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Network-Level Life-Cycle Energy Consumption and Greenhouse Gas from CAPM Treatments

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Partnered Pavement Research Center Strategic Plan Element 4.37:
Use Environmental Life Cycle Assessment to Develop Simplified Tools and Recommend Practices to Reduce Environmental Impact of Pavements

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Abstract:
This report describes a life-cycle assessment (LCA) approach developed to evaluate the energy consumption and greenhouse gas (GHG) reductions from the use of pavement maintenance treatments that improve smoothness on the California State Highway Network, as well as the cost-effectiveness of this approach. This analysis developed optimal roughness values to trigger maintenance and rehabilitation treatments to minimize life-cycle GHG emissions (measured in equivalent CO_2 emissions [CO_2-e]) as a function of the traffic volume of each pavement segment in the network. A set of pavement characteristics were used to describe each segment of the network and to evaluate the impact of pavement-induced rolling resistance under different pavement and traffic conditions. With the optimal trigger values, annualized reductions on the California State Highway Network over a ten-year analysis period were calculated to be 0.82, 0.57, and 1.38 million metric tons compared with results using historical trigger values, recently implemented values, and no strategic intervention (reactive maintenance), respectively. Abatement costs calculated using $/metric-ton CO_2-e for agency costs alone were higher than those reported for other transportation sector abatement measures. However, consideration of the user cost benefits associated with pavement smoothness, such as increased vehicle life and lower maintenance, substantially improves the abatement cost. Also considered in the report are the effects of delaying construction after optimal triggering.

Keywords:
Pavement; network; pavement management system; smoothness; roughness; maintenance; life-cycle assessment

Proposals for implementation:
Implement life-cycle inventory results in the Caltrans pavement management system and use them to provide first-order estimates of life-cycle GHG emissions from different scenarios for pavement maintenance and rehabilitation. If warranted by the increased agency cost, use roughness as the trigger for maintenance on the lane-miles in the network with the highest 10 to 30 percent of vehicle miles traveled, and move the trigger level closer to the optimized 101 inches/mile (1.6 m/km) value identified in this study. Continue to improve specifications for constructed smoothness. Consider these recommendations within a larger pavement maintenance and rehabilitation funding-level analysis that compares it with other strategies used in the transportation sector and other sectors.

Related documents:

- UCPRC Life-cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance, by T. Wang, I.-S. Lee, J. Harvey, A. Kendall, E.B. Lee, and C. Kim. UCPRC-RR-2012-02. April 2012.
- Impact of Pavement Roughness on Vehicle Free-Flow Speed, by T. Wang, J. Harvey, J. Lea, and C. Kim. UCPRC-TM-2013-04. September 2013.
- Pavement Life-cycle Assessment Workshop: Discussion Summary and Guidelines, by J. Harvey, A. Kendall, I.-S. Lee, N. Santero, T. Van Dam, and T. Wang. UCPRC-TM-2010-03. May 2010.

Signatures

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DISCLAIMER

PROJECT OBJECTIVES

The objectives of this subproject are:

- Develop the optimal roughness values to trigger the defined set of treatments to minimize the life-cycle energy consumption and greenhouse gas emissions from the California highway pavement network, considering treatment and Use Phase vehicle emissions together.
- Assess the greenhouse gas emissions reduction from implementation of the optimal trigger values, and compare them with emissions under Caltrans' historical and current trigger values, and with no strategic intervention (reactive maintenance) values.
- Compare the cost-effectiveness of implementing the optimal trigger values with other transportation sector greenhouse gas abatement measures found in the existing literature.

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EXECUTIVE SUMMARY

The national pavement network is a key component of the transportation infrastructure that the U.S. economy depends on for the movement of people and goods. The vehicles that use the pavement network are responsible for about 23 percent of the U.S.'s greenhouse gas (GHG) emissions and nearly a quarter of the nation's fossil energy consumption. In the state of California, on-road vehicle use contributes an even larger share, comprising more than 35 percent of the state's GHG emissions.

In 2006, the California State Legislature passed Assembly Bill 32 (AB 32), the Global Warming Solutions Act of 2006, which aims to reduce GHG emissions from all sources throughout the state. AB 32 requires that statewide GHG emissions be reduced to 1990 levels by 2020, and to 20 percent of 1990 levels by 2050. The California Air Resources Board (CARB), the lead agency for implementing AB 32, estimated that baseline total GHG emissions in the year 2020 will be 507 million metric tons (MMT) of CO_2-equivalent (CO_2-e), with 168.1 MMT of CO_2-e from on-road traffic. Of these 168.1 MMT of CO_2-e emissions, 127.0 MMT will be from passenger vehicles and 41.1 MMT from heavy trucks.

The objectives of AB 32 have led to many studies that have focused on the reduction of GHG across various industrial sectors. In the context of AB 32, decisions concerning pavement construction and maintenance and rehabilitation (M&R) can affect two of these sectors. The first is the *transportation* sector, because vehicle fuel economy and the associated GHG emissions are affected by pavement conditions, and the second is the *industry* sector, because pavement materials are produced by oil extraction and refining, cement manufacture, aggregate mining, and recycling activities. The transportation of materials to a pavement construction site and the operation of construction equipment also produce GHG emissions.

Although the implementation of measures to meet the objectives of AB 32 has led to studies that focus on the reduction of GHG emissions in each of the state's industrial sectors and comparisons of the cost-effectiveness of different treatments within and between sectors, to date no evaluation of the potential for pavement management strategies to help meet the objectives of AB 32 has been undertaken. Nor have there been any studies comparing the cost-effectiveness of pavement management strategies for reducing GHG emissions against the current strategies being promoted by state government.

The process of pavement management includes measuring the different parameters of pavement condition and using those data to program maintenance and rehabilitation (M&R) treatments that will achieve the goals set for the pavement network. Typically, these goals are based on decreasing either the roughness of the network or the severity and extent of cracking, while minimizing the costs to the agency and road user delay. Cracking and roughness (or its equivalent "smoothness") are often related in that once extensive cracking appears on a pavement surface, roughness tends to increase at a faster rate. Therefore, cracking is a "leading indicator" of the roughness that will follow it, and so managing the network to minimize cracking can also help to reduce roughness. On the other hand, construction quality control problems or problems with the pavement that are not related to cracking can result in relatively rough pavement from the time that an M&R treatment is first placed on it.

Numerous studies have demonstrated that a life-cycle assessment (LCA) approach is needed to comprehensively evaluate the total environmental burden created by a product or to reduce the risk that a policy or strategy for dealing with environmental problems might produce unintended negative consequences. A project-level pavement LCA model was developed to evaluate the energy consumption and air emissions of selected pavement M&R activities that provide the foundation for the network-level analysis that is the subject of this study. This project-level model primarily focused on the Use Phase to address the relationship between pavement surface characteristics, namely roughness (or smoothness) as measured by International Roughness Index (IRI) and macrotexture as measured by mean profile depth (MPD), rolling resistance, and vehicle fuel economy, and is described in detail in a separate report. The study's Use Phase submodel does not yet include rolling resistance due to pavement structural response (deflection), but this is the subject of current research. In the model, a reasonable assumption is made that the pavement structural response under traffic would change very little with the application of the M&R treatments considered.

Extending the project-level model to the pavement network allows for strategic decision-making to maximize the environmental benefits of M&R treatments through a pavement management system (PMS). To date, few if any PMSs adopted by state transportation agencies have included environmental impacts in their analysis frameworks. As noted, the most common criteria currently used for selecting treatment options are based on benefit-cost or life-cycle cost analyses, with the aim of either increasing smoothness or eliminating cracking. However, greater attention is starting to be paid to the environmental impacts of pavement networks.

In order to characterize network-level M&R and to address questions regarding GHG emissions and energy use from operation of the Caltrans pavement network, this study used the outputs from a set of scenarios generated by applying the earlier project-level model to a PMS framework. Those questions are:

- What are the optimal roughness values (IRI) that trigger a defined set of treatments to minimize life-cycle energy consumption and greenhouse gas emissions from the California highway pavement network, considering treatment (Materials and Construction Phases) and Use Phase vehicle emissions together?

- If the optimal trigger values are implemented in the state PMS, what would be the changes in GHG emissions and energy use compared with use of Caltrans's historical and current trigger values, and how would these compare with no strategic intervention (reactive maintenance)?
- What is the cost-effectiveness of implementing the optimal trigger values compared with other transportation sector greenhouse gas abatement measures found in the existing literature?

The trade-off in triggering M&R treatment is that if the roughness trigger is set too low, GHG emissions from the material production and construction processes required for the frequent M&R treatments needed to maintain a smooth pavement can exceed the GHG reduction from improved fuel economy in the Use Phase. On the other hand, if the roughness trigger is set too high, the additional GHG from vehicles operating on rougher pavements may exceed the theoretical material and construction emissions that would occur from more optimal pavement M&R.

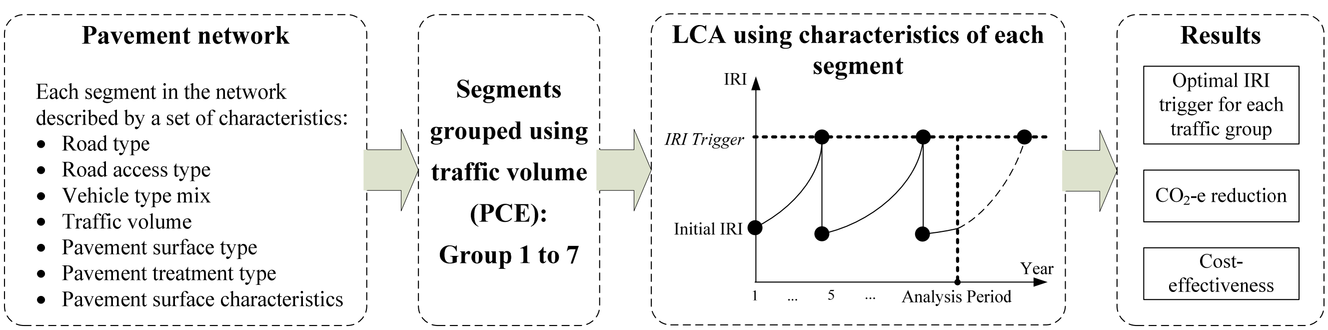
The scope of the network simulation consists of an analysis of a ten-year planning horizon for the pavement network operated by Caltrans. A set of common M&R treatments for which sufficient information has been observed and collected are modeled. The set is not exhaustive, but the approach developed can be extended to consider other M&R treatments as life-cycle inventories (LCIs), performance models, and other data become available and as common practices change. The modeled treatments given primary consideration are two pavement preservation treatments used in the Caltrans Capital Preventive Maintenance (CAPM) program: (1) a medium-thickness asphalt overlay applied on all asphalt-surfaced pavements, and (2) diamond grinding with slab replacement on a concrete-surfaced pavement with less than 10 percent shattered slabs. This study also included another treatment in the Caltrans Rehabilitation program, one consisting of the reconstruction of concrete lanes with new concrete pavement when there are more than 10 percent shattered slabs. This last treatment is used far less often than the CAPM treatments. In this report, these three treatments together are referred to simply as *CAPM treatments* for brevity despite the fact that the concrete lane reconstruction is not a CAPM treatment.

A major limitation of this study is that its goal and scope address only two impact indicators: GHG emissions and energy use. CAPM treatments were selected for this study because they allow a roadway to be kept in a good condition between major rehabilitation projects or reconstruction works, and they are used extensively before the pavement reaches an advanced state of deterioration again when M&R funding levels are insufficient to allow for long-life treatments. Studies have shown that long-life rehabilitation followed by pavement preservation treatments can have lower life-cycle costs and potentially lower life-cycle environmental impacts than shorter-lived CAPM treatments. The CAPM treatments included in the study do not differentiate between the materials and design options and only consider general categories—such as the use of various types of rubberized asphalt materials, open-graded mixes and seal coats for asphalt pavements, and different types of grinding and slab replacement materials and designs for concrete pavements.

Work zone traffic delay was not considered in this study because it was assumed that nearly all CAPM work would be performed during nighttime closures, when traffic flow is very low. The net effect of nighttime traffic closures can be either a reduction in fuel use, if traffic speeds are reduced and there is minimal congestion, or an increase, if there is congestion. (The effects of work zone traffic delay are the subject of a future study.) It was also assumed that improved smoothness does not change the speeds at which drivers travel. This assumption is also the subject of a companion report (*Impact of Pavement Roughness on Vehicle Free-Flow Speed,* UCPRC-TM-2013-04), which showed that this assumption is generally correct.

Sensitivity analyses considered the variability in the change in initial smoothness resulting from CAPM treatments and the effect of the length of the analysis period compared with the ten-year analysis period used in this study. The analysis period sensitivity was investigated to evaluate the sensitivity to the truncation procedure used at the end of the analysis period. The independence of the effects of pavement roughness and texture on fuel consumption from the effects of different vertical gradients (uphill or downhill) was investigated and considered in the analysis.

The pavement network is composed of segments—each of which is described by a set of characteristics, such as traffic volume, traffic composition, and pavement surface condition—that influence the optimal IRI trigger for M&R treatments to reduce GHG emissions. Each pavement segment presents a unique combination of these characteristics. The following figure shows the analytical approach used in this study.



Analytical approach of this study.

Because of the computational and practical complexity of developing thousands of segment-specific triggers, the network is divided into seven groups based on each segment's traffic level as measured by passenger car equivalents (PCEs). To calculate PCE, each truck is counted as 1.5 equivalent passenger cars regardless of the type of the truck. Traffic level was identified as the most important segment characteristic for determining whether there is a net reduction of CO_2-e emissions from an M&R treatment. Then, the life cycle CO_2-e emissions were calculated for each group over a range of IRI triggers to identify the optimal trigger for reducing CO_2-e emissions for each group. This approach is intended to maintain a balance between computational intensity and thoroughness.

Characteristics of segments that were considered included the following:

- Road type: rural or urban
- Road access type: restricted (freeway) or unrestricted access
- Vehicle type mix: passenger cars and trucks with different numbers of axles
- Traffic volume in terms of daily directional PCE
- Pavement type: concrete or asphalt surface
- Pavement treatment type: medium asphalt overlay for asphalt-surfaced, grinding with slab replacement or concrete lane replacement for concrete-surfaced
- Pavement surface characteristics: roughness in terms of IRI and macrotexture in terms of MPD over time predicted by performance equations

The network was divided into quartiles of traffic volume in terms of daily directional PCE, and then to improve calculation of traffic-induced emissions, a finer resolution of 10 percent intervals was used for those segments above the median. The dividing points are therefore at the 25^{th}, 50^{th}, 60^{th}, 70^{th}, 80^{th}, and 90^{th} percentiles for analysis of optimal IRI trigger level for M&R.

