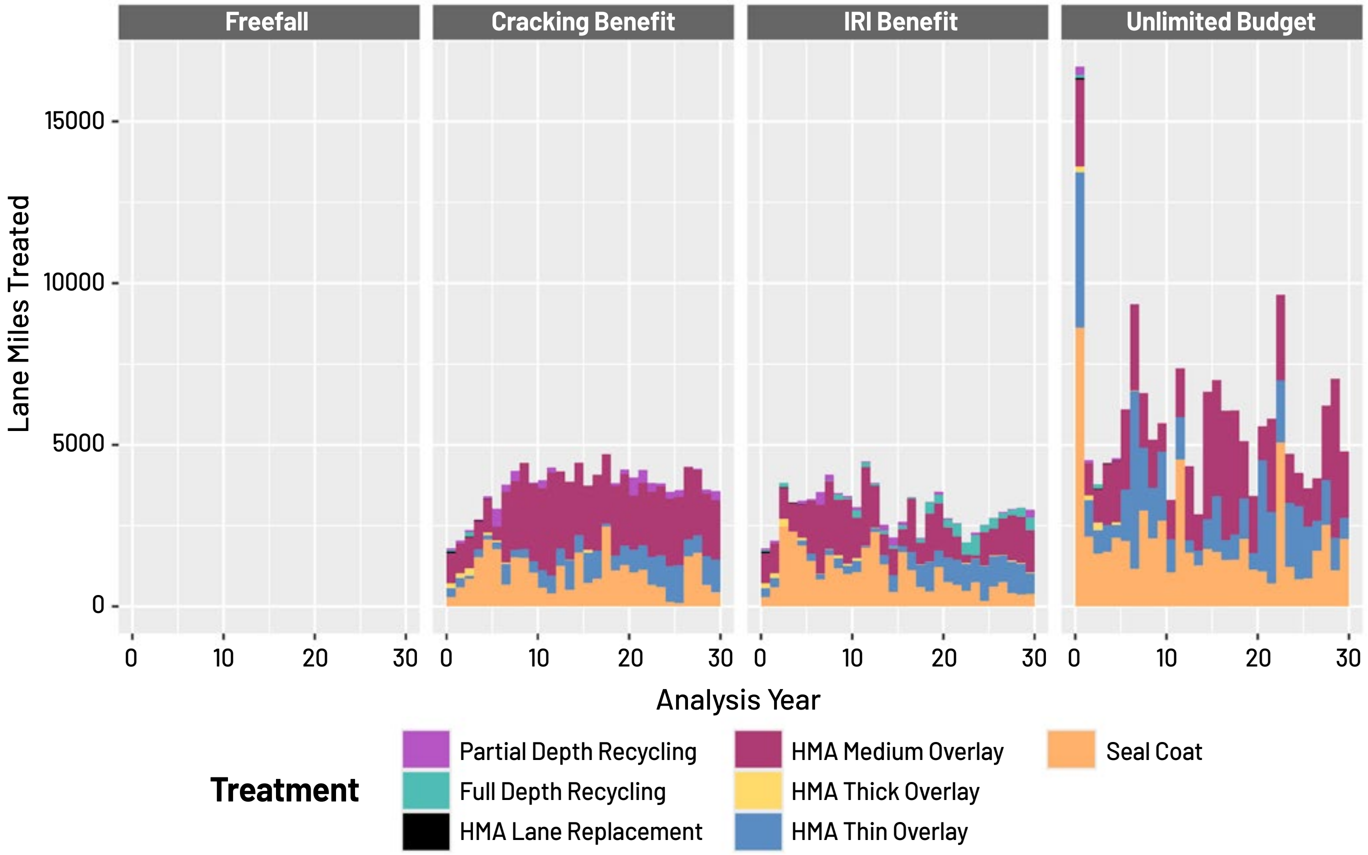


Figure 9. **Treated lane-miles for each California scenario**

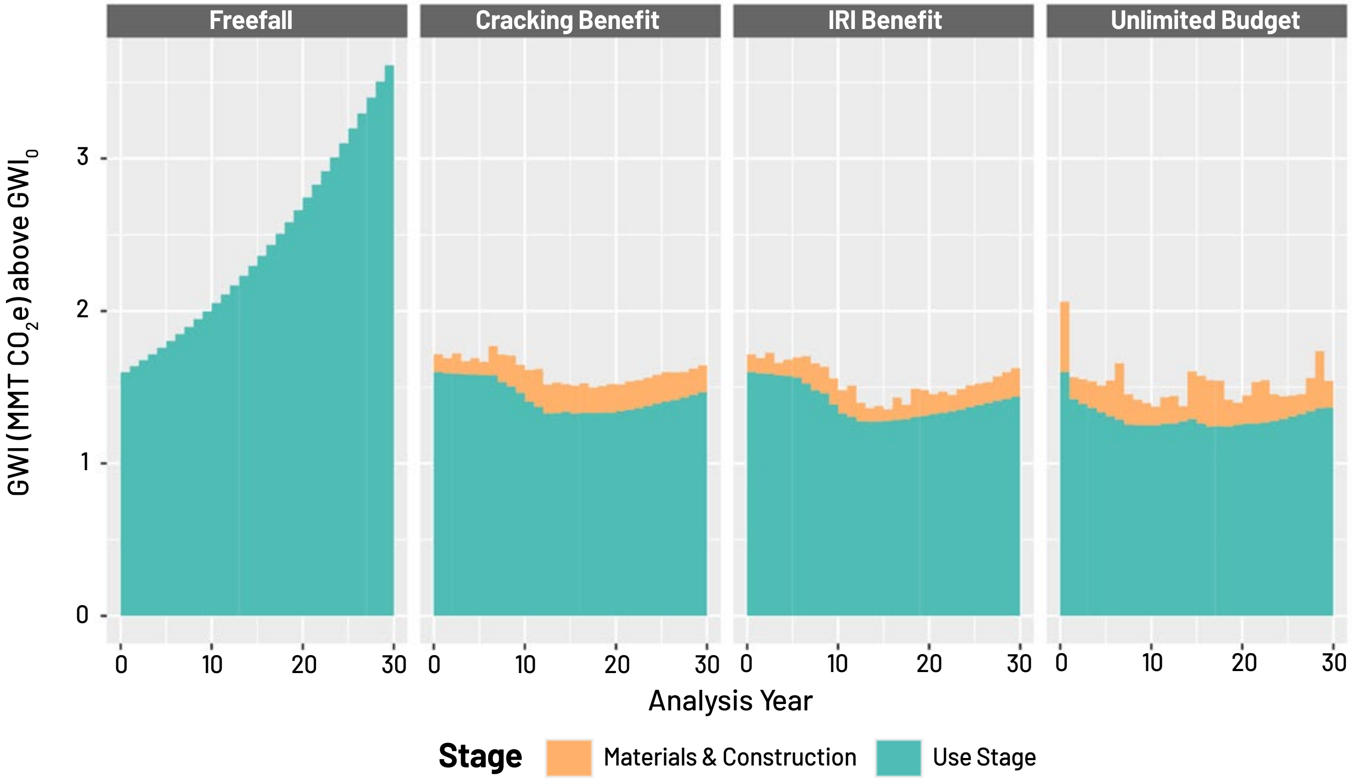


Figure 10. **GWI above baseline for California scenarios**

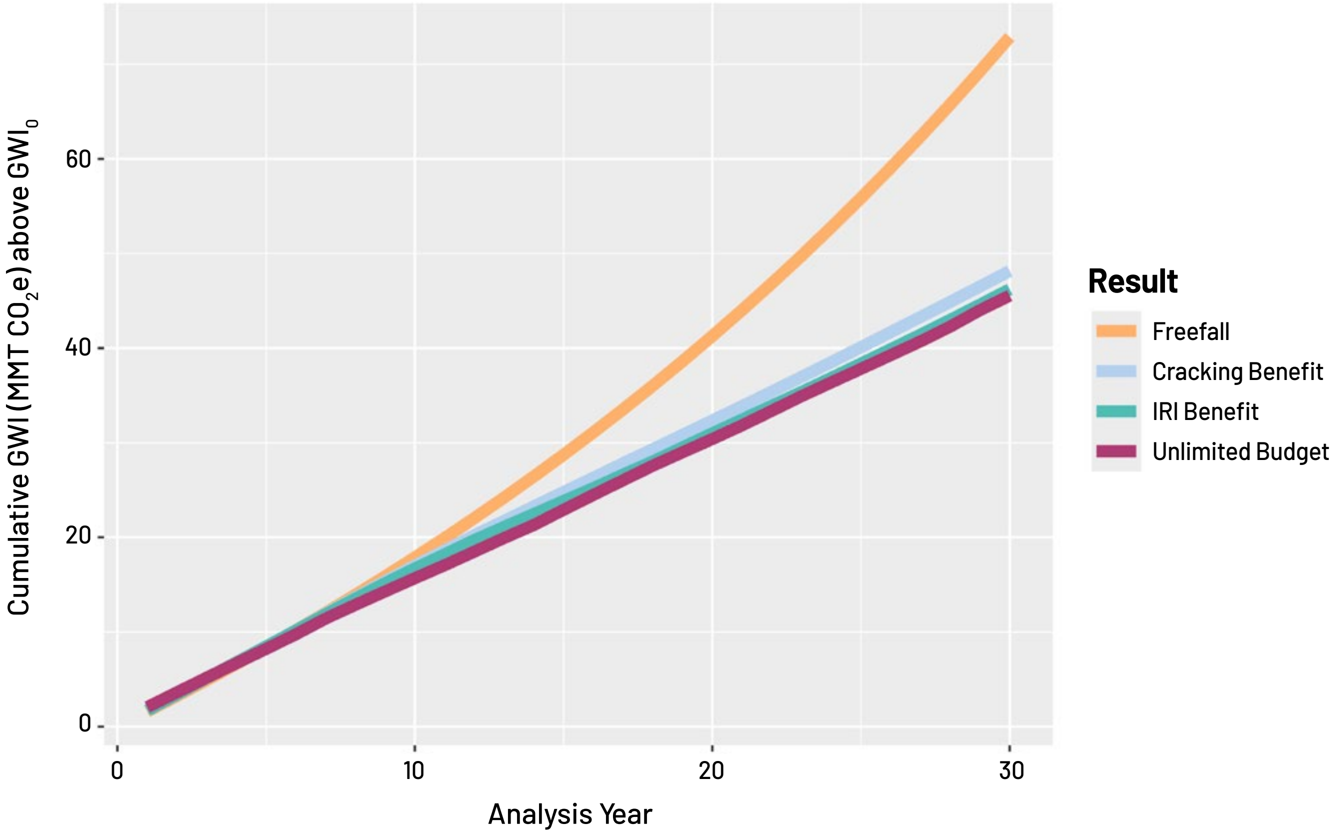


Figure 11. **Cumulative GWI for the California scenarios**

excess fuel consumption (EFC), or fuel consumption beyond what would occur on a "perfect" pavement with no roughness, macrotexture, or structural response causing rolling resistance (Mohanraj and Merritt 2023).

The main takeaway from these scenarios is that by simply changing to selecting projects based on their smoothness improvement, California can make a small but significant change to the GHG emissions from the network and, in fact, come very close to the results for an unlimited budget, which targets a large number of lane miles for minimal actual improvement in the network condition and pays the penalty of materials and construction GWI that is not improving smoothness much.

3.5.2 *Evaluating Improvements in Construction Smoothness*

Caltrans currently has a construction smoothness specification for some overlays that sets the allowable post-construction IRI based on the IRI before construction and has a maximum post-construction IRI of 75 in/mi. It is impossible to evaluate relaxing this limit since it is not known what the worst-case scenario would be if smoothness were not monitored, but it is possible to evaluate tightening this specification. To this end, three additional scenarios were evaluated, and all used the unlimited budget work plan detailed above. The three scenarios are to implement the smoothness specification for all treatments (even seal coats) and set the maximum post-construction IRI to 75, 60, and 40 in/mi. Clearly, 40 in/mi is an extreme case and would be very difficult to apply in the field, but it demonstrates the importance of building roads as smoothly as possible. The cumulative GWI values for these scenarios are shown in **Figure 12**. Even without considering the postponement of future maintenance that would occur if the roads were built smoother, it can be seen that tightening the smoothness specification would result in considerable GWI reductions over 30 years.