This study performed life-cycle GHG calculations on each pavement segment and summed the results within each traffic group. The scope of the analysis included the Material Production, Construction, and Use phases. Only the transport of materials removed during the treatments is modeled for the End-of-Life (EOL) phase. This study mainly focused on repeated treatments with relatively short design lives, so a ten-year analysis period (2012 to 2021) has been adopted to cover approximately 1.5 times the design lives.

In the life cycle modeling, each directional segment in the network was evaluated through two scenarios: (1) the *M&R* scenario and (2) the *Do Nothing* scenario. Then, the results were compared to current and historical Caltrans policies for IRI triggers. Historically, Caltrans has used an IRI trigger of 224 inches/mile (3.53 m/km) for asphalt pavement and 213 inches/mile (3.36 m/km) for concrete pavement but recently changed to a trigger of 170 inches/mile (2.68 m/km) for all pavements. These policies are, in practice, constrained by budget limitations, meaning that pavement roughness often exceeds trigger values until funding is sufficient.

In the *M&R* scenario, when the IRI of a segment reaches the trigger, a treatment is performed, bringing down the IRI based on historical Caltrans data. The emissions and cost from the material production and construction of the treatment were calculated based on the material quantity and construction activity. The Use Phase CO_2-e was calculated based on the pavement surface characteristics and traffic composition and volume. The well-to-wheel (WTW) emissions of fuels are always used when there is fuel consumption.

In the *Do Nothing* scenario, the pavement is maintained at approximately its current roughness and macrotexture using repairs by local Caltrans forces. Emissions from material production and construction for these localized repairs are not calculated due to uncertainty about the particular activities and materials that might be used, and the fact that only small quantities of material are likely to be used. This assumption is probably less important when M&R treatments occur more frequently under lower treatment IRI trigger values that would reduce the need for localized repairs in between M&R treatments. The Use Phase emissions for the *Do Nothing* scenario were calculated similarly to the M&R scenario. It should be noted that the state would never implement a *Do Nothing* strategy on the entire network, and would only implement a *Do Nothing* strategy on those sections for which there is insufficient funding, with the constrained funding resulting in a de facto implementation of a *Do Nothing* strategy.

The difference in CO_2-e emissions between these two scenarios was calculated over the analysis period. This procedure was repeated for all segments in the network and the difference from each segment was summed for the final result over the analysis period. Ten IRI triggers, evenly distributed from 38 to 279 inches/mile (0.6 to 4.4 m/km), were assessed for each traffic group and the value that led to the highest CO_2-e reduction was considered optimal. The selection of the IRI triggers was intended to cover the common range of IRI values on modern paved highways in the U.S. It should be emphasized that the “optimal triggers” developed in this study only apply to the CO_2-e emission reduction on the modeled highway using the selected maintenance treatments. Other social benefits such as increased safety, and social dis-benefits such as diversion of funding for other purposes, were not included in the analysis and the results may not be optimal considering a broader range of objectives or a larger system definition.

Cost-effectiveness describes the cost of abatement per unit of pollution (here metric tons of CO_2-e emission, or tCO_2-e). A lower cost-effectiveness value indicates that less money is needed to achieve the same level of CO_2-e reduction. This study assessed two types of costs: *agency cost* and *modified total cost*. *Agency cost* reflects the total contracted expenditures of the transportation agency, while the *modified total cost* is the *agency cost* minus the cost of saved fuel for road users. A negative modified total cost indicates that this measure in the long term can reduce CO_2-e as well as save money for the two stakeholders considered (agency and road users) and is therefore a “no-regrets” strategy. A *total cost* calculation would consider additional costs of rougher pavement due to vehicle maintenance, vehicle life, accidents, etc. However, high-quality data for these costs are not readily available, which is why a modified total cost was used.

The modeling of emissions from the Material Production and Construction phases is described in the project-level study report that this network-level study built on. When applied to the network, the modeling of these phases was calculated based on the materials quantities and total lane-miles of each treatment. For cost analysis, the agency cost of each treatment was acquired from the Caltrans PMS. The fuel price for the saved energy consumption was acquired from the U.S. Annual Energy Outlook. A discount rate of 4 percent was used in accordance with Caltrans practice for life cycle cost analysis.

The selection and timing of treatments roughly followed Caltrans guidelines and the decision tree in the Caltrans PMS for the treatments modeled in this study, with the assumption that pavement surface type (asphalt or concrete) does not change.

The Use Phase of the pavement life cycle considered in this study included the additional CO_2-e from vehicle operation due to pavement deterioration. Because CO_2 contributes over 99.8 percent of the vehicle tailpipe CO_2-e emissions, other tailpipe GHG emissions were not included. The well-to-pump (WTP) CO_2-e emissions for fuel included were based on vehicle fuel consumption using the GREET model.

To conduct the network-level analysis, vehicle tailpipe CO_2 emission factors were developed as a function of selected pavement segment characteristics. Sensitivity analyses were performed to evaluate whether additional characteristics were needed to represent the network's heterogeneity. The characteristics include the effects of congestion on urban restricted-access roads and different road vertical gradients on mountainous roads. Both had very small impacts on the relationship between pavement roughness and fuel consumption, and therefore were omitted.

The vehicle tailpipe CO_2 emission factors were developed as a continuous function of MPD and IRI for each combination of the categorical variables. A series of IRI and MPD values under each combination of the categorical variables were modeled using *MOVES* to calculate the tailpipe CO_2 emission, and then linear regression was used on the results to develop the function. Because pavement surface characteristics are inputs in the Use Phase and they change every year, the performance models for IRI and MPD developed by Tseng, Lu et al., and Rao et al. were used. These models are mainly functions of truck traffic level and climate.

Optimized IRI trigger values for M&R are shown in the following table. The results indicate that the 10 percent of the network (daily directional PCE greater than 95,184) with the highest traffic yielded nearly 35 percent of the CO_2-e emissions reductions, despite similar or lower roughness (as of 2012) compared to the next lower traffic groups. For the segments that made up the bottom quartile of the network based on traffic volume (daily directional PCE lower than 2,517) there was no IRI trigger that yielded a reduction, indicating that emissions from the Material Production and Construction phases are always higher than reductions during the Use Phase.

IRI Trigger for the Maximum CO_2-e Reductions over the Ten-Year Analysis Period for the Entire Network

Traffic Group	Daily Directional PCE	Total Lane-Miles	Percentile of Lane-Miles	Optimal IRI Trigger in inches/mile[a]	Modified Total Cost-Effectiveness[b] ($/t$CO_2$-e)
1	< 2,517	12,068	0 to 25	—	N/A
2	2,517 to 11,704	12,068	25 to 50	152 (2.4)	1,169
3	11,704 to 19,108	4,827	50 to 60	127 (2.0)	857
4	19,108 to 33,908	4,827	60 to 70	127 (2.0)	503
5	33,908 to 64,656	4,827	70 to 80	101 (1.6)	516
6	64,656 to 95,184	4,827	80 to 90	101 (1.6)	259
7	> 95,184	4,827	90 to 100	101 (1.6)	104

Notes:
[a]: m/km is in the parentheses. "Optimal" here only applies to CO_2-e reductions and does not include other social benefits.
[b]: N/A = not applicable since no net CO_2-e reduction. "Modified total cost" is the agency cost minus the cost of fuel saved by road users.

The annualized CO_2-e emissions reduction that can be achieved if these optimal IRI triggers are implemented is 1.38 MMT over ten years compared to *Do Nothing*. For comparison, CARB has estimated that the average annual baseline emissions from on-road vehicles will be about 168.1 MMT CO_2-e between 2006 and 2020. Therefore, the potential reduction estimated from this study would contribute to about a 0.8 percent decrease compared to *Do Nothing*.

Caltrans PMS prioritization policies prior to 2011 used an IRI trigger of 224 inches/mile (3.53 m/km) for asphalt pavement and 213 inches/mile (3.36 m/km) for concrete pavement. Since 2011, the trigger has been 170 inches/mile (2.68 m/km) for all pavements. In practice, meeting these policy goals is constrained by budget, which does not permit all segments in the network to receive planned treatments.

By interpolating this study's results, the historical and current Caltrans IRI triggers lead to an annualized CO_2-e reduction of 0.57 and 0.82 MMT compared to *Do Nothing* over ten years, with a modified total cost-effectiveness of $355/t$CO_2$-e and $520/t$CO_2$-e, respectively. Therefore, compared to the historical trigger, the current trigger of 170 inches/mile (2.68 m/km) substantially reduces CO_2-e, although it is less cost-effective. Compared to the historical and current Caltrans IRI triggers, the optimal IRI triggers can achieve an annualized marginal CO_2-e reduction of 0.82 and 0.57 MMT, with a marginal modified total cost-effectiveness of $457/t$CO_2$-e and $266/t$CO_2$-e, respectively. The current Caltrans IRI trigger of 170 inches/mile (2.68 m/km) is much closer to the set of optimal IRI triggers than the historical triggers, and this leads to a very small marginal cost change and an improved cost-effectiveness.

In practice, even if the IRI of a segment has reached its designated trigger, a treatment may not occur until one to three years later because of project development and delivery time, or longer if there are budget constraints. Therefore, the actual CO_2-e reductions and the cost in the analysis period are likely to be reduced. For a two-lane (per direction), one-mile long, rural freeway with a one-direction annual average daily traffic of 12,000 and 10 percent trucks (PCE of 12,600), treatment should be triggered at 127 inches/mile (2 m/km). If a treatment is performed one, two, or three years after the IRI reaches the trigger, the CO_2-e reductions can drop by approximately 6 percent, 13 percent, and 18 percent, respectively, compared to an on-time treatment. It is also evident that the cost drops faster than the CO_2-e reductions. Although a delay can lead to better cost-effectiveness, in part because fewer treatments are triggered in the analysis period, it also reduces potential CO_2-e reductions.

Lutsey examined GHG mitigation strategies for the transportation sector and their cost-effectiveness. The cost-effectiveness of the pavement preservation treatments in this study are considerably lower than many alternative measures Lutsey identified, which were as low as $60/t$CO_2$-e or less, as shown in the following table.

Comparison of Cost-Effectiveness between Pavement and Some Alternative Measures in the Transportation Sector *(Lutsey, 2008)*

Measure	Annual CO_2-e Emission Reduction[1]	Total Life-Cycle Cost-Effectiveness ($2008/t$CO_2$-e)[2]
Light duty vehicle: Incremental efficiency	20% tailpipe reduction	-75
Light duty vehicle: Advanced hybrid vehicle	38% tailpipe reduction on new vehicles	42
Commercial trucks: Class 2b efficiency	25% tailpipe reduction	-108
Alternative refrigerant	Replacement of HFC-134a with R-744a (CO_2)	67
Ethanol fuel substitution	Increase mix of cellulosic ethanol to 13% by volume	31
Biodiesel fuel substitution	Increase mix of biodiesel to 5% by volume	51
Aircraft efficiency	35% reduction in energy intensity	-9
Use of optimized pavement roughness triggers [this study].	1.38 MMT	390

Notes:
[1]: The first seven measures calculated by Lutsey are the value in 2025. The value for use of optimized pavement roughness triggers from this study is an annualized value between 2012 and 2021.
[2]: This result was calculated in 2012 dollars and is converted to 2008 dollars in this table using the consumer price index (CPI).

This result for pavement occurs because the construction of civil infrastructure is expensive and, more importantly, the costs evaluated in this study only include the agency and fuel cost, and exclude other road user costs. Because the main functionality of pavement is to maintain the mobility of goods and people using vehicles, one of the primary purposes for pavement management is to ensure transportation safety and efficiency, which is what road users care about most. Therefore, a more comprehensive benefit analysis would include other social benefits such as vehicle life, safety, tire consumption, goods damage, vehicle maintenance, driver comfort, and the value of time. From this point of view, the CO_2-e reduction can be considered a "co-benefit" from pavement management when used as a GHG mitigation measure, and will be more cost-effective if all road user costs are included.

A preliminary study showed that while fuel consumption (and therefore fuel cost) exhibits a linear relationship with roughness, total road user cost can increase exponentially with pavement roughness. The ratio between total road user cost and fuel cost ranges from 6 to 10, depending on the vehicle type, driving speed, and pavement condition. A first-order estimate shows that total cost-effectiveness can range from -\$710/tCO_2-e to -\$1,610/tCO_2-e (compared to the \$416/tCO_2-e as shown in the previous table) if all road user costs are included. This result indicates that pavement management, when properly programmed as in this study, can potentially be a cost-competitive measure to reduce GHG emissions if total road user cost is considered. In fact, once the total cost models as a function of pavement roughness for California are fully developed, the comparison with other transportation strategies should be performed again.

Constructed smoothness is primarily controlled by construction practice, quality control, and the existing pavement condition, and to a lesser degree by treatment type. In terms of sensitivity analysis, for constructed smoothness, three levels of initial IRI after construction were considered. The results show that the constructed smoothness can change the optimal triggers by as much as 51 inches/mile (0.8 m/km). With a good constructed smoothness, the GHG reduction benefit from the treatment can be more than doubled compared to the average constructed smoothness; likewise, with a poor constructed smoothness the benefits can be reduced by more than half.

The following conclusions are based on the analyses in this study:

- Neither the presence of congestion nor the road gradient have a substantial impact on the fuel economy change brought about by a reduction in rolling resistance due to roughness and macrotexture. This indicates that the impact of rolling resistance on total vehicle fuel consumption is relatively robust and not strongly influenced by these factors.
- Traffic level has a substantial impact on GHG reduction and the optimized IRI values that trigger CAPM treatments. Performing CAPM on segments that have very low daily passenger car equivalents (PCEs) in the network does not lead to net GHG reduction or energy benefits.
- The optimal IRI trigger values for segments with higher traffic volumes vary. The higher the traffic volume, the lower the IRI trigger value needed to achieve the maximum net GHG benefit.
- Cost analysis shows that the optimal IRI trigger values from this study can achieve a cost-effectiveness of \$641/metric ton CO_2-e with *agency cost* accounting and \$416/metric ton CO_2-e with *modified total*

cost accounting considering the cost of road user vehicle fuel and agency cost together, compared to the *Do Nothing* scenario over the ten-year analysis period.