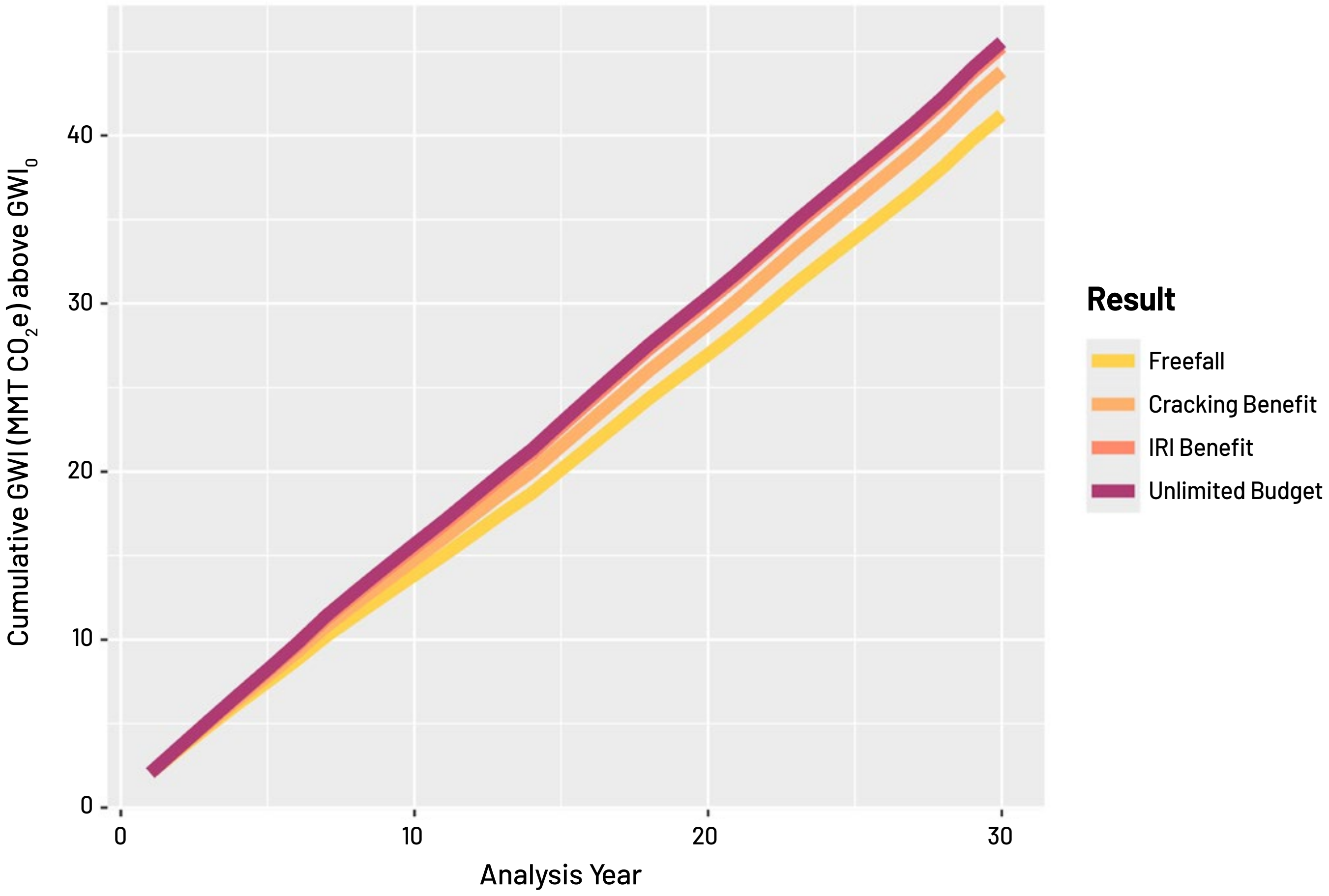


Figure 12. **Cumulative GWI for different smoothness limits**

4 VIRGINIA CASE STUDY

4.1 Background

The Virginia Department of Transportation (VDOT) manages approximately 129,000 lane miles of roadway. In 2021, VDOT concluded two studies on estimating environmental impacts of transportation projects in the Commonwealth. The first was a project-level study quantifying the potential environmental benefits of asphalt pavement recycling—covering the cradle-to-laid stages in the project life cycle (Amarh et al. 2021). One of the deliverables in the cited study was a tool—storing LCIs for various pavement materials and paving processes—that VDOT can use to assess the environmental impacts to aid project-level decisions. The second was a statewide inventory and a forecast of GHG emissions from the surface transportation sector (VDOT 2022). The inventory and forecast include direct operating emissions from system users, including highway vehicles and passenger and freight rail vehicles, upstream emissions associated with the production and transport of transportation fuels, and emissions from highway and rail construction and maintenance activities.

This case study aims to validate and demonstrate the applicability of the framework developed in this report and to quantify the reductions in global warming associated with changes in pavement smoothness due to improved asphalt pavement construction practices using data from the VDOT network. The goal is to demonstrate the feasibility and practicality of adding an LCA component into VDOT's PMS to aid decision-making that optimizes the total environmental impacts on the VDOT network by selecting rehabilitation treatments based on the GWI associated with implementing the selected treatments and their resultant smoothness after construction over an analysis period of 30 years.

VDOT works with four levels of maintenance and rehabilitation in their PMS: Preventive Maintenance (PM), Corrective Maintenance (CM), Restorative Maintenance (RM), and Reconstruction (RC). In this analysis, only bituminous pavements are considered. In addition, the VDOT PMS has different decision trees and performance models for the three networks managed within the PMS: the Interstate (IN), Primary (PR), and Secondary (SC) road networks. Traditionally, VDOT has used a PCI-like index called the Critical Condition Index (CCI) to manage their pavements, which is composed of the lower (worst condition) of either the Load-related Distress Rating (LDR) or Nonload-related distress rating (NDR), which are, in turn, based on the traditional PCI measures. Performance models for these are available in the PMS, along with roughness in the outside lane, but no roughness performance model was available.

4.2 Data and Methods

The framework outlines at least three tasks needed to achieve the stated goals: determining the cradle-to-laid GWI associated with each treatment in the PMS, developing IRI performance models and IRI improvements for various rehabilitation treatments, and determining vehicle-specific traffic for each management segment. The database used for the study was built from various data tables obtained from the VDOT PMS.

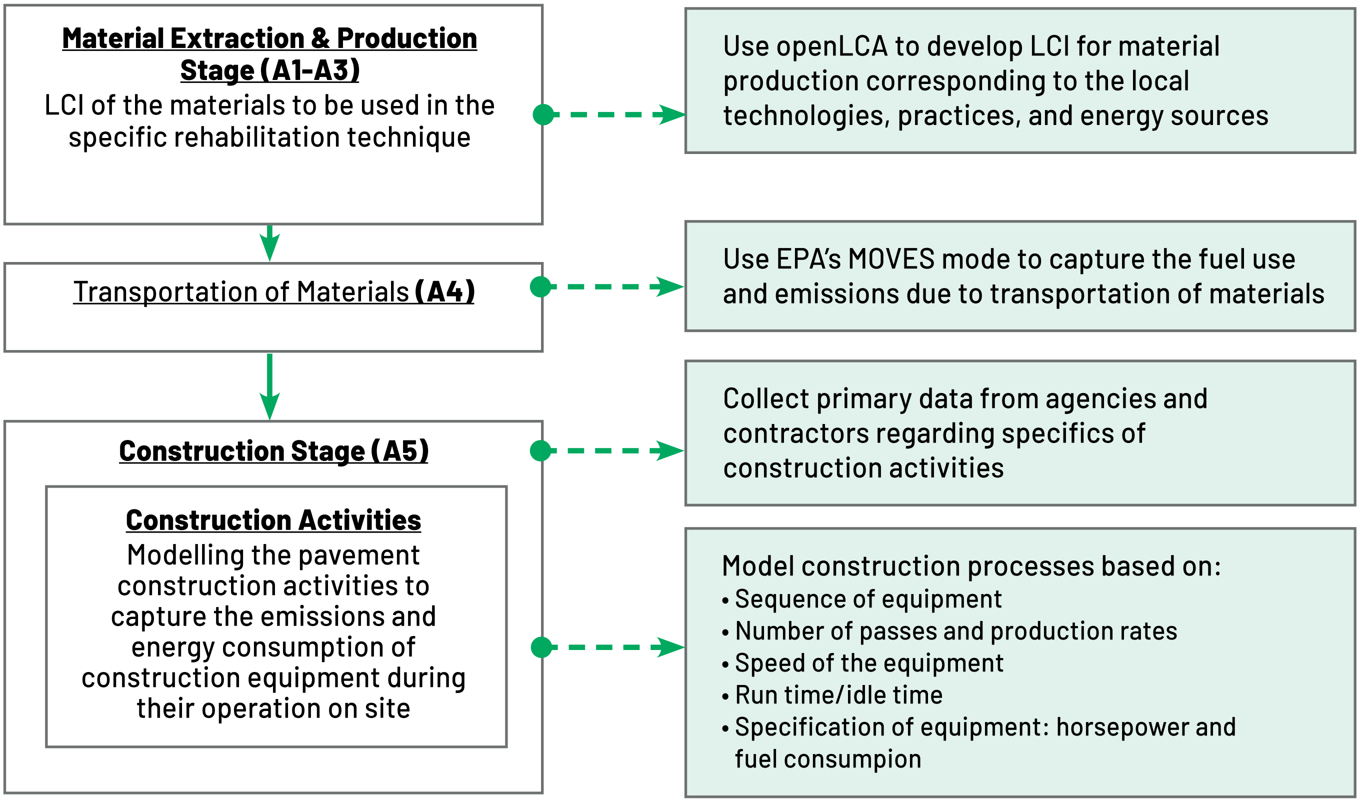
4.2.1 Determination of Cradle-to-laid GW Impacts for Different Treatment Types

The approach to determining the impact of global warming on various rehabilitation treatments in Virginia follows the procedure outlined in section 2.4. Amarh et al. (2021) previously quantified the potential environmental impacts of recycled pavement projects in Virginia using a similar approach outlined in **Figure 13**. The LCIs for pavement materials and paving unit processes compiled and stored in a database for the pySuPave LCA tool—a tool developed in the study by Amarh et al.—were used to complement inventory calculations in this section of the report.

Prepare a List of Treatments. Pavement maintenance and rehabilitation treatments for flexible pavements implemented by the VDOT were obtained from the pavement management system records. Records were extracted from contracts executed between 2007 and 2022, detailing the type of treatments, thicknesses, construction year, rehabilitation category, road network type, and other data. A summary of treatments applied on the interstates, primary, and secondary road network types is given in **Table 5**.

Pavement Layer Dimensions. The layer dimensions associated with different treatments, particularly thicknesses, were also extracted from the PMS. The thicknesses of various pavement layers/treatments are shown in **Table 6**. Depending on the thickness, these rehabilitation treatments can be used in more than one rehabilitation category. A width spanning two standard lanes (of 12ft each) was considered for one mile.

Bill of Materials. Based on the functional unit of one lane mile of roadway section, 12 feet wide, the quantities of materials were calculated from the thicknesses, surface area (length by width of roadway section), and densities of the various rehabilitation treatments identified in the previous steps.



After (Amarh et al. 2021)

Figure 13. Framework for estimation of environmental impacts at different stages of the pavement life cycle

Table 5. List of VDOT's pavement maintenance and rehabilitation treatments.

Category	Treatment	Structure
PM	Thin Treatments	Latex Modified Emulsion Type C
		Chip Seal Modified Single Seal
		Slurry Seal Type C
	Overlays	1 in overlay
		1.5 in overlay
	Mill and Overlay	1.5 in mill + 1.5 in overlay
		2 in mill + 2 in overlay
CM	Thin Treatments	0.75 in THMACO
		Latex Modified Emulsion Type C
		Chip Seal Modified Single Seal
	Overlays	1.5 in overlay
		2 in overlay
	Mill and Overlay	1.5 in mill + 1.5 in overlay
		2 in mill + 2 in overlay
	Recycle and Overlay	2 in mill + 5 in CIR + 3.5 in overlay
RM	Overlays	2 in overlay
		2.5 in overlay
	Mill and Overlay	2.5 in mill + 2.5 in overlay
		4 in mill + 4 in overlay
	Recycle and Overlay	1.5 in mill + 4 in CCPR + 1.5 in overlay
		8 in mill + 7 in FDR-C + 7 in overlay
RC	Mill and Overlay	2 in mill + 2 in overlay
		2.5 in mill +2.5 in overlay
		6 in mill + 6 in overlay
	Recycle and Overlay	2 in mill + 5 in CIR + 2 in overlay
		2 in mill + 6 in CIR + 4 in overlay
		2 in mill + 12 in FDR-C + 2 in overlay
		8 in FDR-C + 3.5 in overlay
		12 in FDR-C + 4 in overlay
		10 in FDR-C + 2 in overlay
		10 in FDR-C + 2 in overlay
	Reconstruction	12 in aggregate base + 9.5 in overlay

Note: PM = Preventive Maintenance, CM = Corrective Maintenance, RM = Restorative Maintenance, RC = Reconstruction, THMACO = Thin Hotmix Asphalt Concrete Overlay, CCPR = Cold Central Plant Recycling, CIR = Cold In-place Recycling, FDR-C = Full Depth Reclamation with Cement.

Estimation of Global Warming Impacts. The GWIs associated with the extraction (A1) and transportation of raw materials to production plants (A2), production of asphalt mixes (A3), transportation of paving materials including paving materials to construction sites (A4), and construction activities (A5) were calculated using FHWA's LCA Pave—an MS Excel-based developed for the assessment of environmental impacts of pavement material and design decisions (Ram et al. 2021).