- Compared to the historical Caltrans IRI trigger value, the optimal IRI trigger values from this study can achieve an annualized marginal GHG emissions reduction of 0.82 MMT CO_2-e, with a marginal *agency cost-effectiveness* of $688/metric ton CO_2-e and a marginal *modified total cost-effectiveness* of $457/metric ton CO_2-e.
- Compared to the current Caltrans IRI trigger value (170 inches/mile [2.68 m/km] on all pavements), the optimal IRI trigger values developed in this study can achieve an annualized marginal GHG reduction of 0.57 MMT CO_2-e over the ten-year analysis period, with a marginal *agency cost-effectiveness* of $502/metric ton CO_2-e and a marginal *modified total cost-effectiveness* of $266/metric ton CO_2-e. It should be noted that this result was derived mainly considering two example CAPM treatments (asphalt overlay and concrete grinding with slab replacement[1]).
- Compared to other measures in the transportation sector, the GHG reduction achieved from roadway maintenance was relatively low in terms of cost-effectiveness. The discussion in this report showed that this was because the cost analysis in this study only included the agency cost and road user fuel cost, and under this situation cost-effectiveness may not be a good indicator for pavement-related strategies because it did not fully capture the additional costs associated with pavement roughness, such as tire wear, vehicle maintenance, reduced vehicle life, and accident costs.
- Sensitivity analysis on constructed smoothness shows that the smoothness achieved from construction has a substantial impact on the results. If poor smoothness (one standard deviation higher than the average historical IRI after the construction) occurs from an M&R activity, then the GHG reduction can be reduced by more than half of that of an average CAPM treatment, and the construction will then result in a very low modified total cost-effectiveness. On the other hand, if a very smooth pavement (one standard deviation lower than the average IRI after the construction) is achieved, then the GHG reduction can be more than twice that for the average CAPM treatment resulting in a higher modified total cost-effectiveness, even if the construction cost was also higher.

The following recommendations are made based on the results of this study:

- The life-cycle inventory results developed for this study should be implemented in the Caltrans pavement management system and used to provide first-order estimates of life-cycle GHG emissions from different scenarios for pavement maintenance and rehabilitation (M&R).
- If an increase in agency cost is considered acceptable after both agency and road user costs have been evaluated, then Caltrans should replace its current pavement maintenance and rehabilitation (M&R)

[1] Although concrete lane replacement was also included in the analysis as an M&R treatment, it was addressed in a very limited and preliminary way.

triggers, which are based on cracking, with triggers that are based on roughness when planning work on the lane-miles in its network that have the highest 10 to 30 percent of daily directional PCE. This IRI-based trigger level should be moved closer to the optimized 101 inches/mile (1.6 m/km) value identified in this study.

- Caltrans should continue using the recent changes made to improve smoothness at the time of construction. Among these changes are the inclusion of smoothness requirements in terms of IRI in pavement construction specifications and the development and implementation of a roughness measurement system certification process for Caltrans and contractors. Additional changes in maintenance and rehabilitation design and construction that can cost-effectively improve pavement smoothness at the time of construction should be developed.
- These recommendations should be considered within a larger pavement maintenance and rehabilitation funding level analysis that includes a comparison of the change in IRI trigger values against other alternative strategies used in the transportation sector and in other sectors. This comparison should be in terms of total GHG reduction and GHG reduction cost-effectiveness, and should use the values developed in this study.

Future Work

The LCA model and its application in the case studies and on the pavement network have shown that LCA can be a useful tool in pavement decision-making for assessing the impacts of pavement M&R strategies on the environment. But there are still numerous areas that can benefit from future research:

- In this study, only relatively short-lived CAPM treatments were selected as potential M&R activities. However, there are situations in which either a major rehabilitation or reconstruction or a less intensive maintenance treatment are warranted by pavement conditions. Rehabilitation followed by pavement preservation and CAPM treatments represents a more comprehensive pavement life-cycle, and studies have shown that this type of M&R strategy is both effective in reducing life-cycle costs and has the potential to reduce the environmental life-cycle impacts. Therefore, it is necessary to develop pavement performance (IRI and macrotexture) models and LCIs of the Material Production and Construction phases for these types of rehabilitation and preservation treatments, and to include these combined treatments in pavement life-cycle assessment.
- This study assumed that the treatments considered had the same life-cycle inventory for materials and construction across all statewide construction projects. Future studies need to improve the life-cycle inventories of Material Production and Construction phases so that when the inventories are applied to the network, they reflect local conditions for material production, transport, and construction.
- Because of the lack of a comprehensive model to address viscoelastic energy dissipation due to structural response in the Use Phase of pavement, this study made the assumption that the pavement

surface type stayed the same when M&R activities were performed and it avoided direct comparisons between asphalt pavement and concrete pavement. However, the comparison between asphalt and concrete pavement is inevitable as the research in pavement LCA advances. The UCPRC is currently working with different modeling groups to develop and calibrate the effects on fuel economy and emissions of the structural response of the pavement.

- The cost-effectiveness analysis in this study only included the agency cost and fuel cost. The total road user cost (such as fuel cost, tire wear cost, car maintenance cost, and safety cost) was not fully evaluated. As a result, the costs in this study do not fully reflect the benefits associated with pavement roughness, and the study's "cost-effectiveness" is not a good indicator for selecting pavement strategies. Therefore, future studies should include both the agency cost and total road user cost to fully analyze the costs from the pavement M&R activities. The benefits can also potentially be expanded to consider the potential for changes in GHG emissions from vehicle replacement and vehicle maintenance as a function of pavement smoothness.

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LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AADTT	Annual average daily truck traffic
AB 32	Assembly Bill 32: Global Warming Solutions Act
ANOVA	Analysis of variance
APCS	Automatic pavement condition survey
ASTM	American Society for Testing and Materials
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies, software
CAPM	Capital Preventive Maintenance
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CPR B	Concrete pavement restoration, class “B”
CSA	Calcium sulfoaluminate
CTB	Cement-treated base
EOF	End-of-life
EPA	Environmental Protection Agency
ESAL	Equivalent Single Axle Loads
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GHG	Greenhouse gas
GWP	Global warming potential
HCM	Highway Capacity Manual
HDM-4	Highway Development and Management software version 4
HMA	Hot-mix asphalt
IPCC	Intergovernmental Panel on Climate Change
IRI	International Roughness Index
ISO	International Organization for Standardization
JPCP	Jointed plain concrete pavement
LCA	Life-cycle assessment
LCCA	Life-cycle cost analysis
LCI	Life-cycle inventory
LDF	Lane distribution factor
M&R	Maintenance and rehabilitation
MIRIAM	Models for rolling resistance In Road Infrastructure Asset Management Systems
MPD	Mean profile depth
MPH	Miles per hour
MTD	Mean texture depth

NO_x	Nitrogen oxides
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects, software
Pb	Lead
PeMS	Performance Measurement System
PCC	Portland cement concrete
PCE	Passenger car equivalent
PCS	Pavement condition survey
PIARC	World Road Association (Permanent International Association of Road Congresses)
PMS	Pavement management system
RAP	Reclaimed asphalt pavement
RHMA	Rubberized hot-mix asphalt
UCPRC	University of California Pavement Research Center
VMT	Vehicle miles traveled
VOC	Vehicle operating cost
VSP	Vehicle specific power
WTP	Well-to-pump
WTW	Well-to-wheel

1 INTRODUCTION

1.1 Background

The national pavement network is a key component of the transportation infrastructure that the U.S. economy depends on for the movement of people and goods. The vehicles that use the pavement network are responsible for about 23 percent of the U.S.'s greenhouse gas (GHG) emissions and nearly a quarter of the nation's fossil energy consumption *(1,2)*. In the state of California, on-road vehicle use contributes an even larger share, comprising more than 35 percent of the state's GHG emissions *(3)*.

In 2006, the California State Legislature passed Assembly Bill 32 (AB 32), the Global Warming Solutions Act of 2006, which aims to reduce GHG emissions from all sources throughout the state. AB 32 requires that statewide GHG emissions be reduced to 1990 levels by 2020, and to 20 percent of 1990 levels by 2050 *(4)*. The California Air Resources Board (CARB), the lead agency for implementing AB 32, estimated that baseline total GHG emissions in the year 2020 will be 507 million metric tons (MMT) of CO_2-equivalent (CO_2-e), with 168.1 MMT of CO_2-e from on-road traffic. Of these 168.1 MMT of CO_2-e emissions, 127.0 MMT will be from passenger vehicles and 41.1 MMT from heavy trucks *(3)*.

The objectives of AB 32 have led to many studies, such as Reference *(5),* that focused on the reduction of GHG across various industrial sectors. In the context of AB 32, decisions concerning pavement construction and maintenance and rehabilitation (M&R) can affect two of these sectors. The first is the *transportation* sector, because vehicle fuel economy and the associated GHG emissions are affected by pavement conditions, and the second is the *industry* sector, because pavement materials are produced by oil extraction and refining, cement manufacture, aggregate mining, and recycling activities. The transportation of materials to a pavement construction site and the operation of construction equipment also produce GHG emissions.

Although the implementation of measures to meet the objectives of AB 32 has led to studies that focus on the reduction of GHG emissions in each of the state's industrial sectors and comparisons of the cost-effectiveness of different treatments within and between sectors, to date no evaluation of the potential for pavement management strategies to help meet the objectives of AB 32 has been undertaken. Nor have there been any studies comparing the cost-effectiveness of pavement management strategies for reducing GHG emissions against the current strategies being promoted by state government.

The process of pavement management includes measuring the different parameters of pavement condition and using those data to program maintenance and rehabilitation (M&R) treatments that will achieve the goals set for the pavement network. Typically, these goals are based on decreasing either the roughness of the network or the severity and extent of cracking, while minimizing the costs to the agency and road user delay. Cracking and roughness (or its equivalent "smoothness") are often related in that once extensive cracking appears on a pavement surface, roughness tends to increase at a faster rate. Therefore, cracking is a "leading indicator" of the roughness that will follow it, and so managing the network to minimize cracking can also help to reduce roughness. On the other hand, construction quality control problems or problems with the pavement that are not related to cracking can result in a pavement that is relatively rough from the time that an M&R treatment is first placed on it.

Numerous studies have demonstrated that a life-cycle assessment (LCA) approach is needed to comprehensively evaluate the total environmental burden created by a product or to reduce the risk that a policy or strategy for dealing with environmental problems might produce unintended negative consequences *(6).* Previous LCAs of pavement systems have highlighted shortcomings and inconsistencies in the application of LCA principles to pavement systems and the challenges of implementing LCAs on long-lived, site-specific systems. Among the the potential problems cited are the difficulty in selecting a functional unit, uncertainty in key parameters such as traffic levels and composition over the pavement lifetime, and a tendency of many studies to neglect the Use Phase (for pavement, the life-cycle includes the material production, construction, use, maintenance and rehabilitation, and end-of-life [EOL] phases). In light of these shortcomings and inconsistencies, comparison across studies has been nearly impossible *(6,7)*. This study addresses these issues.

A project-level pavement LCA model developed to evaluate the energy consumption and air emissions of selected pavement M&R activities provides the foundation for the network-level analysis that is the subject of this study *(8).* This project-level model primarily focuses on the Use Phase to address the relationship between pavement surface characteristics, namely roughness (or smoothness) as measured by International Roughness Index (IRI) and macrotexture as measured by mean profile depth (MPD), rolling resistance, and vehicle fuel economy. By analyzing the additional power required for a vehicle to move because of pavement roughness and macrotexture, the project-level model is able to connect pavement surface characteristics to vehicle emissions, and thereby address the impact of rolling resistance on the pavement Use Phase. Development of the project-level model also required the development of life-cycle inventories for the Material Production and Construction phases specific to California conditions. In the four case studies that were used to develop the LCA model, it was found that the traffic level on a pavement segment plays the most important role in determining whether there will be a net GHG reduction after an M&R treatment is performed. The smoothness achieved through the treatment was found to be the second most important variable, and the type of material used in the construction was found to play the least important role. The study's Use Phase submodel does not yet include rolling resistance due to pavement structural response (deflection), but this is the subject of current research. In the model, a reasonable assumption is made that the pavement structural response under traffic would change very little with the application of the M&R treatments considered.

Extending the project-level model to the pavement network allows for strategic decision-making to maximize the environmental benefits of M&R treatments through a pavement management system (PMS). To date, few if any PMSs adopted by state transportation agencies have included environmental impacts in their analysis frameworks. As noted, the most common criteria currently used for selecting treatment options are based on benefit-cost or life-cycle cost analyses, with the aim of either increasing smoothness or eliminating cracking. However, greater attention is starting to be paid to the environmental impacts of pavement networks, and several research studies have made attempts to integrate PMS operations with LCA to address these impacts. Two such studies, by Lidicker et al. *(9)* and by Zhang et al. *(10),* have attempted to minimize the environmental impacts in the pavement life-cycle, one using project-level case studies and the other using a very small local road network, respectively. Both studies used relatively simple emissions models which optimized M&R frequency and intensity, using multicriteria decision analysis to select and schedule M&R events.

1.2 Goal and Scope

In order to characterize network-level M&R and to address questions regarding GHG emissions and energy use from operation of the Caltrans pavement network, this study used the outputs from a set of scenarios generated by applying the earlier project-level model to a PMS framework. Those questions are:

- What are the optimal roughness values (IRI) that trigger a defined set of treatments to minimize life-cycle energy consumption and greenhouse gas emissions from the California highway pavement network, considering treatment (Materials and Construction Phases) and Use Phase vehicle emissions together?
- If the optimal trigger values are implemented in the state PMS, what would be the changes in GHG emissions and energy use compared with use of Caltrans's historical and current trigger values, and how would these compare with no strategic intervention (reactive maintenance)?
- What is the cost-effectiveness of implementing the optimal trigger values compared with other transportation sector greenhouse gas abatement measures found in the existing literature?

The trade-off in triggering M&R treatment is that if the roughness trigger is set too low, GHG emissions from the material production and construction processes required for the frequent M&R treatments needed to maintain a smooth pavement can exceed the GHG reduction from improved fuel economy in the Use Phase. On the other hand, if the roughness trigger is set too high, the additional GHG from vehicles operating on rougher pavements may exceed the theoretical material and construction emissions that would occur from more optimal pavement M&R.

The scope of the network simulation consists of an analysis of a ten-year planning horizon for the pavement network operated by Caltrans. A set of common M&R treatments for which sufficient information has been observed and collected are modeled. The set is not exhaustive, but the approach developed can be extended to consider other M&R treatments as life-cycle inventories (LCIs), performance models, and other data become available and as common practices change. The modeled treatments given primary consideration are two pavement preservation treatments used in the Caltrans Capital Preventive Maintenance (CAPM) program: (1) a medium-thickness asphalt overlay applied on all asphalt-surfaced pavements, and (2) diamond grinding with slab replacement on a concrete-surfaced pavement with less than 10 percent shattered slabs. This study also included another treatment in the Caltrans Rehabilitation program, one consisting of the reconstruction of concrete lanes with new concrete pavement when there are more than 10 percent shattered slabs. This last treatment is used far less often than the CAPM treatments. In this report, these three treatments together are referred to simply as *CAPM treatments* for brevity despite the fact that the concrete lane reconstruction is not a CAPM treatment.

1.3 Limitations

A major limitation of this study is that its goal and scope address only two impact indicators: GHG emissions and energy use.

This study assumed that the pavement surface type (asphalt or concrete) remains unchanged after an M&R treatment because the Use Phase submodel does not yet consider vehicle energy consumption due to pavement structural response (deflection), and this therefore eliminates potential impacts from pavement deflection. Specifically, it is assumed that network segments with a concrete surface receive either a CAPM treatment or lane reconstruction that will yield a similar structural response, and asphalt-surfaced pavements will only receive asphalt overlays that result in the same structural response after treatment that existed before treatment.