The tool consists of a library (inventory) of materials, equipment, waste, transport, and mix designs, which are used to develop pavement construction, maintenance, and rehabilitation activities. Though the tool comes with default library items for paving materials and construction based on averages for the United States, different agencies can populate the library with specific data tailored to their local practices. **Table 7** summarizes details of the inventory items and data sources used to estimate the cradle-to-laid impacts for Virginia. Using different combinations of materials, transportation modes and distances, and construction operations based on VDOT's rehabilitation treatments, the GWIs associated with various life cycle stages (A1-A5) were derived. The results are presented in **Table 6**.

Table 5 also shows an example of the category, treatment, and structure hierarchy described in the framework. The treatment names are new and are not part of the VDOT PMS. The structures follow standard VDOT terminology, which might differ from other states. In order to select which structure to use as the representative thicknesses for each treatment, the total lane miles built were computed within the construction data, and the structures ranked from most to least lane miles (within each network), and the results are shown in the rank column in **Table 6**. Since the VDOT decision trees make category recommendations, this process was also used to determine which treatment to represent each category and network. For example, a "Mill and Overlay" is the most likely treatment for the corrective maintenance category on the primary network, with a representative thickness of 2 in.

4.2.2 Development of IRI Performance Models & IRI Improvements

Data Extraction. Pavement condition data, traffic volumes, and data on executed contracts were extracted from the VDOT PMS. The data are categorized by pavement type, highway system, and maintenance district. The scope of this work is limited to asphalt pavements on interstate, primary, and secondary roads for all maintenance districts within VDOT. The pavement condition data include the distress year and various distresses (rutting, cracking, bleeding, and patching), roughness (IRI), and summarized pavement condition indices. These pavement condition indices are aggregates of individual distresses into the LDR, NDR, and CCI. The IRI data were used in this analysis section to develop performance models, while the pavement condition indices were used in the latter sections to conduct network analysis.

The contract data typically contain information on various executed or past pavement preservation and rehabilitation treatments—listing the contract number, year completed, rehabilitation categories (PM, RM, CM, RC), and details of various material layers/components in each contract. The traffic dataset lists pertinent information on traffic year, Average Annual Daily Traffic (AADT), and percentages of various vehicle classes. The datasets extracted for the pavement condition and executed contracts spanned 2007 to 2022, while the traffic data covered 2019, the most recent traffic year available in the PMS. SQL scripts were employed to consolidate the three datasets, utilizing a shared field—location identifier—present across all datasets.

Data Processing/Preparation. The joined dataset produced pavement condition information at 0.1-mile road sections for various traffic classes for 13,668 unique contract segments—3,303,793 observations. A new field was created in the dataset to summarize the various contracts into treatment categories utilizing the material layers/components detailed as line items in each contract. The result was a list of preservation and rehabilitation treatments grouped into surface layer, base layer, or combination. The treatment age was calculated as the difference between the distress year and the contract completion year.

Table 6. Global warming impacts for various treatments per lane-mile

Category	Network	Treatment	Structure	Rank	Global Warming Impact (kgCO$_{2\text{-eq}}$/lane-mi)			
					Materials (A1-A3)	Transport (A4)	Construction (A5)	Total (A1-A5)
PM	IN	Thin Treatments	0.3 in Latex Modified Emulsion Type C	1	21,904	926	154	22,984
		Mill + Thin Treatment	0.75 in mill + 0.75 in THMACO	2	16,347	4,532	259	21,138
	PR	Thin Treatments	0.4 in Latex Modified Emulsion Type C	1	29,199	1,235	154	30,588
		Overlays	1.5 in overlay	3	31,489	2,895	462	34,846
		Mill and Overlay	1.5 in mill + 1.5 in overlay	2	31,489	4,093	548	36,130
	SC	Thin Treatments	0.33 in Modified Single Seal	1	11,110	527	224	11,861
		Mill + Thin Treatment	0.25 in mill + 0.25 in Modified Double Seal	3	10,325	698	444	11,467
		Overlays	1 in overlay	2	20,993	1,930	462	23,385
CM	IN	Mill and Overlay	2 in mill + 2 in overlay	1	43,493	5,530	548	49,571
	PR	Overlays	1.5 in overlay	2	31,489	2,895	462	34,846
		Mill and Overlay	2 in mill + 2 in overlay	1	43,493	5,530	548	49,571
		Recycle and Overlay	2 in mill + 5 in CIR + 3.5 in overlay	3	99,550	7,485	1,319	108,354
	SC	Thin Treatments	0.3 in Chip Seal Modified Single Seal	3	10,101	479	224	10,804
		Overlays	1.5 in overlay	1	31,489	2,895	462	34,846
		Mill and Overlay	1.5 in mill + 1.5 in overlay	2	31,489	4,093	548	36,130
RM	IN	Mill and Overlay	4 in mill + 4 in overlay	1	83,971	10,913	988	95,872
		Recycle and Overlay	8 in mill + 7 in FDR-C + 7 in overlay	2	241,001	20,565	1,954	263,520
	PR	Mill and Overlay	2.5 in mill + 2.5 in overlay	1	52,479	6,820	548	59,847
		Recycle and Overlay	1.5 in mill + 4 in CCPR + 1.5 in overlay	2	60,935	5,429	1,110	67,474
		Recycle and Overlay	10 in mill + 10 in FDR-C + 1.5 in overlay	3	165,848	11,835	1,599	179,282
	SC	Overlays	2.5 in overlay	2	52,479	4,824	462	57,765
		Mill and Overlay	2.5 in mill +2.5 in overlay	1	52,479	6,820	548	59,847
RC	IN	Mill and Overlay	6 in mill + 6 in overlay	1	125,956	16,370	988	143,314
		Recycle and Overlay	12 in FDR-C + 4 in overlay	2	245,202	8,865	1,611	255,678
		Reconstruction	12 in No 21B + 5.5 in BM-25D + 4in. SMA	3	209,926	25,228	1,668	236,822
	PR	Mill and Overlay	2 in mill + 2 in overlay	1	43,493	5,530	548	49,571
		Recycle and Overlay	2 in mill + 12 in FDR-C + 2 in overlay	2	204,724	6,676	1,342	212,742
	SC	Mill and Overlay	2.5 in mill +2.5 in overlay	1	52,479	6,820	548	59,847
		Recycle and Overlay	8 in FDR-C + 3.5 in overlay	2	180,962	7,518	1,611	190,091

Note: PM = Preventive Maintenance, CM = Corrective Maintenance, RM = Restorative Maintenance, RC = Reconstruction,
In = Interstate, PR = Primary, SC = Secondary.

Table 7. **Data sources for LCI items used in the LCA Pave**

Library Module	Data Source(s)
Materials (e.g., aggregates, asphalt binders, cement, RAP etc.)	GW/short-ton estimated with OpenLCA by Amarh et al. (2021)
Equipment	Equipment list reported by Amarh et al. (2021). Runtimes validated with data collected for FHWA Climate Challenge. Default values of GWI/hr reported in LCA Pave
Waste	None (end-of-life not considered in system boundary)
Transport	Transportation modes and distances reported by Amarh et al. (2021) Default values of GWI impacts/short-ton-mile reported in LCA Pave
Mix designs (e.g., HMA, WMA, etc.)	EPDs for Virginia mixes from NAPA's Emerald Eco Label Program (2023)

Note: Activities in the LCA Pave library combine various items, including materials, equipment, waste, transport, and mix designs.

Table 8 shows the number of observations grouped by highway system, rehabilitation category, and treatment category.

Data Visualization and Cleansing. Plots of pavement IRI and treatment age grouped by treatment category and highway system were created using JMP statistical software's interactive plot feature. Typically, VDOT districts apply treatments from various rehabilitation categories when the pavement condition falls to predetermined/agreed thresholds, which resets the pavement condition to acceptable levels until the next treatment application is required. Thus, a road segment's IRI deteriorates as the road segment ages until the next contract is executed. The interactive plots were visually analyzed to identify trends in the data that were not consistent with engineering expectations—such as situations where IRI improves after certain treatment ages and then gradually increases over time. Such instances indicate that a new treatment was applied to the road segment but may be missing in the extracted data.

Erroneous IRI data, such as zeroes, blanks, negative values, and unreasonably high values evaluated as outliers, were cleansed from the data before model development. All contract segments with less than 3 data points were excluded from the analysis. Also, all contract segments showing an overall negative slope (IRI to treatment age) were removed from the analysis. At the end of the data processing, 2,083 out of 13,426 contract segments were removed, leaving 11,343 contract segments (84.5% of the data) for the performance modeling.

4.2.3 Development of IRI Prediction Models

Variable Selection. Statistical analysis was conducted to select variables to include in the IRI models. The dataset was fitted to a mixed model with IRI as the response; treatment age, treatment category, rehabilitation category, thickness (of contract segment), highway system, and traffic volume (AADT) as fixed effects; and contracts as a random effect. **Table 9** shows the fit statistics for the resulting mixed model. The results show that among the treatment factors/variables in the model, variations in IRI are not explained by the total thickness of each contract segment. Thus, the thickness was excluded from the model while the other variables were kept.

VDOT currently incorporates performance models for LDR, NDR, and CCI within the PMS. These models are tailored to different rehabilitation categories for each highway system. To align with the current VDOT setup and reduce the number of models created, a decision was made to develop a family of IRI models for various treatment categories, grouped by rehabilitation category and highway system. Four families of IRI models (mill and overlay, overlays, recycle and overlay, and thin treatments) were developed for each highway system-rehabilitation category combination.

Model Screening and Development. Various model shapes, derived from different functions, were initially fitted to the dataset—with IRI as response and treatment age as an independent variable—to assess their goodness-of-fit to trends in the IRI data.

Table 8. Sample size of data extracted for the IRI study

PMS Component	No. of Contracts (count)	IRI (in/mi)			Treatment Age (yr)		No. of Observations (count)
		mean	min.	max.	mean	max.	
Highway System							
Interstate	780	66.6	22	475	4.9	17	413,619
Primary	5408	98.7	22	491	4.9	16	2,261,327
Secondary	7317	172.9	34	492	4.5	18	605,503
All	13426	108.4	22	492	4.8	18	3,280,449
Rehabilitation Category							
CM	7787	102.4	22	491	4.9	17	2,058,641
PM	4874	136.9	22	492	4.5	18	779,090
RC	162	89.7	26	475	4.8	15	101,811
RM	603	84.9	24	475	4.9	14	340,907
All	13426	108.4	22	492	4.8	18	3,280,449
Treatment Category							
FDR-C + Overlay	8	102.3	46	412	4.97	11	1,422
FDR-C + Thin Treatments	4	93.2	44	216	3.88	7	1,256
FDR-E + Overlay	1	142.3	100	348	7.87	15	108
FDR-FA + Overlay	1	109.9	83	181	7.91	15	114
Mill and Overlay	4844	96.3	22	477	4.86	17	1,864,215
Mill and Overlay + Thin Treatment	2	116.5	66	262	4.30	8	825
Mill + CCRPM + Overlay	4	92.9	56	425	2.00	3	1,212
Mill + Cement Base + Overlay	1	122.8	86	148	3.37	6	95
Mill + CIR-EA + Overlay	1	78.3	43	149	5.51	10	1,912
Mill + CIR-FA + Overlay	3	58.3	33	216	6.22	12	2,696
Mill + FDR-C + Overlay	7	80.2	29	426	4.44	11	6,006
Mill + FDR-L + CIR-FA + Overlay	1	48.0	33	173	6.53	12	2,410
Mill + Surface Treatment	15	54.2	22	285	2.57	7	4,238
Overlay + Thin Treatments	3	93.2	35	388	3.38	6	4,720
Overlays	3286	101.1	23	491	5.01	14	655,405
Thin Treatments	5245	146.6	24	492	4.54	18	733,815
All	13426	108.4	22	492	4.82	18	3,280,449

FDR-C = Full Depth Reclamation with Cement, FDR-FA = Full Depth Reclamation with Foamed Asphalt, FDR-EA = Full Depth Reclamation with Emulsion Asphalt, FDR-L = Full Depth Reclamation with Lime, CCPRM = Cold Central Plant Recycling Material, CIR-EA = Cold In-place Recycling with Emulsion Asphalt, CIR-FA = Cold In-place Recycling with Foamed Asphalt

Table 9. **Fixed effects test results**

Model Variables (Effects)	N	DFNum	DFDen	F Ratio	Prob > F
Rehabilitation Category	3	3	12291	22.0	<.0001
Treatment Category	15	15	12046	91.1	<.0001
Treatment Age	1	1	2900000	8104.4	<.0001
Thickness	1	1	2900000	0.0	0.9732
AADT	1	1	2500000	208.0	<.0001
Highway System	2	2	203170	9540.1	<.0001

Table 10. **List of candidate models evaluated for IRI models**

Function	General Equation
Logistic 3P	$\frac{c}{1 + Exp(-a \times (Age - b))}$
Gompertz 3P	$a \times Exp\ (-Exp\ ((-b \times (Age - c)))$
Exponential 3P	$a + b \times Exp(c \times Age)$
Linear	$a + b \times Age$
Exponential 2P	$a \times Exp(b \times Age)$

Note: a, b, c = model coefficients

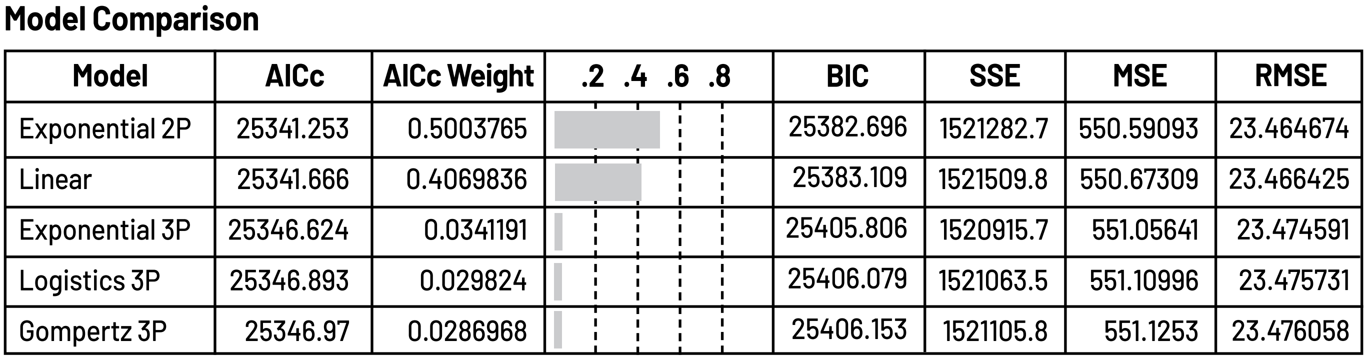
The equations for these candidate models are highlighted in **Table 10**. The final model selection involved evaluating the second-order Akaike information criterion (AICc) weights, with preference given to the model with a weight closest to one. When comparing multiple models, the AICc weight measures the relative likelihood of a model being the "best" (1.0 indicating the highest likelihood). Typically, boundary conditions for the response variable are established, and their impact on the resultant models is re-evaluated.