CAPM treatments were selected for this study because they allow a roadway to be kept in a good condition between major rehabilitation projects or reconstruction works *(11),* and they are used extensively before the pavement reaches an advanced state of deterioration again when M&R funding levels are insufficient to allow for long-life treatments. Studies have shown that long-life rehabilitation followed by pavement preservation treatments can have lower life-cycle costs and potentially lower life-cycle environmental impacts than shorter-lived CAPM treatments *(12).*

A further limitation of this study is that it only looks at state-owned highways in California. The roads maintained by local governments (cities and counties), private organizations, and the federal government are not currently included in the network. In addition, the CAPM treatments included in the study do not differentiate between the materials and design options and only consider general categories—such as the use of various types of rubberized asphalt materials, open-graded mixes and seal coats for asphalt pavements, and different types of grinding and slab replacement materials and designs for concrete pavements.

The study did not consider work zone traffic delay because it was assumed that nearly all CAPM work would be performed during nighttime closures, when traffic flow is very low. The net effect of nighttime traffic closures can be either a reduction in fuel use, if traffic speeds are reduced and there is minimal congestion, or an increase, if there is congestion. (The effects of work zone traffic delay are the subject of a future study.) It was also assumed that improved smoothness does not change the speeds at which drivers travel. This assumption is also the subject of a companion report *(13),* which showed that this assumption is generally correct.

Sensitivity analyses considered the variability in the change in initial smoothness resulting from CAPM treatments and the effect of the length of the analysis period compared with the ten-year analysis period used in this study. The analysis period sensitivity was investigated to evaluate the sensitivity to the truncation procedure used at the end of the analysis period. The independence of the effects of pavement roughness and texture on fuel consumption from the effects of different vertical gradients (uphill or downhill) was investigated and considered in the analysis.

Other potentially important sensitivities that were not explored were the effects of triggering treatments based on cracking thresholds as well as roughness, omission of calculation of emissions from routine repairs performed directly by Caltrans forces in the *Do Nothing* scenario, and consideration of treatments other than those included in this study. In the *Do Nothing* scenario, the pavement is maintained at approximately its current roughness and macrotexture using repairs by local Caltrans forces. Emissions from material production and construction for these localized repairs are not calculated due to uncertainty about the particular activities and materials that might be used, and the fact that only small quantities of material are likely to be used. This assumption is probably less important when M&R treatments occur more frequently under lower treatment IRI trigger values that would reduce the need for localized repairs in between M&R treatments. The performance models for roughness and texture are not specific to climate region, and are currently being updated to include more variables, such as climate region.

The feedstock energy for asphalt materials is not included in the study to simplify presentation of the results. The feedstock energy for different asphalt materials was documented in the previous report that developed the life-cycle inventories for asphalt materials considered in this study *(14)*.

2 METHODOLOGY

2.1 Background

The conclusions from the previous study showed that performing an M&R treatment on a rough pavement can lead to substantial energy savings and GHG reductions *(14)*. However, the question of what level of roughness should trigger an M&R activity so that energy and GHG reduction can be maximized over an analysis period remained unanswered. Figure 2.1 demonstrates this interaction: even though a pavement can be maintained at a very smooth level with a low roughness trigger value (Figure 2.1a), the environmental impacts due to frequent construction can offset the energy and GHG reduction gained during the Use Phase. On the other hand, if the trigger value is set at a high level (Figure 2.1b), the additional energy consumption and GHG emissions due to the rough pavement can be much greater than those from materials and construction.

Figure 2.1 gives a brief description of the highway network based on the Caltrans PMS. A more detailed description is given in Section 3.4 of this report after the network were segmented and divided into groups.

Table 2.1: Summary Statistics of the State Highway Network

Pavement Type[1]	Lane-miles	Maximum AADT[2]	Minimum AADT	Mean AADT	AADT Standard Deviation
Asphalt	37,233	210,600	48	37,065	39,730
Concrete	10,721	225,551	675	79,708	37,988

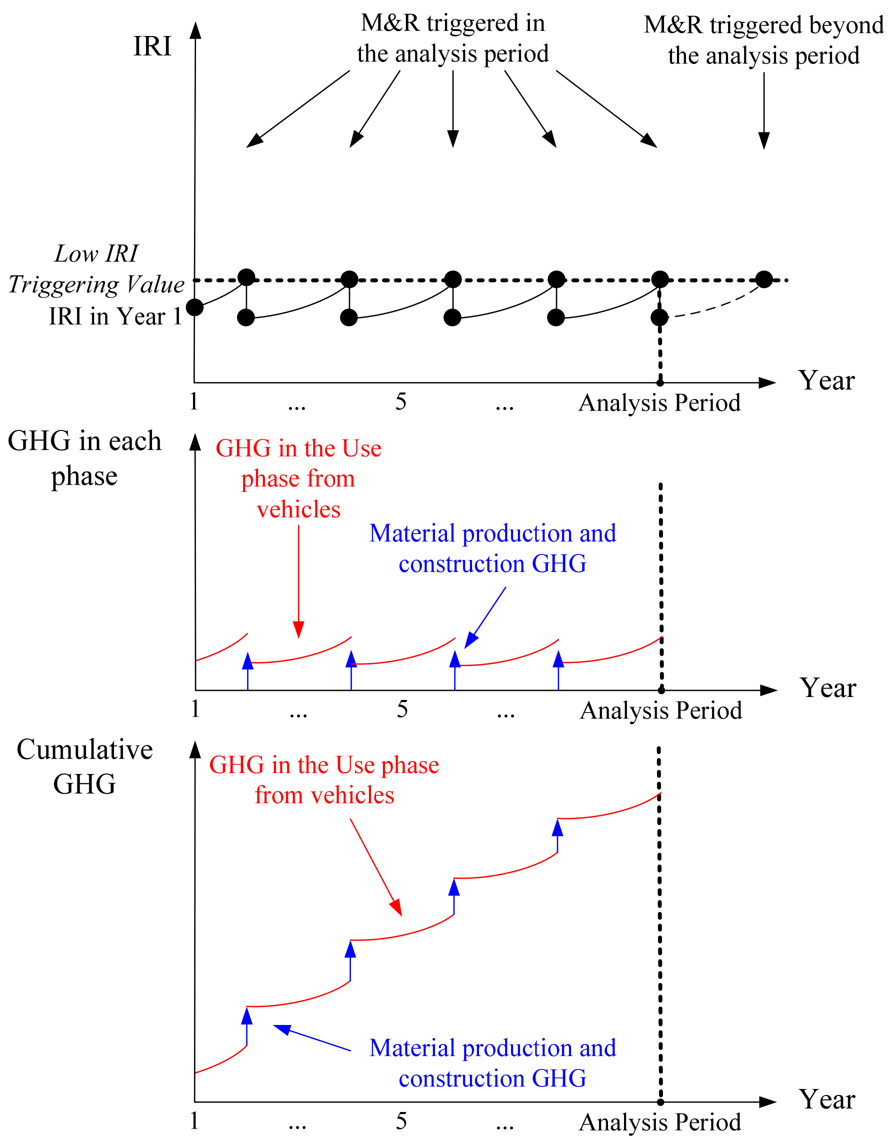
Notes:

[1]: Mixed lanes with asphalt and concrete in the same lane account about 1 percent of total lane-miles and therefore are excluded from this table.

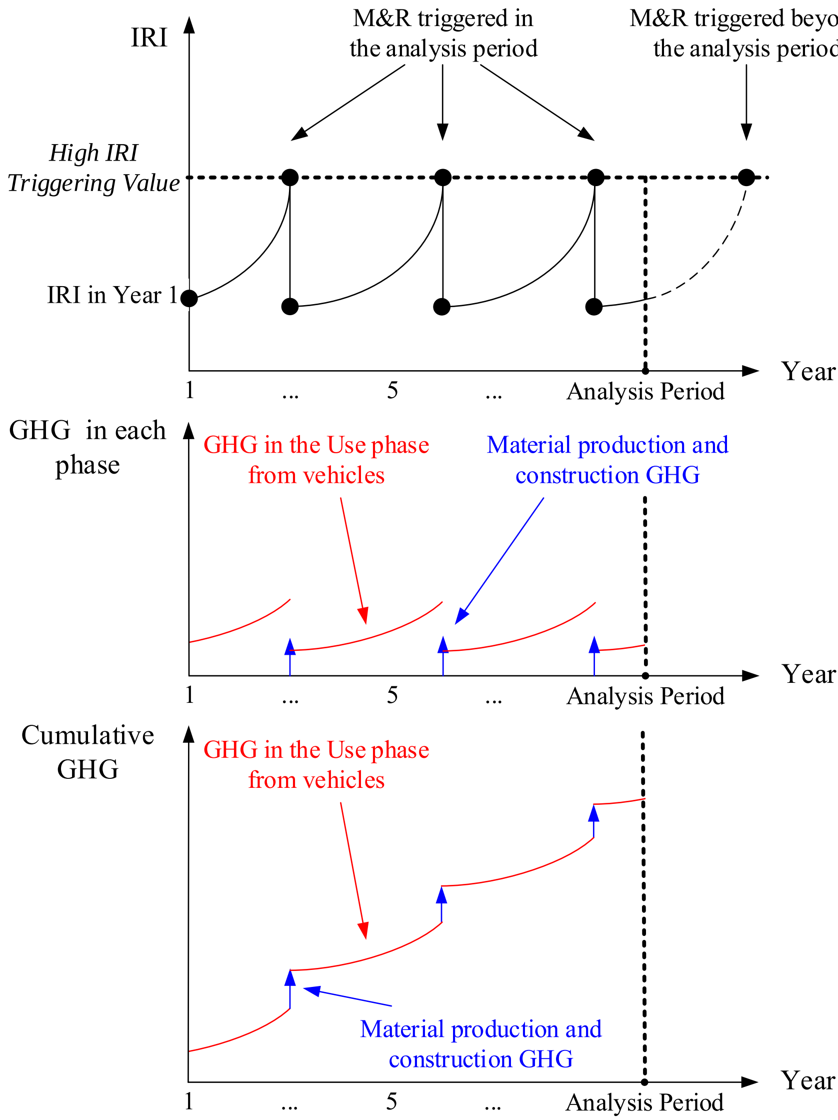
[2]: AADT is the Annual Average Daily Traffic, which is the daily traffic in all lanes and both directions of a road averaged over the year.

2.2 Overall Procedure

The pavement network is composed of segments, each of which can be described by a set of characteristics that influence the optimal IRI trigger for M&R treatments to reduce GHG emissions. Figure 2.2 shows the overall procedure of the network-level analysis. The section of this report describing each element of the procedure is shown in parentheses in the figure.


IRI
M&R triggered in the analysis period
M&R triggered beyond the analysis period
Low IRI Triggering Value
IRI in Year 1
Year
1
...
5
...
Analysis Period
GHG in each phase
GHG in the Use phase from vehicles
Material production and construction GHG
Year
1
...
5
...
Analysis Period
Cumulative GHG
GHG in the Use phase from vehicles
Material production and construction GHG
Year
1
...
5
...
Analysis Period

(a)



(b)

Figure 2.1: How the IRI trigger value affects M&R activities and the resultant GHG: (a) a low IRI trigger value and (b) a high IRI trigger value.

Considering the heterogeneity of the state highway network, setting one IRI trigger value for the whole network might lead to large differences in environmental impact. Each segment in the network has a unique traffic level, traffic composition, and pavement characteristics, so, theoretically, developing an IRI trigger value for each segment in the network could improve the precision of the optimized result. However, such complexity is impractical for an approach to be implemented at the network level. Since the previous project-level study showed that traffic level plays the most important role in determining whether there is a net reduction of GHG and energy consumption after an M&R treatment is performed, in this study traffic level was selected as the defining variable to divide the network into groups. A trigger value was then developed for each group.

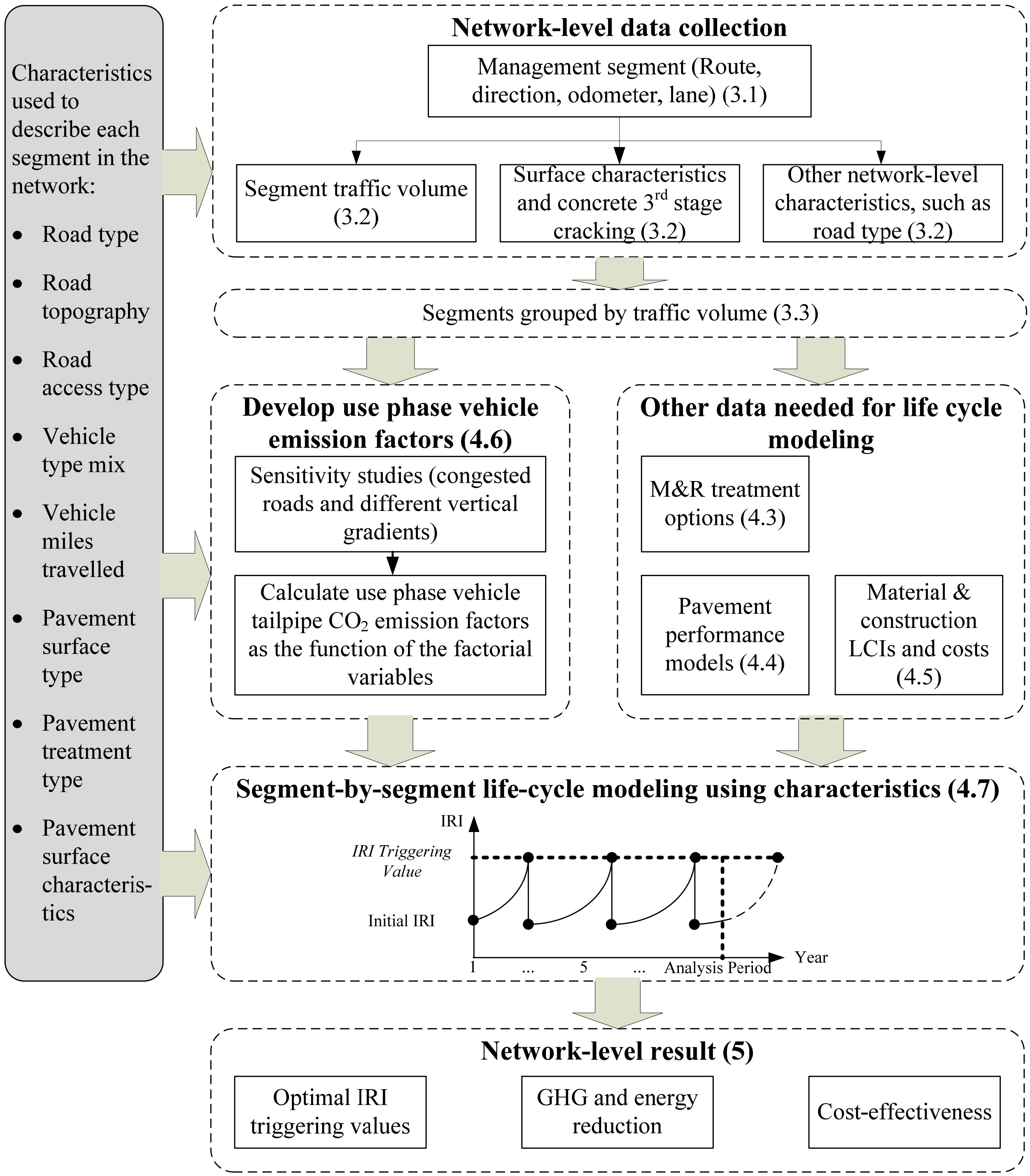


Figure 2.2: Analytical approach of the network-level analysis.
(Note: Sections of this report where details are provided appear in parentheses.)