In this case, no boundary conditions were set for the maximum IRI value, although pavements with an IRI exceeding 500 in/mi are generally considered non-rideable except at low speeds. The model screening was done for each family of IRI models, i.e., mill and overlay, overlays, recycle and overlay, and thin treatments. Results from the model screening exercise highlighting the fit statistics for various model functions on the interstate network are shown in **Figure 14**.

An exponential 2P model was selected as this network's "best" model. The estimates for the "best" fitting model for the various highway system-rehabilitation category combinations are presented in **Table 11**.

4.2.4 IRI Improvement Models

The histories of the pavement IRI before and after the various rehabilitation treatments were applied were evaluated to estimate how much the network will improve when a treatment is selected. For each rehabilitation treatment, the percentage improvement is the difference in average IRI of the last two years before and after the treatment was applied. **Table 12** shows the percentage improvements for treatment categories applied on the interstate network. These results were used in the network analysis, but further refinements may be needed.



Model Comparison

Model	AICc	AICc Weight	.2 .4 .6 .8	BIC	SSE	MSE	RMSE
Exponential 2P	25341.253	0.5003765		25382.696	1521282.7	550.59093	23.464674
Linear	25341.666	0.4069836		25383.109	1521509.8	550.67309	23.466425
Exponential 3P	25346.624	0.0341191		25405.806	1520915.7	551.05641	23.474591
Logistics 3P	25346.893	0.029824		25406.079	1521063.5	551.10996	23.475731
Gompertz 3P	25346.97	0.0286968		25406.153	1521105.8	551.1253	23.476058

Figure 14. **Fit statistics results comparing IRI models for corrective maintenance strategies on the interstate highway system**

Table 11. **Parameter estimates for IRI prediction models**

Network	Rehabilitation Category	Model Family	"Best" Model	Model Coefficients		
				a	b	c
IN	CM	Mill and Overlay	Exp 2P	64.2	0.0223	
		Overlays	Exp 2P	58.5	0.0209	
		Thin Treatments	Exp 2P	68.9	0.0279	
	PM	Mill and Overlay	Exp 2P	57.3	0.0318	
		Overlays	Exp 2P	72.4	0.0082	
		Thin Treatments	Exp 2P	69.7	0.0159	
	RC	Mill and Overlay	Exp 2P	59.9	0.0192	
		Overlays	Exp 2P	51.6	0.0131	
		Recycle + Overlay	Exp 2P	48.0	0.0003	
	RM	Mill and Overlay	Exp 2P	56.5	0.0347	
		Overlays	Exp 2P	71.1	0.0156	
		Recycle + Overlay	Exp 2P	44.4	0.0146	
PR	CM	Mill and Overlay	Exp 3P	138.8	-43.7875	-0.0720
		Overlays	Exp 3P	103.2	-18.7965	-0.8038
		Recycle + Overlay	Exp 3P	85.6	-9.8845	-0.0407
		Thin Treatments	Exp 3P	126.4	0.2286	0.4739
	PM	Mill and Overlay	Exp 3P	59.1	18.2979	0.0952
		Overlays	Exp 3P	108.0	-24.2608	-0.2915
		Thin Treatments	Exp 3P	113.0	-13.6131	-0.6626
	RM	Mill and Overlay	Exp 3P	103.3	-19.9950	-0.4046
		Overlays	Exp 3P	81.7	-16.5606	-0.2446
		Recycle + Overlay	Exp 3P	110.2	-32.6059	-0.3764
	RC	Mill and Overlay	Exp 2P	109.8	0.0114	
		Overlays	Exp 2P	115.0	0.0004	
		Recycle + Overlay	Exp 2P	85.9	0.0284	
SC	CM	Mill and Overlay	Linear	149.8	1.1856	
		Overlays	Linear	144.1	0.6458	
		Thin Treatments	Linear	209.2	0.2448	
	PM	Mill and Overlay	Linear	145.1	0.4528	
		Overlays	Linear	126.2	4.9781	
		Thin Treatments	Exp 2P	196.5	0.0076	
	RC	Mill and Overlay	Linear	101.4	1.2370	
		Overlays	Linear	137.2	2.4634	
	RM	Mill and Overlay	Linear	140.6	0.4379	
		Overlays	Linear	113.2	1.6875	

Table 12. **IRI improvement models for various treatment categories on the interstate network system.**

Category	Treatment Category	IRI 2 Years Before		IRI 2 Years After		Improvement	
		(in/mi)		(in/mi)		(in/mi)	%
PM	Mill and Overlay	91	97	62	62	32	34%
	Overlays	87	96	81	81	10	11%
	Thin Treatments	78	83	61	63	20	23%
CM	Mill and Overlay	91	93	63	64	28	31%
	Overlays	84	87	59	58	27	31%
	Thin Treatments	99	100	78	76	23	23%
RM	Mill and Overlay	93	94	61	61	33	35%
	Recycle + Overlay	89	95	46	46	46	50%
	Overlays	74	82	64	66	13	17%
RC	Mill and Overlay	86	91	54	56	34	38%
	Recycle + Overlay	69	74	62	58	12	16%
	Overlays	79	94	64	49	30	35%

4.2.5 Traffic Impacts

The VDOT PMS data includes traffic information for five vehicle classes: cars, buses, 2-axle trucks, 3-axle trucks, and trucks with trailers. These were mapped to the HDM-4 classes of Medium Car, Coach, Light Truck, Heavy Truck, and Articulated Truck, respectively, and the use stage coefficients from Appendix A were used for the use stage calculations. Since no lane-based roughness was available, it was assumed that all vehicles experienced the same roughness based on the outer lane IRI, so no lane-based traffic assignment was performed.

4.2.6 Network Analysis

The equations and GWIs above were combined with the existing equations for CCI, LDR, and NDR, as well as the decision trees from the VDOT PMS, and implemented in the same MATLAB® environment used for the California case study. As described above, the management segments (21,728 total) were extracted from the PMS using the currently used segmentation with 2022 condition data. Because the detailed traffic segments differed from the management segments, a "finest partition" was performed between the two, resulting in 29,901 final segments. Since the divided segments have the same condition data, they will have the same performance and decisions, with only the use stage GWI being different between the finer segments.

The decision trees used by VDOT are relatively complex, although they still assign only categories. Primarily, they are based on LDR and NDR for the interstate and primary systems and CCI for the secondary system, with some use of IRI and rutting to trigger heavier interventions if needed. Based on experience, it would be relatively simple to adapt these trees to use the treatments developed for this study, but this was not done because these types of changes are the domain of VDOT staff.

Because these models were not implemented into the PMS, running any constrained optimization scenarios on the VDOT network was impossible, and thus, no future budget needed to be determined.

4.3 Results

The first analysis run on the VDOT network considered the first two scenarios used for the California analysis: the "Do Nothing" and the "Unlimited Budget" scenarios. The roughness results from these are shown in **Figure 15**, where it can be seen that the initial roughness on the interstate system is good, at 71 in/mi, while it increases to 102 in/mi and 157 in/mi on the primary and secondary systems. As expected, these deteriorate without maintenance and improve significantly with an unlimited budget.

Figure 16 shows the treated lane miles, which are clearly zero for the Freefall case. VDOT limits the number of consecutive PM and CM treatments that can be applied to the IN and PR systems before doing a more substantive treatment, so these eventually require restorative maintenance but never reconstruction. There are no limits on the SC system, so the budget is mainly spent on PM treatments.
The annual and cumulative GWIs are shown in **Figure 17** and **Figure 18**, respectively, which show similar patterns to the California results. Most importantly, it is clear that even spending an unlimited budget on activities still results in net GWI reductions over halting all work on the network.