The steps for the overall process are discussed below, and the details for each step and the pavement segment characteristics evaluated in the study are covered in Section 2.3.

1. First, acquire the segment information for the network and prepare the network-level data for each segment based on the factorial variables, including traffic level, traffic composition, initial pavement surface characteristics (including IRI and macrotexture), initial third-stage cracking of concrete pavement, road functional classifications (urban/rural roads, restricted [freeway]/unrestricted-access roads), and climate region. Then, divide the network into groups by traffic level. Chapter 3 details the segmentation of the network and the acquisition of the network-level data, and then gives an overview of the whole network.
2. Prepare other data needed for the life-cycle modeling of the network (except the Use Phase), including the potential M&R treatment options, the LCIs and cost information of the Material Production Phase and the Construction Phase, and the pavement performance models for IRI and macrotexture. These tasks are detailed in Sections 4.3 to 4.5.
3. (a) Develop the Use Phase vehicle tailpipe CO_2 emission factors[1] (CO_2 emissions per 1,000 miles) and energy consumption factors (energy consumption per 1,000 miles) for the selected pavement segment characteristics. The vehicle tailpipe CO_2 emissions factors of vehicles in this report, in the unit metric tons of CO_2 per 1,000 vehicle miles traveled (VMT), reflect the tailpipe CO_2 emissions of 1,000 miles under each combination of the factorial variables. The definition of the energy consumption factor is similar in concept, with the unit megajoules (MJ) per 1,000 miles. These factors, together with the well-to-pump (WTP) emissions from the fuel, are used to address the GHG from the Use Phase of pavement in a simpler way than the project-level modeling approach presented in Chapter 3. The detailed procedure for this step is discussed in Section 4.6.

   (b) Perform sensitivity analyses through case studies to evaluate whether additional characteristics are needed or whether some variables can be eliminated based on the impact of the particular variable on the results.

4. Apply the Use Phase vehicle emissions factors and the Material Production and Construction Phase LCIs to evaluate the GHG emissions and energy consumption for different IRI trigger values. This task was performed at the segment level of the network, which means that the life-cycle energy consumption and GHG emissions of each segment in the network were analyzed against a series of IRI trigger values using the values for that segment for all characteristics. These characteristics included the annual IRI

[1] CO_2 makes up over 99.8 percent of the vehicle running tailpipe GHG emissions. Therefore, to reduce the modeling intensity in the Use Phase, only CO_2 emissions were accounted for among GHG tailpipe emissions. Section 4.2 discusses this topic in detail.

and MPD of each segment, the road type and road access type of the segment, and the volume of traffic for each type of vehicle on the segment. Section 4.7 discusses this step in detail.

Since this study focused on repeated pavement prevention treatments (every time the same treatment is applied on each specific segment), and pavement preservation treatments have relatively short design lives compared to major rehabilitation treatments, the study adopted a ten-year analysis period, from the year 2012 to the year 2021, to cover the design lives of the two CAPM treatments considered, and assumed that these treatments would be repeated even beyond the analysis period. Although the *UCPRC Pavement LCA Guideline* suggests using 1.2 to 1.5 times the longest functional design life among all alternatives, given that the treatments analyzed are repetitive and that this study amortized the emissions from M&R events *(15)*, the selection of this analysis period was considered reasonable. Section 4.5 provides a detailed explanation of the treatment on the analysis period. Further, a sensitivity analysis of the analysis period was also performed to assess the effect of this selection, and it is discussed in Chapter 5.

5. Combine the results from all the segments in each group in the network to assess the total CO_2-e and energy reduction across the network, determine the IRI trigger values that can lead to the highest energy saving and GHG reductions, and evaluate the cost-effectiveness of using IRI to minimize GHG. The results and discussions are shown in Chapter 5.

2.3 Description of Pavement Segment Characteristics

As discussed in Section 2.2, this study used traffic level as the criterion for dividing the network into groups and developed an IRI trigger value for each group to facilitate the analysis. In developing an IRI trigger value for each group, a set of pavement segment characteristics was identified as important (see Table 2.2) to consider for finding optimal IRI trigger values and the consequent reduction in energy consumption and GHG emissions. The life-cycle phases (Material Production, Construction, and Use) of each segment in the network were then analyzed against a series of IRI trigger values based on these characteristics, and the results were summed across all the segments in each group of the network at the end of the analysis. The approach used for this study was intended to balance the simplicity of the procedure and the thoroughness of the conclusion.

Table 2.2: Pavement Segment Characteristics

Characteristic	Pavement Life-Cycle Phases Involved	Variable Type	Values
Road type	Use	Categorical	Rural road (uncongested); urban road (congested)
Road topography	Use	Continuous numerical	Different road gradients
Road access type	Use	Categorical	Restricted-access (freeway); unrestricted-access (highway)
Vehicle type mix	Use	Categorical	Passenger cars; 2/3/4/5-Axle trucks at Years 2012 to 2021
Traffic volume	Use	Continuous numerical	Traffic volume of each vehicle type
Pavement type	Material Production, Construction, and Use	Categorical	Asphalt pavement; cement concrete pavement
Pavement treatment type	Material Production and Construction	Categorical	Asphalt overlay, concrete slab replacement and grinding, concrete lane replacment
Pavement surface characteristics	Material Production, Construction, and Use	Continuous numerical	Pavement IRI and macrotexture

In developing the characteristics to evaluate how different highway conditions can affect pavement life-cycle energy and GHG, two main types of variables were considered: traffic and pavement. The traffic variables include *road type, road topography, road access type, vehicle type mix,* and *traffic volume.* The pavement variables include *pavement type, pavement treatment type,* and *pavement surface characteristics.* These characteristics will affect the final result from the pavement perspective, mainly the rolling resistance, and the Material Production and Construction phases in the pavement life-cycle. Because the current model cannot fully address the impact from pavement structure change on rolling resistance and fuel consumption in the pavement, this study assumed that the pavement surface stays the same after treatment. In addition, the Use Phase is discussed in greater detail in Section 4.6. Each of the pavement surface characteristics is discussed below.

Road Type: Rural Road or Urban Road

This variable mainly affected the hourly traffic distribution, driving pattern, and average speed distribution, all of which can affect vehicle emissions. Studies have shown that drivers operating vehicles on urban roads and rural roads can behave differently. Road type and road access type together determine the average speed distribution of a road segment, defining the time spent in different speed categories including consideration of congested periods on restricted-access roads. The method used to develop the average speed distributions for different levels of congestion is discussed in Section 4.6.1 using data from the Caltrans Performance Measurement System (PeMS) *(16).*

The data for this characteristic were taken from the California Road System (CRS) maps *(17).* The urban roads shown in the CRS maps are in areas identified as "urban" in Year 2000 U.S. Census Bureau population data. In this current study, roads in the network that were not identified as "urban" were considered "rural." Because there were only two possible values associated with this characteristic, it was treated as a categorical variable.

Road Topography: Different Road Gradients

Road topography, which is indicated by the vertical gradient of a segment, mainly affects the engine power needed to propel the vehicle. On mountainous roads, an engine expends additional energy to overcome gravitational resistance when moving uphill and expends less energy when going downhill. The vertical gradient can also have an impact on vehicle speed, although this impact may be small. In this study, a sensitivity analysis was performed on the road gradient for mountainous areas (Section 4.6.2). Considering that the maximum extended gradient for freeways is 6 percent *(18)*, the values used in the sensitivity analysis were 0 percent, 3 percent, and 6 percent. The sensitivity analysis results showed that different road vertical gradients have a very small impact on how pavement roughness affects GHG output and energy consumption. Therefore road topography was not included in the final set of characteristics and all roads were modeled as flat (0 gradient). It should be noted that the although the additional GHG emissions caused by mountainous regions was not considered in the analysis of the changes in GHG emissions caused by M&R treatments, vertical gradient needs to be considered in calculation of the total GHG emissions and energy consumption of vehicles in mountainous areas.

Road Access Type: Restricted-Access (Freeway) or Unrestricted-Access (Non-Freeway)

Road access type affects the speed distribution of vehicles. The definition of *restricted-access roads* (freeways) used in this study was adopted from the *Highway Capacity Manual 2000* (HCM) *(18):* "a divided highway with full control of access and two or more lanes for the exclusive use of traffic in each direction." *Unrestricted-access roads* in this study, then, included all roads that did not meet this definition. Because restricted-access roads can provide uninterrupted flow, and there are no signalized or stop-controlled intersections, vehicles speeds do not fluctuate much in uncongested conditions. On unrestricted-access roads, intersections and other traffic controls result in frequent acceleration, deceleration, and stops. The Caltrans photolog of the California state highway system was used to identify the restricted-access and unrestricted-access roads *(19)* based on the definition from the HCM. Because there were only two values associated with this characteristic, it too was treated as a categorical variable. The method followed to develop the average speed distributions for the different road access types used data acquired from the Caltrans PeMS *(16)*.

Vehicle Type Mix: Passenger Cars and Different Types of Trucks in Calendar Years 2012 to 2021

Previous studies have shown that different types of vehicles exhibit different relationships between GHG emissions and pavement roughness because of their different engine technologies and vehicle weights *(14)*. Therefore, *vehicle type* is an important variable for determining how pavement roughness affects vehicle GHG emissions in the pavement Use Phase. The vehicle types considered in this study were passenger car, 2-axle truck, 3-axle truck, 4-axle truck, and 5-or-more-axle truck for each year in the analysis period. All the vehicles were divided into these five categories to match available traffic count data. Because vehicle-emission technologies may differ in different years, each calendar year was modeled separately for this characteristic. Therefore the total number of possible values for this characteristic was 50. The vehicle types were selected from the *Caltrans Truck Report* and are based on the number of axles for each truck *(20)*. Under this definition, *passenger cars* mostly include cars, sport utility vehicles (SUVs), vans, and pickup trucks[1], and most of them are gasoline powered. *Trucks* mostly include buses, single- and double-unit trucks (except pickup trucks and vans with only four tires), and they are mostly diesel powered.

Traffic Volume: Traffic Volume of Each Vehicle Type

The variable *traffic volume* essentially determines the linear multiplier for how much fuel consumption can be saved by performing an M&R treatment on the pavement. GHG and energy consumption are linearly related to the traffic volume for each type of vehicle, so vehicle emission factors were developed for each type of vehicle and then applied to the traffic volume for each vehicle type. Each segment in the network has a unique vehicle population and therefore this characteristic was treated as a continuous numerical variable. Traffic volume data were acquired from the Caltrans traffic volume report and Caltrans truck traffic count (together referred to as *CalTruck*) *(5)*. This traffic database includes the Annual Average Daily Traffic (AADT) of all lanes for each segment (therefore not differentiated by lanes), truck percentage in the daily traffic, and the percentage of each type of truck (2-axle, 3-axle, 4-axle, and 5-or-more axle) in the truck traffic.

Pavement Type: Asphalt or Concrete Pavement

Although this study did not consider changes of *pavement type* due to the lack of an appropriate model for addressing the pavement structural effect on rolling resistance, asphalt and concrete pavements show different performance with regard to surface characteristics and have different treatment options. Therefore, pavement type was included and treated as a categorical variable.

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[1] Under Caltrans' definition, the 2-axle truck category excludes pickup trucks and vans with only four tires which are counted as cars.

Pavement Treatment Type: Different Pavement Treatment Options

Pavement treatment type is the M&R treatment. This variable considered possible M&R treatments based on road conditions. Each M&R treatment option has unique material production and construction processes, and has a unique effect on the pavement surface characteristics considered in this study (IRI and macrotexture). The complete list of pavement treatments from the Caltrans PMS includes *(21):*

- Asphalt overlay (thick overlay: thickness > 0.25 ft. [75 mm]; medium overlay: 0.1 ft. [30 mm] < thickness ≤ 0.25 ft. [75 mm]; and thin overlay: thickness ≤ 0.1 ft. [30 mm]), where a new asphalt layer is placed, with or without partial milling of the existing layer of old asphalt
- Asphalt cold in-place recycling, where the upper 0.25 to 0.33 ft. (75 to 100 mm) of the existing asphalt pavement is recycled without heating to produce a restored pavement layer. This process includes stabilization with asphalt emulsion and cement *(22).*
- Asphalt full-depth recycling, where the depth of all asphalt layers plus a predetermined depth of the base material are recycled and used as aggregate base (no stabilization) or stabilized with one or more of the following: cement, foamed asphalt, asphalt emulsion, and/or lime *(23).*
- Asphalt seal coat, sometimes termed as chip seal or bituminous surface treatment, where a thin protective wearing surface using asphalt and aggregate is applied to a pavement or base course. It is a preventive treatment to slow the damage to the pavement structure from sun and water *(24).* There are various types of chip seals, as well as slurry seals and microsurfacings.
- Concrete crack, seat and overlay (CSOL), where the existing concrete slabs are broken into smaller pieces by repeatedly dropping a large weight, the pieces are then seated by two to three passes of a large rubber-tired roller, and finally an asphalt overlay is placed on top, often with inclusion of a fabric interlayer embedded in the asphalt.
- Concrete diamond-grinding and slab replacement, where the slabs showing third-stage cracking are replaced and the entire concrete surface is diamond ground.
- Concrete lane reconstruction, where an existing concrete lane is demolished and reconstructed as new concrete, which may include removal of the base layer as well and reconstruction of both the base and concrete.

This study only considered a medium asphalt overlay for asphalt pavement, and concrete diamond-grinding and slab replacement for concrete pavement, with a few segments programmed for concrete lane replacement[1], under the assumption that that pavement surface does not change because of the treatment. These strategies are discussed in detail in Section 4.3. *Pavement treatment type* was also treated as a categorical variable in the analysis.

[1] Concrete lane replacement was addressed in a limited and preliminary way. Section 4.3 of Chapter 4 details the practice.

Pavement Surface Characteristics: IRI and Macrotexture

The focus of this study is on how pavement roughness (IRI) and macrotexture affect the rolling resistance and fuel consumption of vehicles in the Use Phase of pavement. Therefore these characteristics were included as variables to evaluate how they can affect the Use Phase energy consumption and GHG at the network level. Because each segment in the network has different IRI and macrotexture values, and these values change over time, these characteristics were treated as continuous numerical variables. When the vehicle emission factors in the Use Phase of pavement were developed (see Section 4.6), the emission factors were shown as a continuous function of IRI and MPD, with the coefficients in the function differing for each combination of categorical characteristics.

Table 2.3 shows a detailed breakdown of the state network using these characteristics. The first level is road topography, which is represented by flat roads and mountainous roads. The second level is road type, and includes urban roads and rural roads. This study assumed that there are no urban roads in mountainous areas, therefore this combination was eliminated. The third level is road access type, which includes restricted-access roads and unrestricted-access roads, the main characteristic that affects driving behavior. The estimated annual VMT for each combination of the characteristics is shown for each combination. These VMT numbers were calculated based on the Caltrans PMS and Caltrans traffic count report *(20)*. However, because the PMS database and the traffic report did not include the road topography, the VMT from all road topography is shown under the flat road category. Nevertheless, these estimated values give an indication of the relative amount of traffic on each combination of characteristics.

As discussed previously, sensitivity analyses were performed on some combinations before applying the analysis to the whole network in order to evaluate whether additional characteristics were needed or if some characteristics could be eliminated to reduce the computational intensity of the analysis. These characteristics include the effects of congestion on urban restricted-access roads and the interaction of roughness and texture with different road vertical gradients on mountainous roads.

Sensitivity analysis for congestion was performed for flat, urban restricted-access roads because of the high VMT for this category in the network and its urban location, which can result in frequent congestion. The analysis used the average speed distribution to evaluate the impact of changing rolling resistance under different traffic conditions (such as segments with frequent low-speed traffic flow). Case studies were performed to evaluate the fuel savings from pavement M&R activities under frequent low-speed traffic flow conditions (indicating a traffic condition with frequent congestion) and the results were compared with the calculation using the state-average traffic condition. Results from the analysis showed that traffic condition had a very small impact on the relationship between pavement roughness and fuel consumption, and therefore it was not necessary to include traffic condition as a factorial variable.

For flat, urban unrestricted-access roads, an additional sensitivity analysis was not performed because of the small fraction of VMT this category accounted for in the whole state highway network and the lack of available representative traffic-flow condition data. Similar sensitivity analyses were not performed on flat rural roads because the results from urban roads showed the impact from traffic condition was insignificant and there is far less congestion on rural roads.

On mountainous roads, sensitivity analyses were performed on the effect of road gradient to assess its impact on fuel savings. The results from these case studies showed that road gradient was also insignificant for the relationship between pavement roughness and fuel consumption, and therefore all road segments were modeled as flat roads (0 percent gradient).

Table 2.3: Breakdown of Network Based on Factorial Variables

Road Topography	Road Type	Road Access Type	Other Variables	Estimated Lane-Miles Using Caltrans PMS[1] (Thousand miles)	Estimated Annual VMT Using Caltrans PMS (Billion miles)	Additional Sensitivity Analysis Factors in Case Studies
Flat	Urban	Restricted	Pavement type; treatment type; vehicle type; traffic level; IRI and MPD	14.6	100.1	Two traffic conditions (state average and low-speed)
		Unrestricted	Pavement type; treatment type; vehicle type; traffic level; IRI and MPD	4.8	12.6	Not performed because of the low VMT fraction and the lack of representative data[2]
	Rural	Restricted	Pavement type; treatment type; vehicle type; traffic level; IRI and MPD	7.6	24.4	Not performed because the results from urban roads showed insignificant impact
		Unrestricted	Pavement type; treatment type; vehicle type; traffic level; IRI and MPD	21.4	22.5	Not performed because the results from urban roads showed insignificant impact
Mountainous	Rural	Restricted	Pavement type; treatment type; vehicle type; traffic level; IRI and MPD	Data not available	Data not available	3 gradients (0%, 3%, 6%)
		Unrestricted	Pavement type; treatment type; vehicle type; traffic level; IRI and MPD	Data not available	Data not available	3 gradients (0%, 3%, 6%)

Notes:
[1]: The lane-miles and VMT on mountainous roads are not available. Therefore the total lane-miles and VMT are shown under flat roads.
[2]: The urban unrestricted-access road category in this study generally does not include city and county streets. It only includes U.S. numbered routes and state routes in urban areas, which is why it lacks the traffic-monitoring stations to provide enough data.

3 NETWORK-LEVEL DATA ACQUISITION

This chapter introduces the basic segmentation of the network and how the network-level data were applied to each segment, as discussed in Step 1 of Section 2.2. Included are The data on pavement surface characteristics, concrete third-stage cracking, traffic level and composition, road type, road access type, and climate region. An overview of the network is given at the end of this section.

3.1 Management Segment

In this study, the base unit for the analysis has been called a *management segment*. The segmentation of the state highway network into management segments was based on county boundaries, route, direction, number of lanes, Caltrans climate region, bridge start and end point, traffic, surface type (asphalt or concrete), and substantial changes in the thickness of the surface layer (found in the Caltrans PMS database from the recently completed statewide ground penetrating radar [GPR] study). Each management segment is uniquely defined by county, route, direction, lane number[1], starting and ending postmile[2], and starting and ending state odometer reading[3]. For the purposes of this study, each record in the Caltrans PMS database was designated a management segment, and all of the management segments with the same starting and ending state odometer reading in one direction of a given route were called a *directional segment*. Stated another way, *a management segment is the lane-by-lane record of directional segment.*

The total number of management segments used in this report was about 65,000, and these segments covered about 48,000 lane-miles of the state highway network. Figure 3.1 shows the cumulative distribution plot of the length of the management segments.

3.2 Mapping Data to Management Segments

This section describes the procedure used to map the available data (for pavement IRI, macrotexture, concrete pavement third-stage cracking, traffic, road type, road access type, and climate region) to the management segments using the state odometer location reference system developed used for this study. (Note: this system was under development for the Caltrans PMS.)

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[1] Lane number is defined according to location relative to the centerline of the road, with the innermost lane being Lane 1, and increasing moving to the outer lane.

[2] Postmile was used because the algorithm of equivalent single axle load (ESAL) calculation requires postmile (*23*). State odometer reading was the main highway reference system used in this study because it is a linear reference system along the highway network, while the postmile system uses many prefixes and suffixes which complicates the calculation.

[3] State route odometer reading is the absolute distance from a location in a given route to the starting point of this route. The starting point of a route is either the west end (for east-west–bound routes) or the south end (for north-south–bound routes). It differs from the postmile system in that it is a continuous measurement, not reset by county boundary and without prefix or suffix to indicate breaks in actual distance due to shortening or lengthening of the route through realignment.

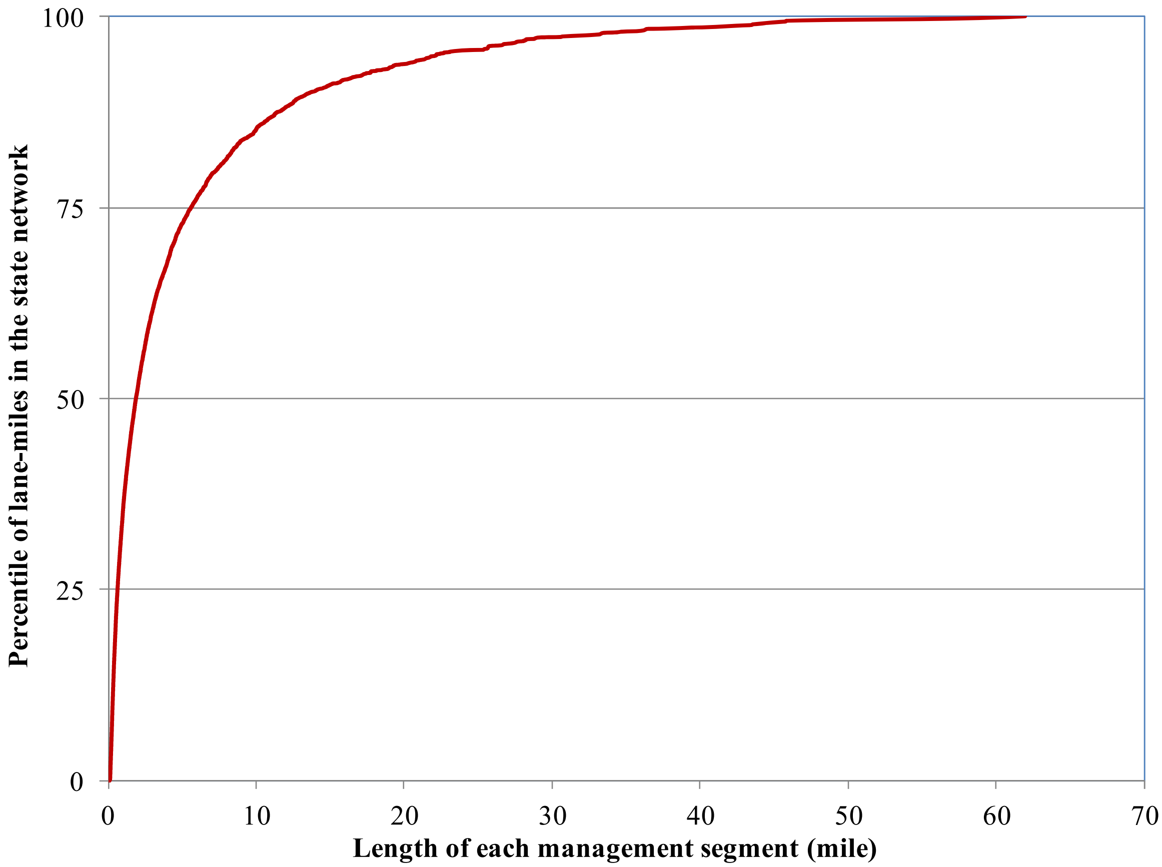


Figure 3.1: Cumulative distribution plot of the length of management segments.

3.2.1 Mapping Pavement Surface Condition and Third-Stage Cracking

The pavement surface condition (IRI for both asphalt and concrete pavement, and MPD for asphalt pavement) and third-stage cracking (for concrete pavement) data used for the initial condition states of the pavement network in this study were acquired from the Caltrans Automated Pavement Condition Survey (APCS) performed in 2011[1]. That survey included the latest information on pavement surface characteristics and third-stage cracking available for the state pavement network. Data for the pavement surface characteristics were used to calculate pavement-induced rolling resistance, and the data on third-stage cracking were used to calculate the required number of concrete slab replacements. The longitudinal data collection resolution of IRI and MPD in the APCS data is 33 ft (10 m) for asphalt-surfaced pavement and per slab for jointed plain concrete-surfaced pavement. Each record in the APCS database was uniquely identified by the route number, direction, lane number, and state odometer reading from the APCS data segment center point. The following algorithm was used to map the APCS data to management segments:

[1] As of the time of this work in the report, the APCS data had not been applied to the management segments in PaveM (the Caltrans pavement management system). Therefore this study mapped APCS data to the management segments. The APCS data were later mapped to PaveM by Caltrans and UCPRC researchers.

- For each management segment, find all the APCS records that meet the following conditions: the route number, direction, and lane number for the management segment and APCS data segment is the same, and the center-point state odometer reading of the APCS data segment is between the starting and ending state odometer readings of the management segment.
- Next use Eq. 3.1 and Eq. 3.2 to calculate the average IRI or MPD and third-stage cracking for the given management segment, respectively.

$$Average\ IRI\ or\ MPD\ on\ a\ management\ segment$$
$$= \frac{\sum\left(IRI\ or\ MPD\ of\ \ APCS\ segment_i \times Length\ of\ \ APCS\ segment_i\right)}{\sum Length\ of\ \ APCS\ segment_i} \qquad \textbf{(3.1)}$$

$$3^{rd}\ \ Stage\ cracking = \frac{Length\ of\ \ slabs\ with\ 3rd\ stage\ cracking}{Length\ of\ \ all\ slabs\ in\ this\ segment} \qquad \textbf{(3.2)}$$

For the longer management segments in the network, this equation will average out any short rough data segments in them. Because the effect of IRI on fuel economy is approximately linear, it was assumed that averaging IRI within the management segments would result in a value similar to using IRI on the 10 m data segments.

3.2.2 Mapping Road Type and Road Access Type

Road type and road access type data were organized into two tables, an urban road table and an unrestricted-access road table, each with location information for each section meeting the definition of urban or unrestricted-access (freeway). All segments not in the respective tables were considered to be rural and/or restricted access. In these tables, each record had a unique identity based on the route number and the starting and ending state odometer readings; this means that any segment within the boundaries defined by the two tables is either an urban road or an unrestricted-access road, respectively. This study adopted the following algorithm to determine the road type of each management segment:

- Find all management segments which match the route number in the urban section table and have at least an overlap of 50 percent of the management segment length with the urban road boundaries. These segments were identified as urban roads.
- Identify all the rest of the management segments as rural roads.
- The same principle was used to identify unrestricted-access and restricted-access roads.

3.2.3 Mapping Climate Region Classification

Since the climate region where a pavement is located has a big impact on pavement performance, and especially the progression of IRI, it was also necessary to identify the climate region of each management segment. The climate region database was organized into a table that showed the state odometer boundaries of different Caltrans climate regions *(25)*. Each record in the climate region table was uniquely identified by its route number, direction, and starting and ending state odometer reading. Therefore each management segment can be assigned its climate region using similar procedures as for road type and road access type. If a management segment fell into two climate regions, the climate region with a higher portion of the segment was considered as the climate region of that segment.

3.2.4 Mapping Traffic Data

Traffic data were acquired from the Caltrans traffic volume report and Caltrans truck traffic count (together referred to as *CalTruck* data) *(20)*. The traffic database included the AADT of all lanes for each set of directional segments (and was therefore not differentiated by lanes), the truck percentage in daily traffic, and the percentages of each type of truck (2-axle trucks, 3-axle trucks, 4-axle trucks, and 5-or-more axle trucks). Because pavement performance (such as IRI and macrotexture) is different on each lane but the traffic count (AADT) and truck type percentage are not differentiated by lanes in the Caltrans database (i.e., the traffic data is based on directional segments), this study adopted the following three-step mapping procedure to assign the traffic for each management segment:

1. Map the AADT and truck composition from the traffic database to the directional segment level in the management segment database. For each set of directional segments, find all the traffic data that meet the following conditions: the route number and direction are the same between the directional segments and traffic database, and the state odometer reading of the traffic monitoring station is between the start and end state odometer readings of the directional segments. Next, use Equation 3.3 to calculate the average traffic (of all lanes) for a given record of directional segments.

$$\begin{aligned} &\textit{Average traffic of a set of directional segments} \\ &= \frac{\sum\left(\textit{traffic of station}_i \times \textit{Distance from station}_i \textit{ to the end of directional segments}\right)}{\sum \textit{Distance from station}_i \textit{ to the end of directional segments}} \end{aligned} \qquad \textbf{(3.3)}$$

2. Calculate the lane distribution factor (LDF) for passenger cars based on the truck LDF from the weigh-in-motion (WIM) study *(26)*, with the inputs lane number, total number of lanes (one direction), and road type (rural/urban roads). In the WIM study, the truck LDFs were developed for rural and urban

roads. However, because LDFs for passenger cars are dependent on truck LDFs and the truck percentage in traffic flow is different for each segment, the LDFs for passenger cars were calculated for each management segment.