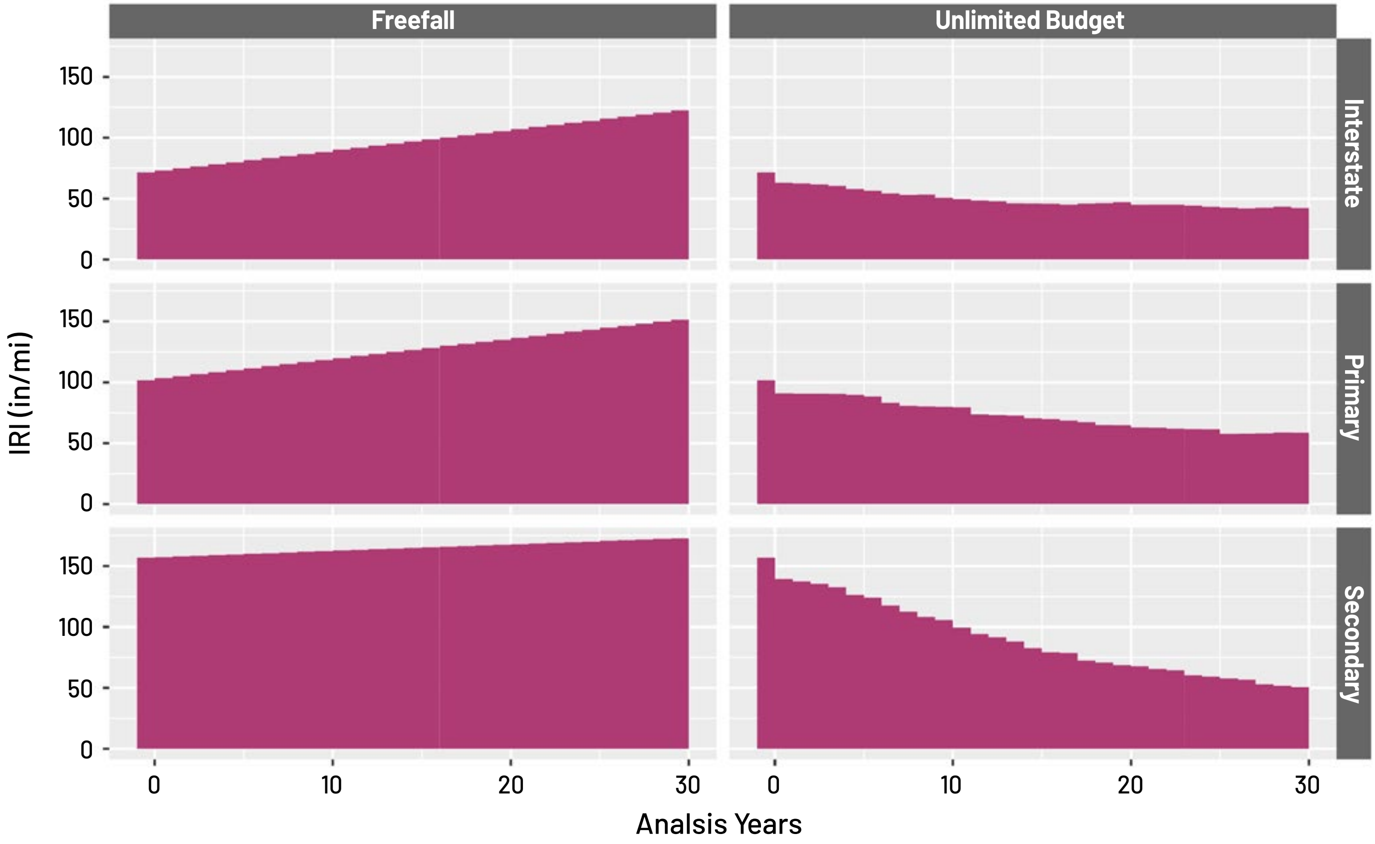


Figure 15. **Average roughness for different Virginia budget scenarios**

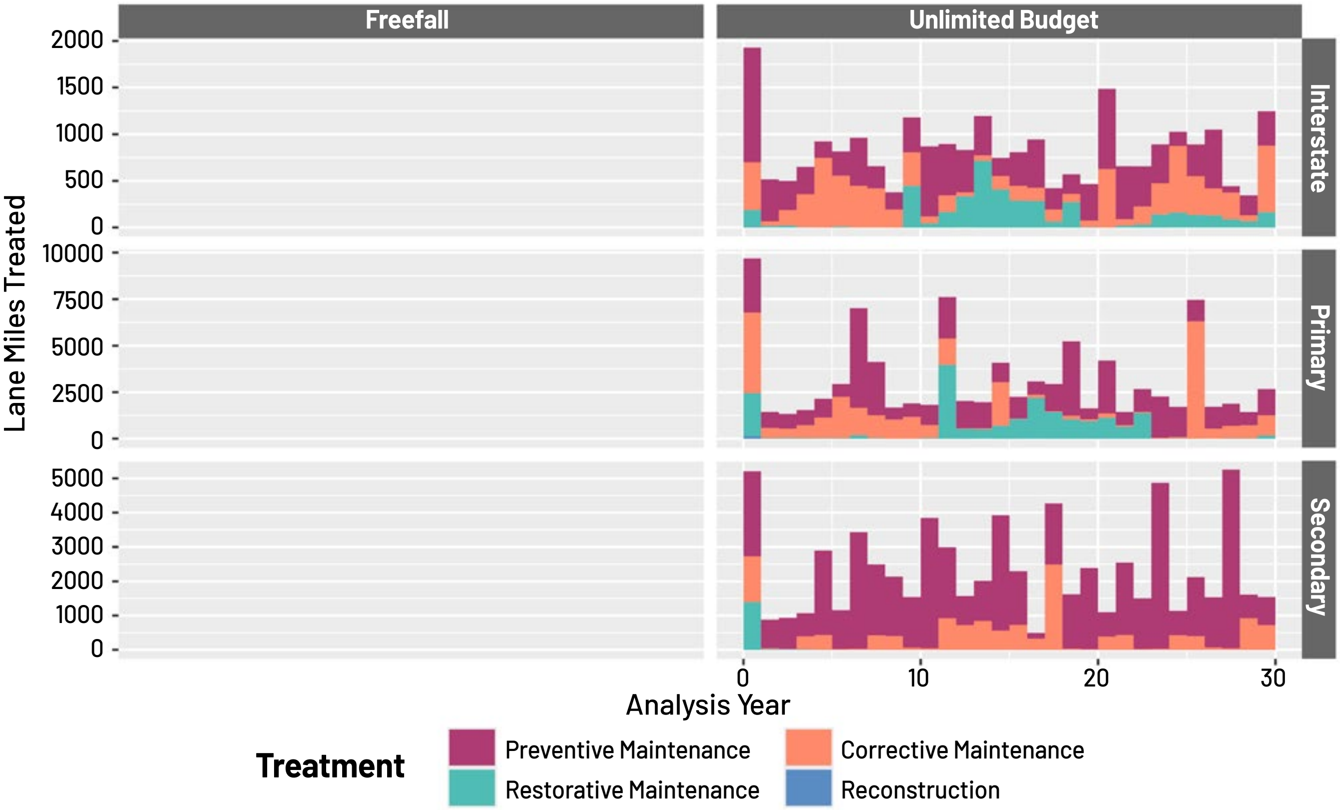


Figure 16. **Treated lane miles for each Virginia budget scenario**

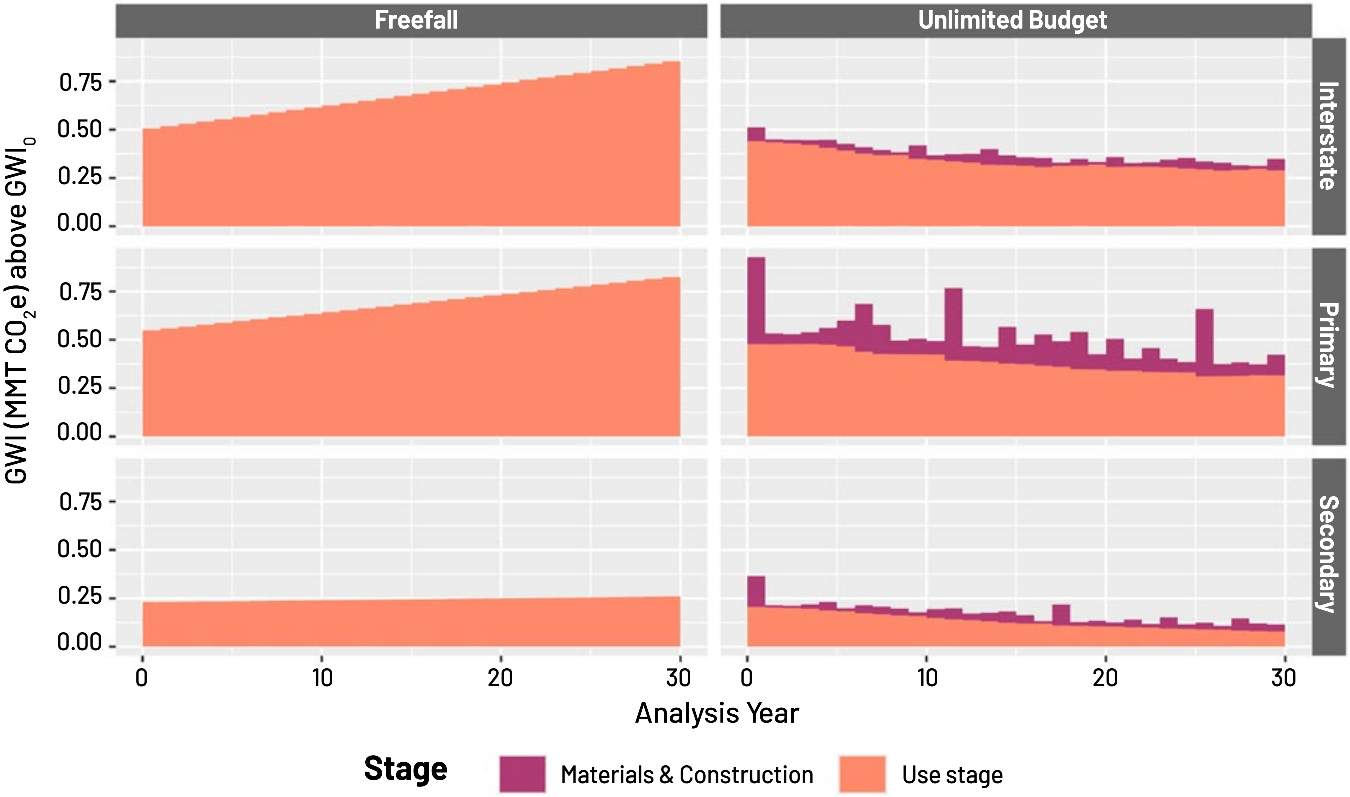


Figure 17. **GW impact above baseline for Virginia budget scenarios**

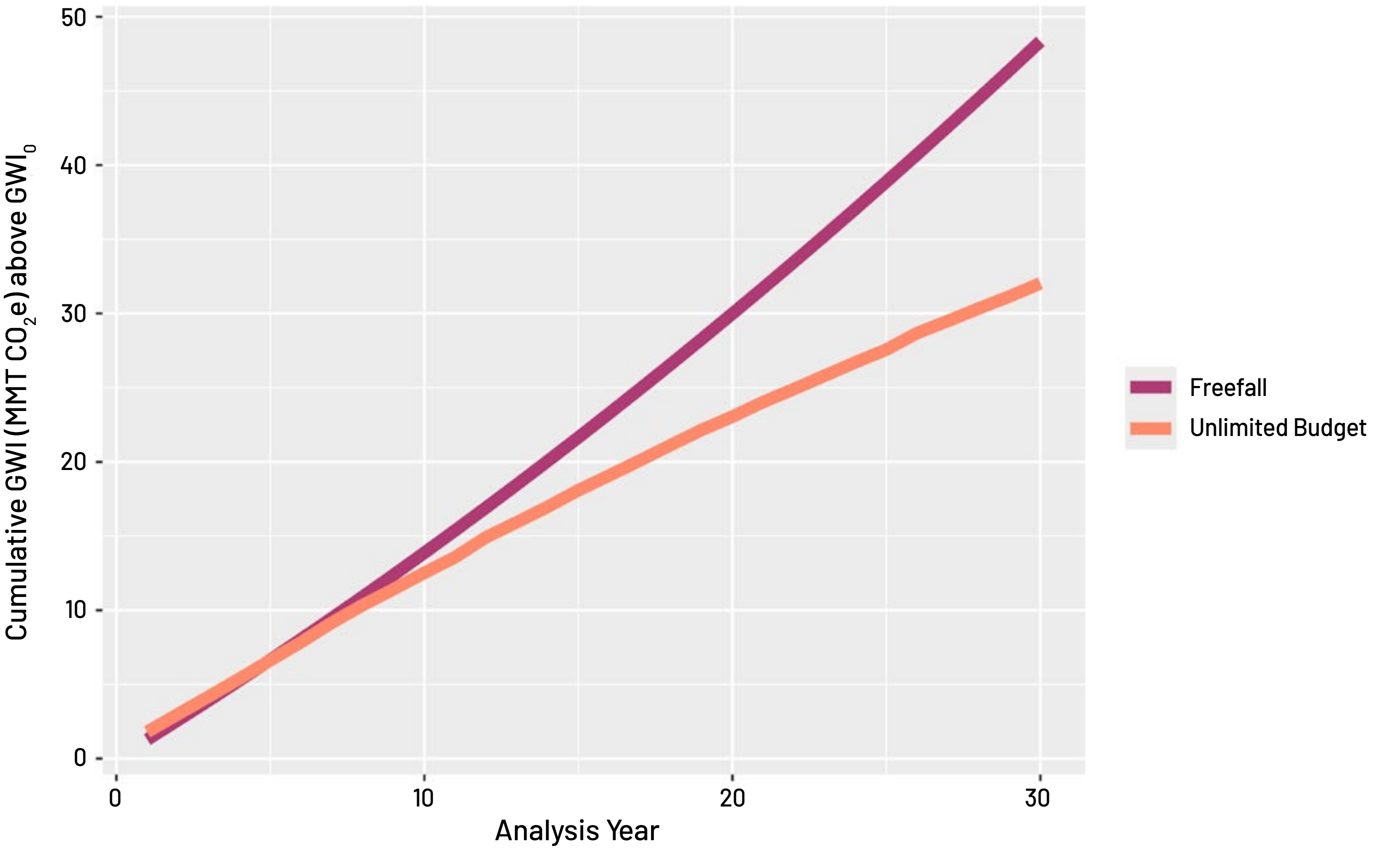


Figure 18. **Cumulative GW impact for the Virginia budget scenarios**

4.3.1 Optimized IRI Triggers

The VDOT PMS decision trees contain several IRI trigger levels. In the following exercise, these were replaced with lower and lower IRI values to test for improvements in the IRI trigger levels. The secondary network has no IRI triggers, so its results do not change and are excluded. In all cases, the budget is unlimited. **Figure 19** shows the changes in roughness in the network, **Figure 20** shows the activities, and **Figure 21** shows the cumulative GWIs. **Figure 22** shows the changes in cumulative GWI and roughness as a function of the trigger roughness.