The basic assumption followed for calculating the LDF of passenger cars was that the total passenger car equivalent (PCE) of each lane is the same. Passenger car equivalent converts the number of trucks to the equivalent number of passenger cars that can displace the trucks. The PCE factor of trucks was acquired from the *Highway Capacity Manual 2000 (18)*, and a value of 1.5 was used in this study. Equation 3.4 shows the overall calculation. The LDF of passenger cars and trucks can be calculated by solving this set of equations. This study assumed that all types of trucks have the same LDF on a given segment.

$$\begin{cases} T_{Lane\,1} = (1-TruckP)\times PC\_LDF_{Lane\,1} + TruckP\times Truck\_LDF_{Lane\,1}\times PCE_{Truck} \\ T_{Lane\,1} = (1-TruckP)\times PC\_LDF_{Lane\,1} + TruckP\times Truck\_LDF_{Lane\,1}\times PCE_{Truck} \\ \cdots \\ T_{Lane\,N} = (1-TruckP)\times PC\_LDF_{Lane\,N} + TruckP\times Truck\_LDF_{Lane\,N}\times PCE_{Truck} \\ T_{Lane\,1} = T_{Lane\,1}\cdots = T_{Lane\,N} \end{cases} \qquad \textbf{(3.4)}$$

Where:

$T_{Lane\ i}$	is the total PCE of Lane i;
TruckP	is the truck percentage of this set of directional segments (same for all lanes);
$PC\_LDF_{Lane\ i}$	is the LDF for passenger cars in Lane i;
$Truck\_LDF_{Lane\ i}$	is the LDF for trucks in Lane i (depending on the road type); and,
PCE_{Truck}	is the passenger car equivalent factor of trucks, 1.5 was used in this study.

3. Calculate the 80 kN equivalent single axle load (ESAL) based on the AADT, truck composition, county, route, postmile, total number of lanes, and lane number for each management segment. Using ESALs is a common approach for converting the damage from wheel loads of various magnitudes and repetitions to an equivalent number of standard loads. The most commonly used equivalent load in the U.S. is the 18,000 lb. (80 kN) ESAL load *(27)*. It is an important input used to evaluate pavement performance in a given analysis period. The algorithm used to calculate ESALs was from the WIM study by the UCPRC *(26)* and used the Caltrans approach for ESAL calculation, which includes treating multiple axles as singles and use of an exponent of 4.2 for damage calculation.

Using this procedure, the total traffic and the truck composition associated with each management segment (lane by lane in each set of directional segments) were calculated.

3.3 Dividing the Network Based on Traffic Level

As noted in the Section 2.2, this study first divided the network into groups based on the traffic level of directional segments, then developed the IRI trigger value for each group. The reason that the traffic on directional segments rather on management segments (the lane-by-lane record in each set of directional segments) was used is that PaveM (the Caltrans new PMS) requires that the asphalt overlay and concrete diamond-grinding with slab replacement treatments—the two main strategies evaluated in this study—be performed on all the lanes in a particular direction once they are triggered on a single lane. The approach was chosen because it allows consistent elevation of the pavement across all the lanes. Therefore, it is more appropriate to examine the GHG emissions and energy consumption of each directional segment if the results are to be summed up across all groups at the end of the process. However, all the calculations were still performed at the lane level because pavement performance (such as IRI and macrotexture) was different on each lane.

With the traffic data mapped to the directional segments, the cumulative distribution plot of traffic could be created. This plot was the basis for grouping the segments in the network for analysis. The traffic level affects GHG reduction in two ways: the pavement performance from traffic loading (mainly trucks) in the form of ESALs, and the multiplier effect of fuel economy change on every vehicle (both passenger cars and trucks). Therefore, the traffic level indicator needed to reflect both passenger vehicles and trucks, with trucks having a higher weighting factor.

Lanes that mostly carry passenger vehicles (such as the innermost lanes) carry very few ESALs, while the number of passenger vehicles they carry can be very large and thus have a large impact on the final GHG. To achieve this balance, this study used the passenger car equivalent (PCE) from the *Highway Capacity Manual* to facilitate the determination of traffic level: each truck is considered to be 1.5 equivalent passenger cars[1] *(18)*. In this way, the daily traffic in the form of total PCE on each set of directional segments can be calculated by considering trucks equal to 1.5 cars. Figure 3.2 shows the cumulative distribution plot of the daily PCE based on the lane-miles in the state network. Considering the strong effect of traffic volume on emissions, this study used a finer resolution on the higher traffic volume part in the cumulative distribution curve. The dividing points in the network were determined at the 25th, 50th, 60th, 70th, 80th and 90th percentile traffic levels in the cumulative distribution plot, which corresponds to total daily PCEs on directional segments of 2,517, 11,704, 19,108, 33,908, 64,656, and 95,184, respectively, as shown in Figure 3.2 and Table 3.1.

[1] It should be noted that PCE is only used to divide the network into groups. When calculating the traffic damage to pavement and vehicle fuel economy, specific algorithm and emission factors that are applicable for each type of vehicle, including heavy duty trucks, were applied.

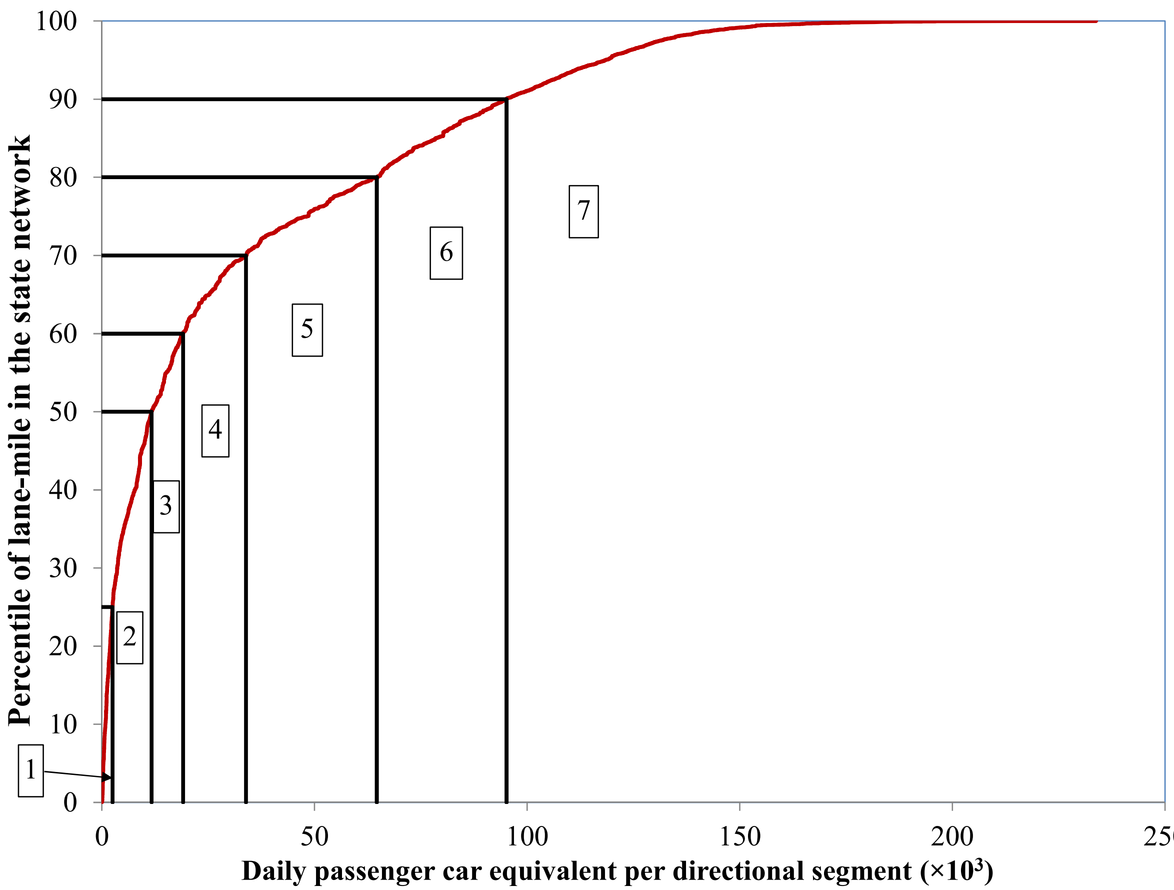


Figure 3.2: Cumulative distribution plot of daily passenger car equivalent per directional segments (group number is shown in the box).

Table 3.1: Grouping Networking Using Passenger Car Equivalents

Traffic Group Number	Percentile Range of Lane-Miles in the Cumulative Density Plot	Total Lane-Miles	Total Daily PCE Range
1	0 < Percentile ≤ 25th	12,068	0 < PCE ≤ 2,517
2	25th < Percentile ≤ 50th	12,068	2,517 < PCE ≤ 11,704
3	50th < Percentile ≤ 60th	4,827	11,704 < PCE ≤ 19,108
4	60th < Percentile ≤ 70th	4,827	19,108 < PCE ≤ 33,908
5	70th < Percentile ≤ 80th	4,827	33,908 < PCE ≤ 64,656
6	80th < Percentile ≤ 90th	4,827	64,656 < PCE ≤ 95,184
7	90th < Percentile ≤ 100th	4,827	95,184 < PCE

3.4 Overview of the Network

Table 3.2 and Figure 3.3 show some descriptive statistics of the highway network based on the traffic groupings developed and the management segments and the network-level data that were mapped to the segments. These data were used as the initial state of the analysis in this study. Overall, asphalt-surfaced pavement accounted for about 76 percent of the total lane-miles. It can be seen that asphalt pavement comprised the greater portion of the segments with a daily PCE less than 33,908, which covered 70 percent of the total lane-miles in the network. With regard to IRI, the average IRI value and the standard deviation of IRI on each type of pavement and each network traffic level group were similar: the IRI value was around 114 to 120 inches/mile (1.8 to 1.9 m/km), and the standard deviation was around 44 inches/mile (0.7 m/km). The concrete pavement in Group 1 (lowest traffic) can be considered as an outlier because there were only six segments (0.9 lane-miles in total) in that group so the result was not representative. The different types of pavement and the pavements in each traffic group had different demographics in terms of pavement age and time since the last surface treatment. They also are reflective of some of the design practices used when much of the network was built from the 1950s through the 1980s.

Table 3.2: Descriptive Statistics of IRI Value on Each Group of the Network (Based on 2011 Pavement Condition Survey) [1,2]

Traffic Group Number	Pavement Type	Lane-Miles	Percent in the Total Lane-Mile	Number of Management Segment	Max. IRI (m/km)	Min. IRI (m/km)	Average IRI (m/km)	IRI Standard Deviation (m/km)
1 (lowest traffic)	Asphalt	12,700	26.7	4,927	12.60	0.56	1.95	1.04
	Concrete	0.9	0.0	6	3.67	2.29	2.83	0.50
2	Asphalt	10,863	22.9	8,457	8.39	0.53	1.77	0.79
	Concrete	1,015	2.1	942	5.54	0.64	1.82	0.73
3	Asphalt	4,131	8.7	4,605	11.90	0.47	1.79	0.90
	Concrete	604	1.3	768	6.19	0.80	1.90	0.81
4	Asphalt	3,683	7.7	4,743	9.37	0.27	1.77	0.91
	Concrete	881	1.9	1,393	5.05	0.67	2.02	0.71
5	Asphalt	2,559	5.4	4,900	9.86	0.51	1.63	0.71
	Concrete	2,447	5.1	5,066	9.25	0.68	1.98	0.77
6	Asphalt	1,679	3.5	4,608	5.85	0.55	1.55	0.57
	Concrete	2,627	5.5	6,593	8.10	0.65	1.89	0.78
7 (highest traffic)	Asphalt	1,343	2.8	4,563	9.51	0.56	1.67	0.62
	Concrete	2,999	6.3	9,999	6.30	0.65	1.79	0.73

Notes:

[1]: The mixed lanes (with both asphalt and concrete in one lane) accounted for about 1 percent of the total lane-miles of the network and therefore were not included in this statistics.

[2]: This data is based on the IRI on the management segments.

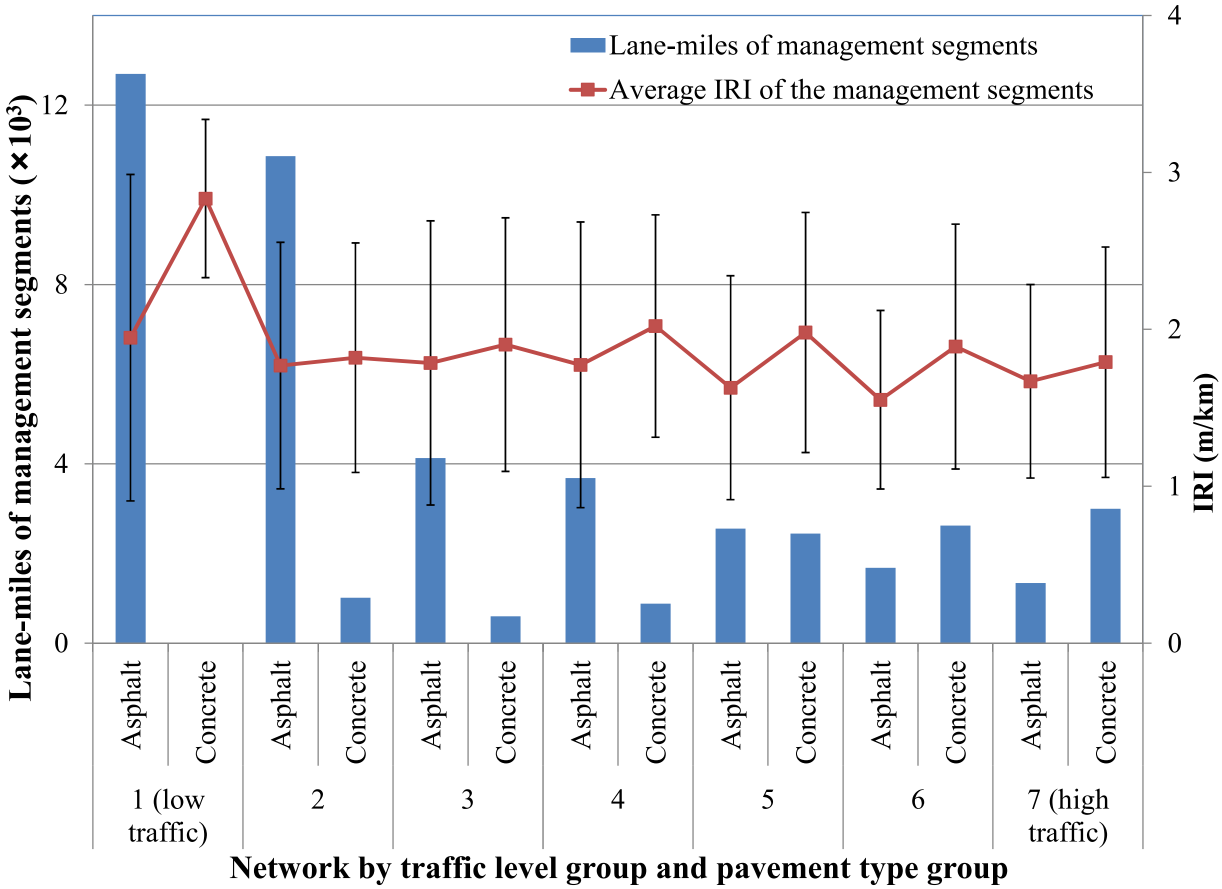


Figure 3.3: Descriptive statistics of IRI and lane-miles on each traffic level (PCE) group. [1,2]
(1 m/km = 63.4 inches/mile).