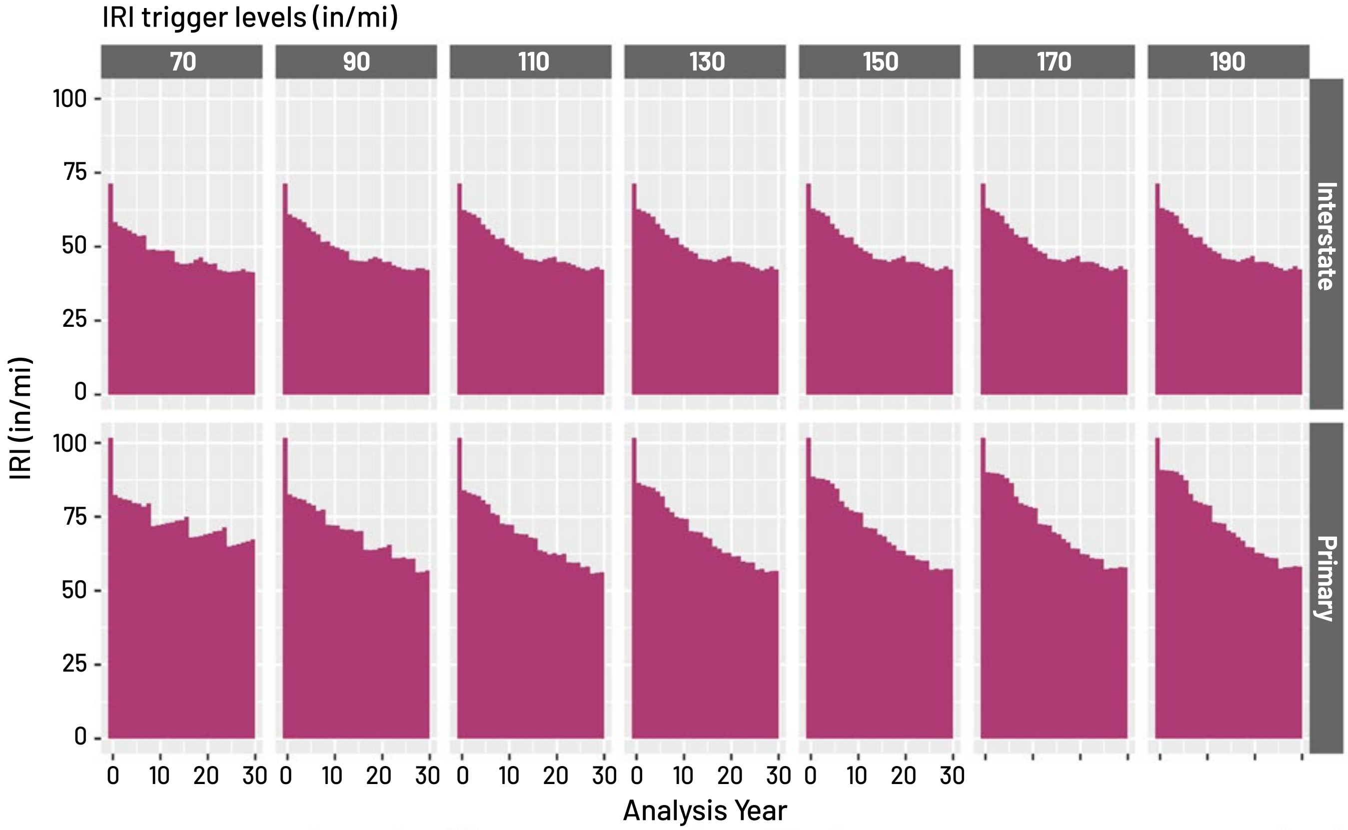


Figure 19. **Average roughness for different Virginia unlimited budget scenarios at varying IRI trigger levels**

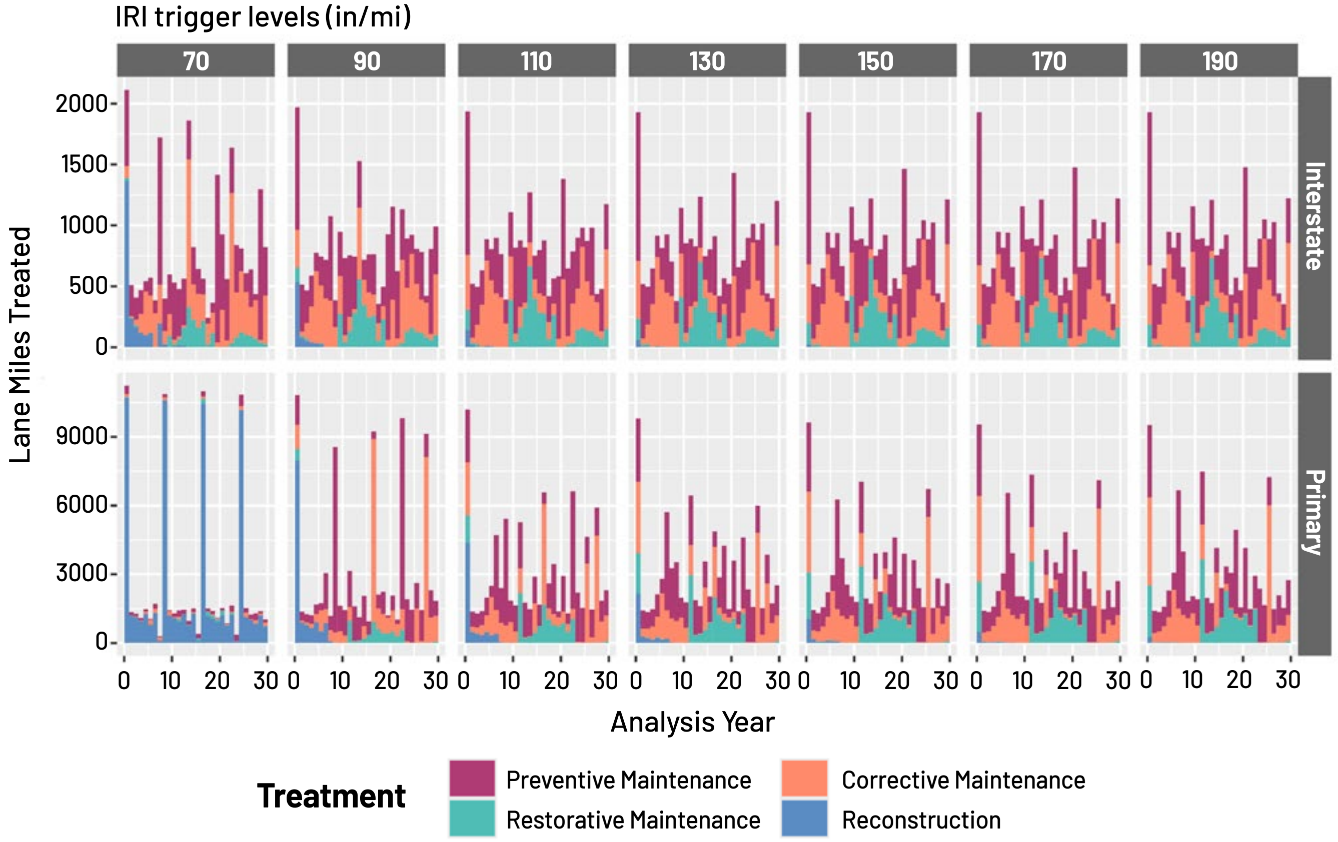


Figure 20. **Treated lane-miles for the Virginia unlimited budget scenario at varying IRI trigger levels**

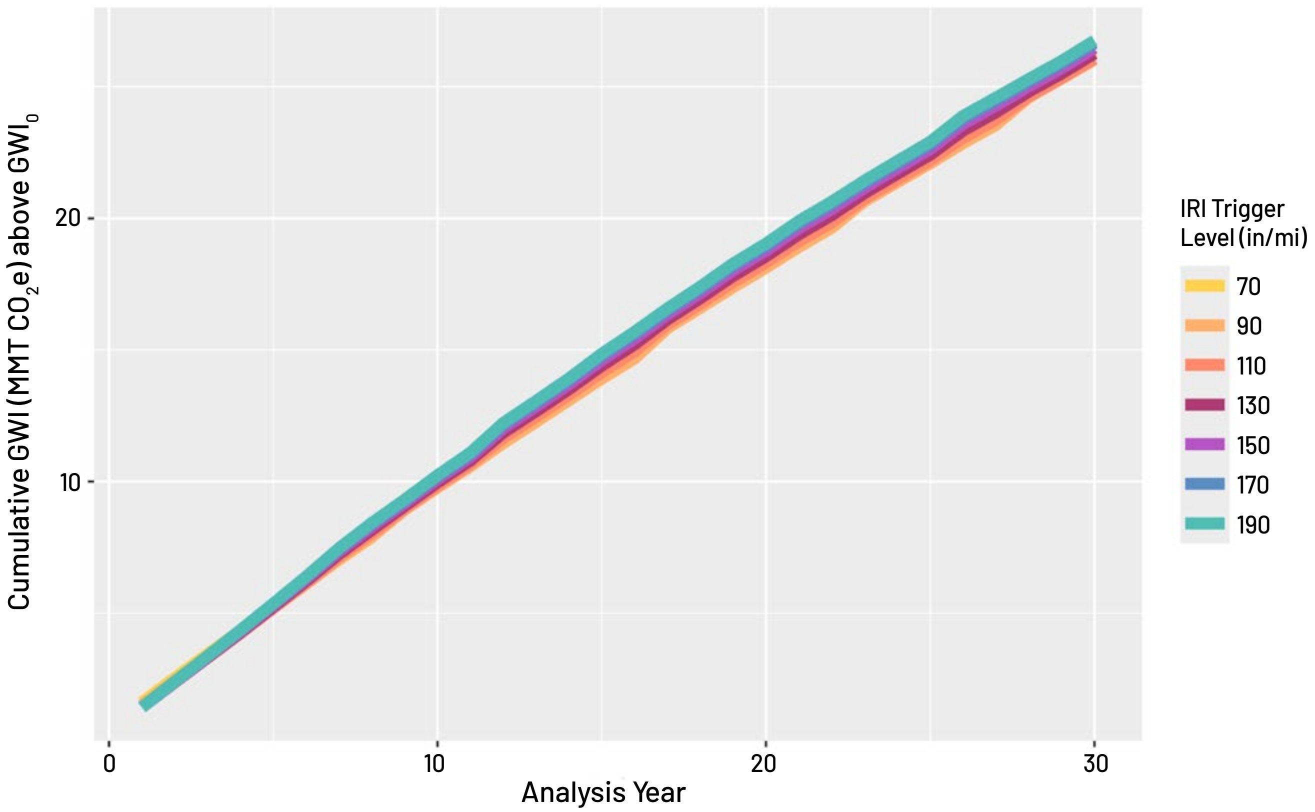


Figure 21. **Cumulative GW impact for the Virginia unlimited budget scenarios at varying IRI trigger levels.**

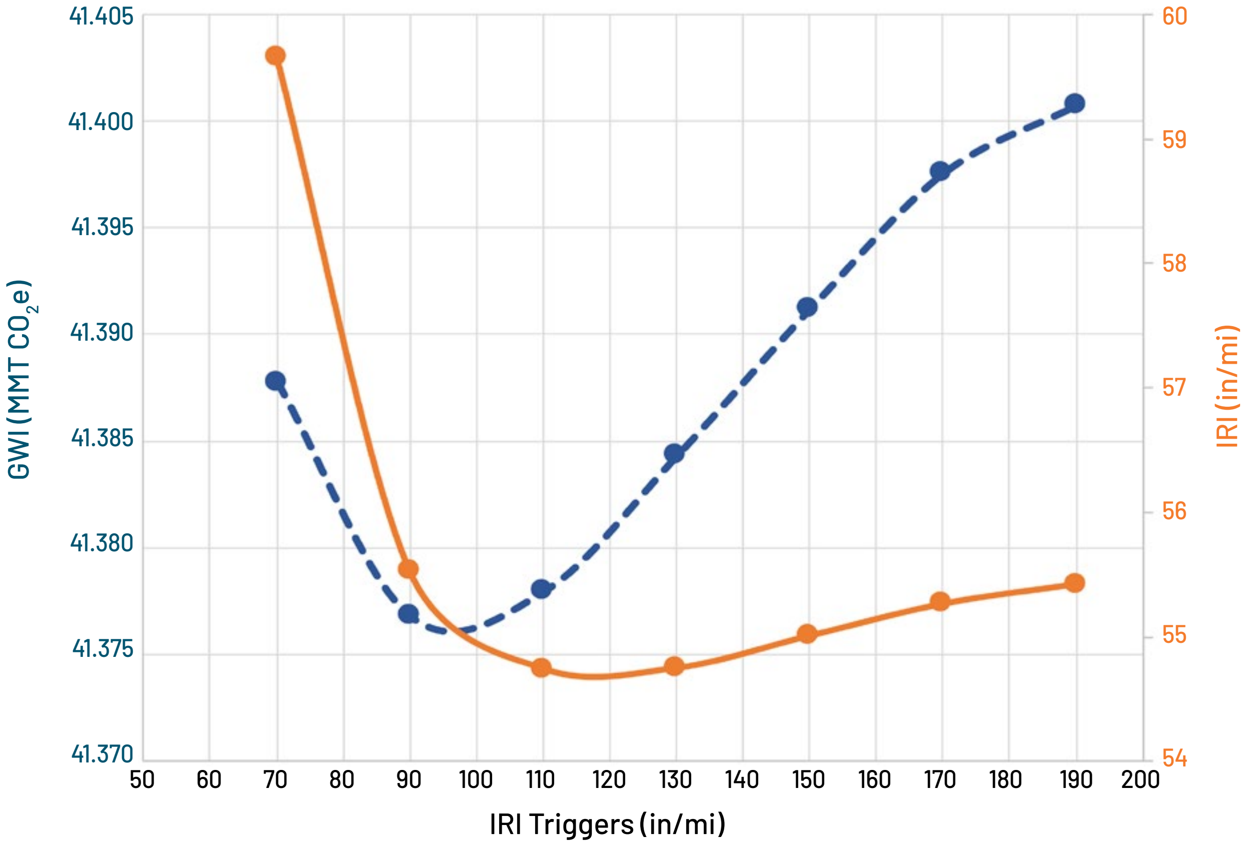


Figure 22. **Trend showing the change in direction from decreasing to increasing GW impact for the Virginia unlimited budget scenario and average network IRI at varying IRI trigger levels.**

It was hoped that the reduction in IRI trigger levels would result in lower network roughness, but once the unlimited budget meets the current needs in the first year, there are not many opportunities to maintain rough roads – they are all repaired at the slightest sign of distress. This pattern continues until the decision trees recommend repeated reconstructions below a trigger level of 90 in/mi (**Figure 20**). Other constraints limit what can be done in the following years, so the average IRI on the system increases. This approach does not yield significant savings in GHG emissions, at least regarding how the VDOT PMS is configured, so other changes will likely need to be pursued, although the results might be different if this analysis was performed with a realistic budget. However, this test would have to wait until the models were implemented within VDOT's PMS. In addition, rethinking the decision trees regarding treatments would probably result in more targeted interventions based on the actual distresses rather than the generic categories.

5 CONCLUSIONS AND RECOMMENDATIONS

As demonstrated in the case studies, it is possible and practical to incorporate an LCA with minimum requirements for feasibility into an existing PMS and perform analyses to aid agencies in achieving global warming impact emissions reductions. The steps involved would depend on the current configuration of an agency PMS and on the assumption that roughness data are already being collected. These steps are: 1) determining the M&C GHG associated with each treatment in the PMS, 2) developing IRI performance models and improvements, and 3) determining vehicle type specific traffic for each management segment. With these components in hand, an agency, university, or consultant should be able to implement the framework outlined in this report.

Some high-level conclusions likely to apply to most highway networks can be drawn based on the results of both case studies presented in this report. First, the GHG emissions are driven by vehicle travel, not pavement roughness, so that the network-wide emissions will be highly dependent on changes in the vehicle fleet (particularly electrification) and the electricity sources. As various jurisdictions transition to renewable energy, the role of transportation in GHG will reduce (as is implied by the con-cept of net-zero), but this does not mean that pavement condition will not be important: rough roads require additional energy, so maintaining the highway network in a smooth state will always be neces-sary, even if it is to increase range of electric vehicles. Thus, continuing to maintain pavements, even if this requires the generation of emissions, is essential because the case studies show that, left unmaintained, the roughness of a network will increase, and the impacts from additional fuel use will quickly outweigh the impacts from construction. Second, the case studies also show that achieving smoothness in construction is one of the best ways to reduce impacts, suggesting that more emphasis be placed on smoothness and uniformity in construction.

To go further than the minimal LCA will likely require additional data collection by the agency. Firstly, while this report does present a model for IRI on inside lanes, a more accurate approach would be to collect data on all lanes and directions. If this cost is excessive, it may be possible to use crowd-sourced or connected vehicle data to obtain lane-based IRI values, although none of the current providers of this type of data offer lane-based data. However, this might not be an issue because the values are being summed over the lanes, so if some proportion of the vehicles report one IRI and some another, then computing the GWI and summing in proportion to the vehicle counts may be a workable solution.

Detailed traffic information for each lane across the network may be more challenging to obtain, and there are no published papers on traffic models that perform lane-based vehicle assignments at a network level, especially not for trucks. Besides the crowd-sourced data mentioned above, the other data sources within a DOT would be loop detectors and Weigh-In-Motion stations, but this would require additional research to develop a traffic model. Additional details on traffic GWI would require a more detailed breakdown of the types of vehicles using the roads, which are not currently available, along with calibration parameters for models such as the HDM-4 model. This gap also represents a research opportunity, which might be feasible using deep-learning detection of vehicles from traffic monitoring cameras and collaboration with connected vehicle data suppliers to obtain fuel use information. Many of the models within HDM-4 are also based on old vehicle technologies and should possibly be verified.

On the materials side, there are an increasing number of materials for which EPDs are available, so the development of GWIs for treatments should become routine. However, expanding on the minimal LCA would probably require most agencies to use more detailed treatments within their PMS, which would only be feasible with more detailed roughness and cracking models for each treatment. While this might be welcomed in some jurisdictions, others might not see the benefit to cost ratio of this change.

Nonetheless, even with a minimal implementation of this framework, it is possible to meet the goals outlined and position an agency to show that pavement maintenance can improve sustainability in terms of global warming impacts from road maintenance and use. While in the early years of implementation it is likely that some treatments will be over or underestimated, as was the case with recycling treatments in California, this should not prevent an agency from starting to implement this framework—the analysis must start somewhere—but they should be cautious of results that seem illogical, especially if they are being used to promote one treatment type to the exclusion of others. Highway Pavement Management." In Climate Change, Energy, Sustainability

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APPENDIX A: COMPUTATION OF GWP FROM HDM-4 MODELS

The HDM-4 fuel use model (Greenwood and Bennett 1995; Bennett and Greenwood 2003), as calibrated in NCHRP720 (Chatti and Zaabar 2012), allows the computation of fuel consumption as a function of several pavement, vehicle, traffic, and other parameters. The model is structured as an energy balance so that the fuel use is computed as a function of the energy content of the fuel, the losses due to combus-tion and friction, and the forces opposing the vehicle's motion. The model result is fuel use per distance traveled by the vehicle, computed over a standardized distance (one kilometer in HDM-4). The parame-ters fall into three distinct types: vehicle parameters that are fixed for a particular calibration vehicle (such as fuel type and engine power), parameters that are fixed for a particular section (such as gradient and curvature, and—for this analysis—roughness and texture), and vehicle transit specific parameters (such as air temperature, speed, and vehicle mass).

Within an LCA analysis of a pavement section, the interest is in the total GWI of a traffic stream over long periods, not in specific emissions from individual vehicles. However, to facilitate the integration of the minimal feasible LCA into the network-level PMS framework, these impacts need to be partially computed to combine with section and traffic information for a management segment to obtain final results. Thus, the goal is to produce intermediate results for the expected GWIs for a set of parameters known in the PMS and "integrate out" the other parameters from the HDM-4 model based on their distribution or expected value. Variables included in this process would depend on which were available at a segment level in the PMS.

As with the main framework, this relies on both assuming that the expected fuel consumption over some range of an input is the same as the fuel consumption at the expected value of that input and that the proportion of some observation in the data is the same as the probability of observing that value at each observation. The focus here is on producing equations for the framework, not for more general use, so the critical factor is if two different treatments would be ranked the same, not the absolute fuel consumption numbers, although these do need to be accurate to ensure a correct balance between treatment impacts and use impacts.

There are forty-one parameters in the HDM-4 model, but thirty-one of these are fixed once one chooses a calibration vehicle. The remaining ten parameters are gross vehicle mass, speed, acceleration, excess fuel consumption due to congestion (based on the drive cycle and called dFuel), segment altitude, gradient, curvature, roughness, mean profile depth (MPD), and air temperature. The vehicle mass is a function of the type of vehicle, with only the goods vehicles changing significantly from their empty mass. For this analysis, the mass was fixed at the maximum mass (as listed in the calibration tables).

Segment altitude, gradient, and curvature could be variables in the PMS but were fixed as 200 m, 0%, and 3000 m (their HDM-4 defaults), respectively because they were unknown for the two case studies. These variables would be fixed for a particular segment. While both example PMSs do have values for MPD, this was also fixed at 1 mm since it has little effect on the analysis. Roughness was set to different levels to obtain fuel consumption at these levels since this simplification's objective is to obtain a curve of fuel consumption versus roughness for each vehicle, leaving only the drive cycle variables (speed, acceleration, and congestion) and air temperature. Theoretically, air temperature, drive cycle, and vehicle mass are correlated since they depend on when the vehicle transits the segment. In practice, the air temperature has a limited impact, so it was also fixed at 15°C, and as mentioned, mass was fixed, leaving only the drive cycle. For most purposes, the acceleration in HDM-4 is set to zero, and the acceleration is han-dled through the dFuel parameter, which scales the fuel consumption based on acceleration variability during driving. This analysis assumed uncongested flow since the pavement does not impact congestion, so dFuel was set to zero. A representative uncongested speed profile was also selected, with different speeds for cars and trucks on weekdays and weekends, as shown in **Figure 23**, and the associated volumes are shown in **Figure 24**.

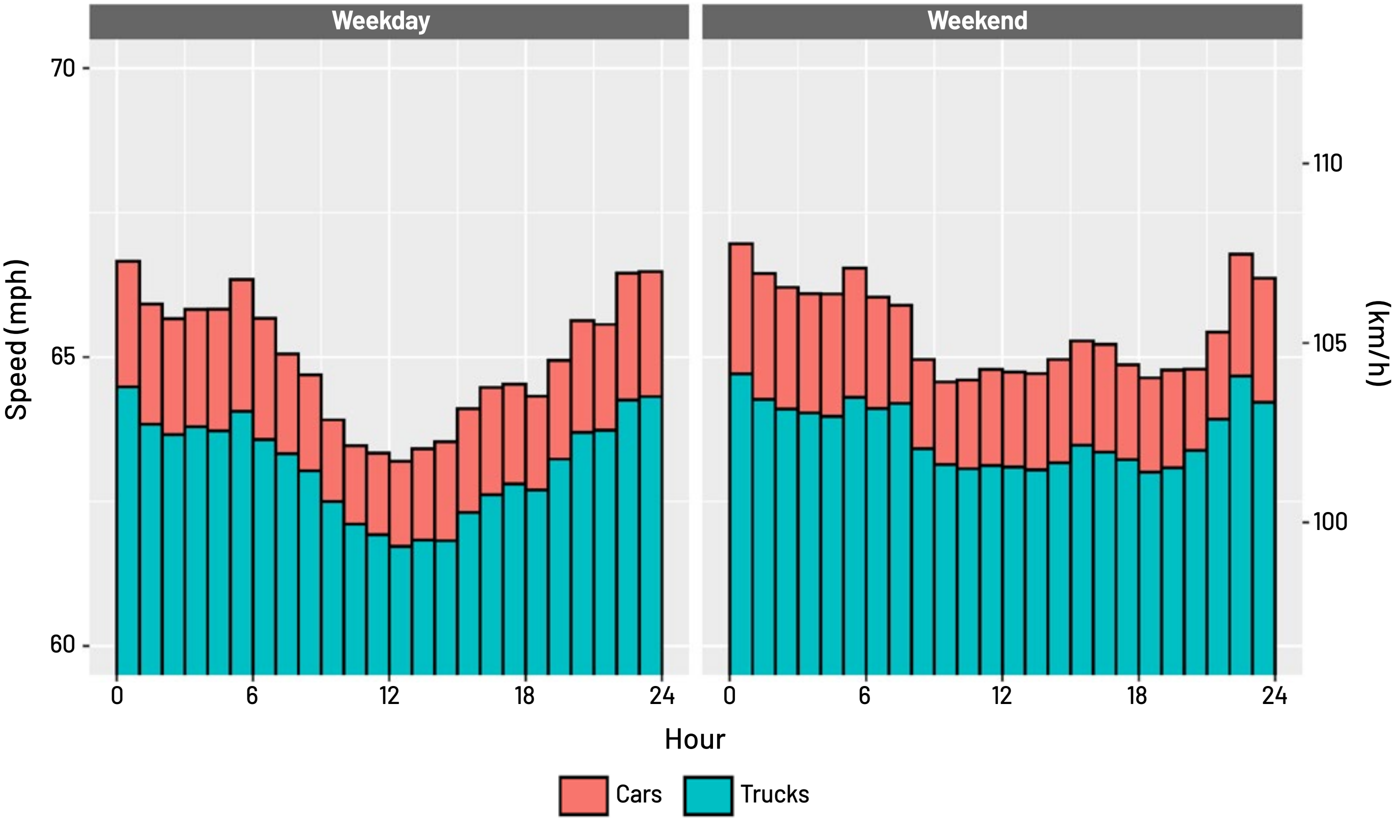

Figure 23. Speed distribution used in coefficient development

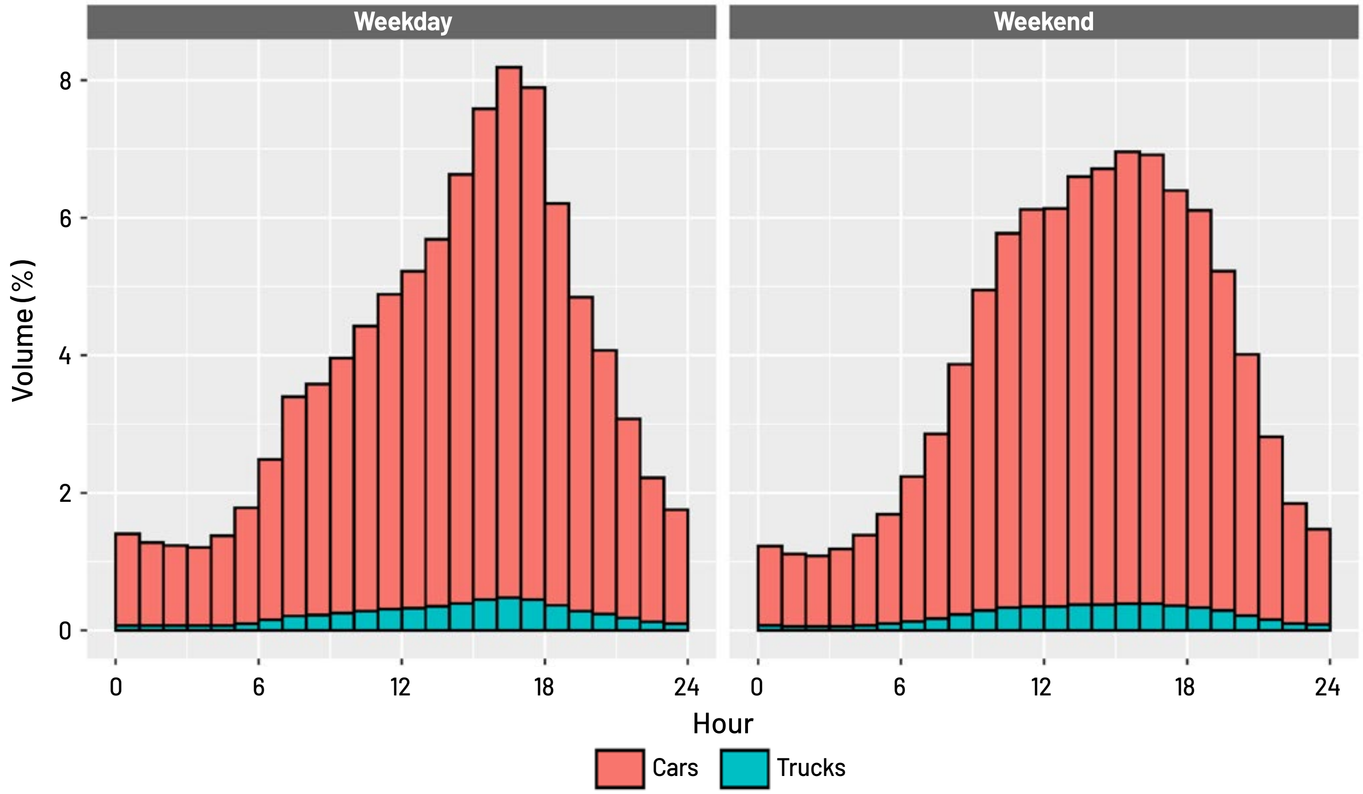

Figure 24. **Volume distributions used in coefficient development**

With these default values in place, selecting a calibration vehicle and a roughness value is possible, al-lowing one to run the HDM-4 model to obtain the fuel consumption for a unit distance. These are computed for each hour of each week or weekend day and summed with the appropriate weighting, as shown in (3).

The fuel consumption can then be converted into GWI using appropriate well-to-wheel values for the region or state. For this analysis, these were 9.52 and 11.92 $kgCO_2e/gal$ for gasoline and diesel, respectively, calculated using eLCAP.

$$fc_v(IRI) = \frac{365 * 1.609344}{3785.411784}\left(\frac{5}{7}\sum_{t=1}^{24} wdv_{vt}IFC_v(IRI, wds_{vt}) + \frac{2}{7}\sum_{t=1}^{24} wev_{vt}IFC_v(IRI, wes_{vt})\right) \qquad (3)$$

Where

$fc_v(IRI)$ is the fuel consumption (in gal/mi/year),
$IFC_v(\bullet)$ is the HDM-4 instantaneous fuel consumption (in mL/km)
wdv_{vt}, wev_{vt} are the weekday and weekend volumes for vehicle type v during hour t
wds_{vt}, wes_{vt} are the weekday and weekend speeds for vehicle type v during hour t.

The final values are converted to values per year because it is common to express traffic as Average Annu-al Daily Traffic (AADT), so if a particular section has, for example, only one large car as the AADT, then this would represent emissions from that one vehicle driving daily over the section for a year. When these equations are used, the emissions are multiplied by the AADT values for each vehicle class (as determined by available traffic data), then by the segment length, and finally by the appropriate impact (depending on the vehicle fuel type) to obtain the annual impact per segment. These are typically reported in metric tonnes not kilograms, so an appropriate divisor is needed. The fuel consumption results for a single vehi-cle and lane mile are shown in **Figure 25** and the corresponding GWIs are shown in **Figure 26**. Since the models are linear as a function of IRI, a simple linear fit can be used to derive the final equation coefficients in **Table 13**.

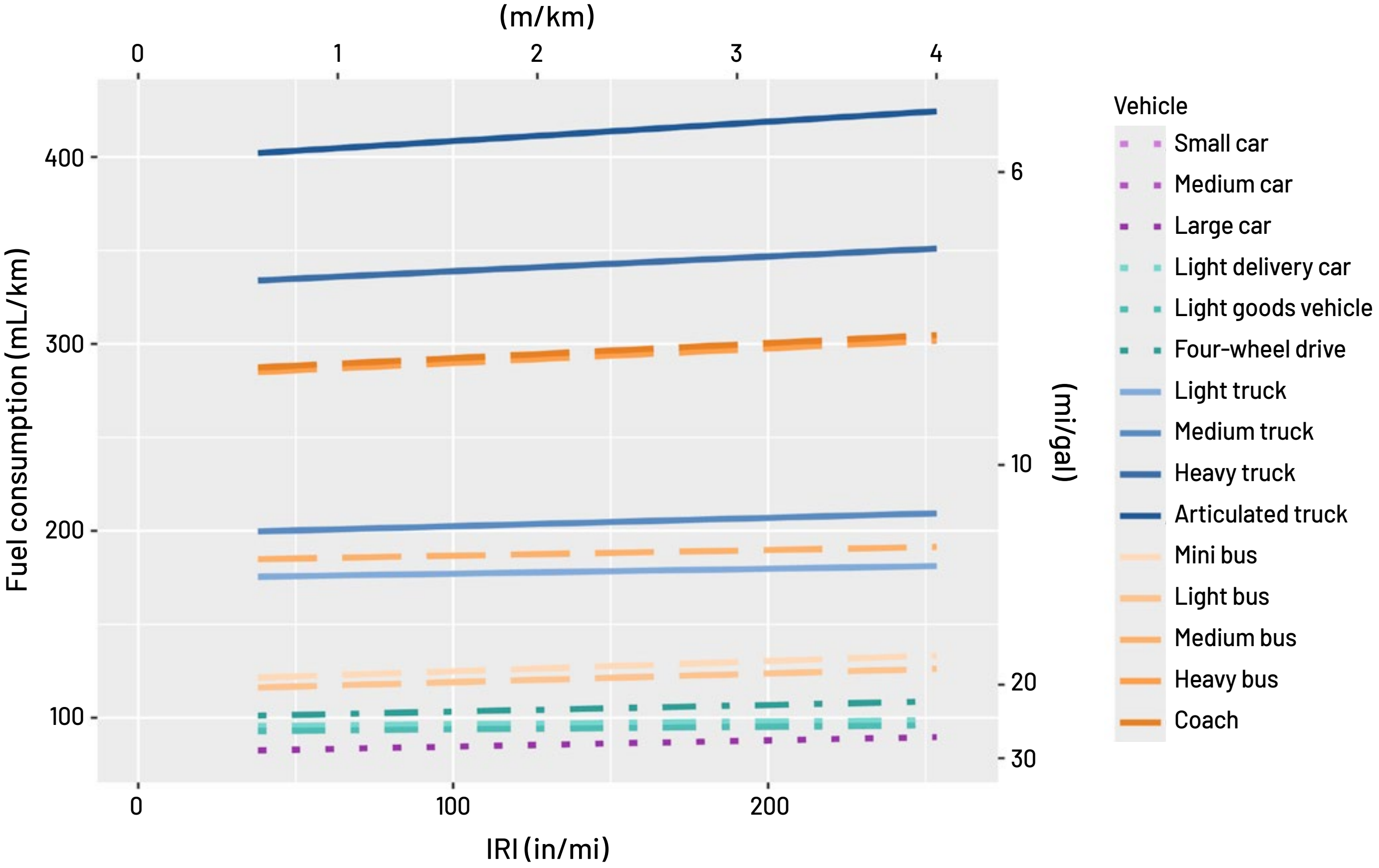

Figure 25. **HDM-4 derived fuel consumption for each vehicle type as a function of IRI.**

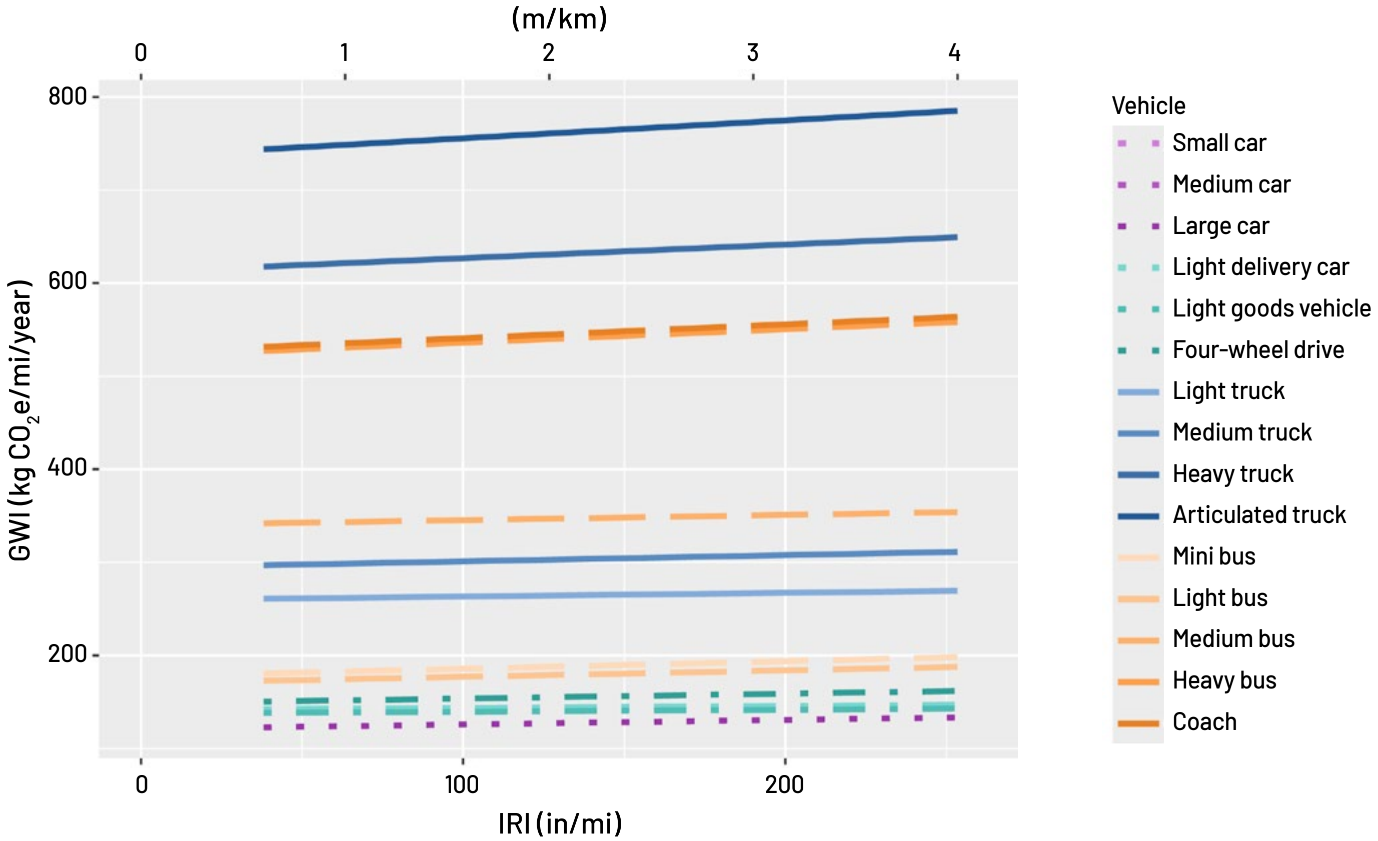

Figure 26. **HDM-4 derived GWI as a function of vehicle type and IRI**

Table 13. Final model coefficients for fuel use and GWI as a function of IRI

Vehicle	Fuel	Fuel use (gal/mi/year)		GWI (kgCO$_2$e/mi/year)	
		Intercept	Slope (per in/mi)	Intercept	Slope (per in/mi)
Small car	Gas	12.61	0.0052	120.8	0.049
Medium car	Gas	12.61	0.0052	120.8	0.049
Large car	Gas	12.61	0.0052	120.8	0.049
Light delivery car	Gas	14.76	0.0023	141.4	0.022
Light goods vehicle	Gas	14.33	0.0022	137.3	0.021
Four-wheel drive	Gas	15.48	0.0055	148.3	0.053
Light truck	Gas	27.07	0.0041	259.3	0.039
Medium truck	Gas	30.72	0.0070	294.3	0.067
Heavy truck	Diesel	51.36	0.0123	612.2	0.146
Articulated truck	Diesel	61.79	0.0161	736.5	0.192
Mini bus	Gas	18.53	0.0085	177.5	0.081
Light bus	Gas	17.75	0.0072	170.0	0.069
Medium bus	Diesel	28.50	0.0047	339.8	0.056
Heavy bus	Diesel	43.76	0.0121	521.6	0.145
Coach	Diesel	44.12	0.0125	525.9	0.149

A more complex version of this analysis could be performed for each management segment if distributions of various parameters, such as gradient, vehicle masses, air temperatures, or others, were known, resulting in segment-specific parameters for each vehicle class. What benefit this would hold in the analysis is unclear, but as more computing power and data are available, this should probably be pursued as an additional research task.