Notes:

[1]: The error bar shown with the average IRI value is the standard deviation of the IRI in each group.

[2]: There are only 0.9 lane-miles of concrete pavement in Group 1, so the average IRI value in that group combination is very high and may not be representative.

4 PAVEMENT LIFE-CYCLE MODELING

This study is part of the larger UCPRC pavement LCA study program, which earlier had developed a project-level pavement LCA model based on the *UCPRC Pavement LCA Guidelines (15)*. This chapter describes the procedure for applying the project-level model to the pavement network and developing the optimized IRI values for triggering maintenance treatments. A complete description of the life-cycle phases and the system boundary of the project-level model are presented in the project-level pavement LCA study report: *UCPRC Life-cycle Assessment Methodology and Initial Case Studies on Energy Consumption and GHG Emissions for CAPM Treatments with Different Rolling Resistance (14)*. The life-cycle phases considered in the UCPRC pavement LCA study include the *Material Production Phase,* the *Construction Phase,* and the *Use Phase.* Only the transport of demolished materials in the *End-of-Life* (EOF) *Phase* is not included in the current LCA model. The model can be used where it can be assumed that the EOL phase is the same for the alternatives being evaluated, thus eliminating the need for a net result comparison.

4.1 Project-Level Pavement LCA Model

Because the project-level LCA model provides the foundation of the network-level analysis, a brief description of the project level is provided here. A detailed description can be found in the pavement LCA study report *(14)*. Figure 4.1 shows an overview of the complete project-level pavement LCA model and its modules. The model includes four modules: the *Pavement and Environment* module and three submodels for the life-cycle phases. The Pavement and Environment module is for collecting the general inputs for the model, such as functional unit, analysis period, and pavement dimension. The submodels for the life-cycle phases include the Material Production Phase model, the Construction Phase model, and the Use Phase model.

The Pavement and Environment module defines the entire project. This module includes the definition of the scope of an LCA study, such as the functional unit and analysis period. It also collects the information to be used in all other submodels, such as pavement dimensions, traffic (such as AADT and truck composition), climate region, and initial pavement surface characteristics.

The Material Production Phase model assesses the impacts from the pavement Material Production Phase. In this model, the various LCI data sources described in Section 4.5 are adapted and converted to fit California conditions. Impacts from the Material Production Phase are evaluated using the pavement dimensions from the Pavement and Environment module. This model and the related calculations were developed by Lee *(28).*

The Construction Phase Model calculates the environmental impacts from the Construction Phase. In this model, the construction schedule, including equipment usage and the duration of construction, is modeled using the modeling tool *CA4PRS*. Emissions factors for various types of construction equipment are acquired from different data sources such as *EMFAC* and *OFFROAD*. With the emission factors and equipment activities, the total emissions from the Construction Phase can be assessed. The model and the related analysis were performed by Lee et al. *(14)*.

The Use Phase model calculates vehicle emissions and fuel consumption from vehicles caused by the deterioration of pavement, as represented by changes in pavement roughness, texture, and rolling resistance, during the operating period of a pavement. Using the Traffic Information and Pavement Performance models, this model is able to calculate the rolling resistance induced by the pavement, and then uses the Vehicle Emissions model, *MOVES*, to address the additional fuel consumption due to the increasing rolling resistance in the pavement Use Phase. The environmental burdens associated with the pavement effects in the Use Phase are reported as the difference between the burden of the business-as-usual (*Do Nothing*) scenario and the M&R treatment scenario.

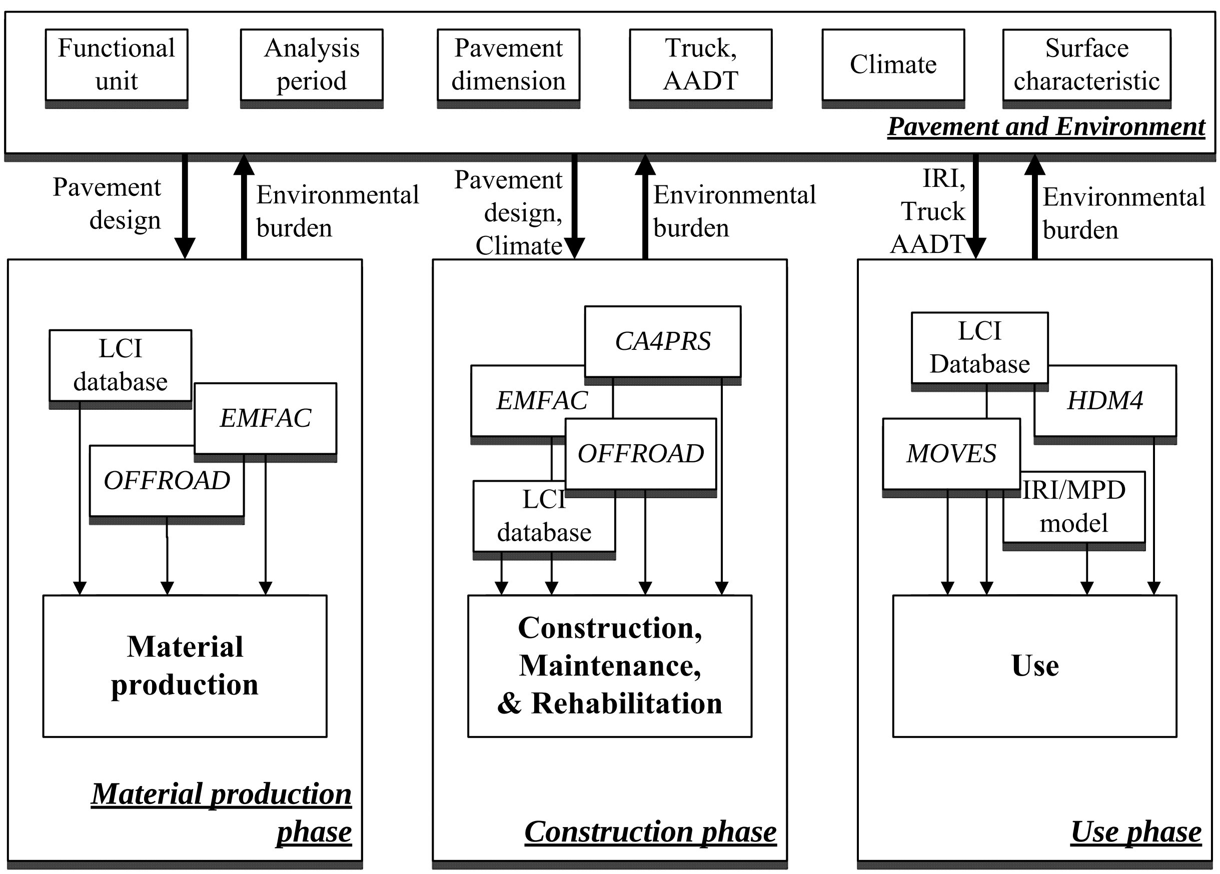


Figure 4.1: Overview of UCPRC Pavement LCA model *(14)*.

4.2 Environmental Impact Categories

According to ISO standards, a complete LCA study should include an impact assessment *(29).* Life-cycle impact assessment is the stage where various life-cycle inventory results are translated into the evaluation of potential human health and environmental impacts. The LCA guideline published by the U.S. EPA defines eleven commonly used life-cycle impact categories *(30),* including global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, aquatic toxicity, human health, resource depletion, land use, and water use. ISO has defined nine similar categories *(29)*.

Although the inclusion of more impact categories is recommended in LCA studies *(6),* this research only included energy consumption and total GHGs (measured in CO_2-e) as the environmental impact categories. This decision was made based on the scope of this study, which is to evaluate the potential contribution from pavement management decisions on global warming and broad interest in the fossil-energy dependence of on-road transportation systems (*4*). *Global warming potential* (GWP), expressed in terms of equivalent mass of carbon dioxide (CO_2-e), is the most common indicator used for global warming. This indicator is a midpoint indicator (as opposed to endpoint indicator, such as damage to the economy due to sea level rise or damage to ecosystems), and its use is supported by various scientific studies *(31).* Although energy consumption in this study is closely tied to GHG emissions through the burning of fossil fuel, there are some situations where GHG emissions are not generated from burning fossil fuel, such as the generation of electrical energy by means other than burning of fossil fuel, the pyroprocess in cement production, and methane (CH_4) emissions that occur during construction equipment usage.

In LCA, energy consumption is typically reported as *primary energy*, in the unit megajoule (MJ). Primary energy includes the full life-cycle energy, meaning the energy required to process and to deliver an energy carrier, as well as use of that energy carrier (such as producing and delivering gasoline and then burning it). Energy consumption includes the consumption of energy resources such as fuels and other energy carriers (such as electricity), but also the energy that is available in the product itself if it were to be used as a fuel source. This latter energy is referred to as *feedstock energy*. Feedstock energy is a characteristic of material, its chemical energy, and can be characterized by its heating value.

The reporting of feedstock energy for asphalt was the subject of a session at the 2010 Pavement LCA Workshop in Davis, California *(32).* Participants in the session agreed to report feedstock energy to maintain compliance with ISO standards, but to do so separately from other primary energy in recognition of the fact that the feedstock energy in asphalt would likely never be used as an energy resource, unless it was diverted at the refinery into the production of products other than asphalt, in which case it would not be used in the pavement. Ventura and Santero reviewed the current concept of feedstock energy and also proposed a framework for accounting for energy flow with a similar concept *(33).* The project-level study that preceded this network study adopted the recommended practice and lists the feedstock energy separately. In this network-level analysis, the feedstock energy is not reported; however the values per ton of asphalt mix can be found in the previous project-level report *(14)*.

Global warming is caused by an increase in radiative forcing caused by GHGs in the atmosphere. GHGs absorb thermal (infrared) radiation, thus disturbing the balance between the energy absorbed by and radiated from the earth *(34).* GHGs may be short-lived (such as CO and NO_x) or long-lived (such as CO_2, CH_4, N_2O, and SF_6) in the atmosphere. The primary GHGs of concern in most LCA studies are CO_2, CH_4, and N_2O, although many other GHGs exist. The GHGs assessed in this study only include CO_2, CH_4, and N_2O. By using GWP, which was developed by the Intergovernmental Panel on Climate Change (IPCC), each type of GHG can be converted to CO_2-equivalents (CO_2-e) based on its contribution to the radiative forcing compared with CO_2. This study adopted 100-year GWPs for CO_2, CH_4, and N_2O (1, 25, and 298, respectively) as reported by the IPCC in 2007 *(34)*. In the Use Phase of this study, where vehicle tailpipe emissions due to the pavement-induced rolling resistance are addressed, vehicle-emissions modeling results showed that CH_4 and N_2O accounted for less than 0.2 percent of the total GHG of the vehicle tailpipe emissions. Therefore, only CO_2 emissions were accounted for when modeling vehicle tailpipe GHG emissions in order to reduce the computational intensity, whereas CO_2, CH_4, and N_2O were all accounted for in the form of CO_2-e in all other situations. The well-to-pump (WTP) GHG emissions of fuels are always accounted for when there is fuel consumption, using the factors derived from the GREET model from Argonne National Laboratory *(35).*

4.3 Pavement M&R Treatment Options

This study focused on two Caltrans Capital Preventive Maintenance (CAPM) treatments as examples of Caltrans pavement preservation treatments (treating the pavement before it reaches an advanced state of deterioration) and a limited number of concrete lane replacements. Because the corresponding life-cycle inventories for major rehabilitation and reconstruction had not been developed as of the time of this study, only CAPM treatments with limited concrete lane replacements were considered. A more complete analysis should include major rehabilitation treatments using an approach similar to the one taken in this report.

As discussed in Section 2.2, this study adopted a ten-year analysis period, from the year 2012 to the year 2021, which covers the longest design life of the CAPM treatments used in this study. This is based on the assumption that the treatments will be repeated beyond the analysis period (except the concrete lane replacement). A sensitivity analysis regarding the analysis period length was performed at the end of this study to evaluate its impact (shown in Section 5.4.2). It was found that the analysis period did not substantially affect the result with regard to the scope of this study (i.e., IRI trigger values optimized for GHG reduction).

This study also assumed that pavement surface type stayed the same during CAPM treatments, because the current model cannot fully address the impact from pavement structure on rolling resistance and fuel consumption in the pavement Use Phase, as discussed in the previous project-level study report *(14)*. Therefore an asphalt overlay was only performed on asphalt pavement, and grinding and concrete slab replacement was only performed on concrete pavement. This study also assumed that all construction activities were performed during nine-hour nighttime work zone traffic closures so there was minimal impact from traffic delay.

The CAPM treatments adopted in this study roughly followed the Caltrans CAPM manual *(11)* and the treatment decision tree in PaveM (excluding major rehabilitation or reconstruction) *(21)*. In the asphalt CAPM treatment, a 75 mm asphalt overlay using conventional HMA (with 15 percent RAP) was placed on an asphalt pavement segment after 45 mm milling of the existing asphalt layer when its IRI reached the designated trigger value (this study only considered IRI as the trigger for overlay treatment on asphalt pavement and did not consider cracking).

RHMA was not included in the network analysis because this study focused on how segments with different traffic levels should be triggered by different IRI values. Therefore, to simplify the process, only conventional HMA was used. The difference in the material production and construction effects of RHMA and HMA in medium overlays can be seen in the earlier project-level study report *(14)*. The 75 mm (0.25 ft.) thickness was determined from the Caltrans CAPM guideline *(11)*. In PaveM, this thickness is categorized as a Medium Overlay treatment (between 0.1 ft. and 0.25 ft.). PaveM also includes Thick Overlay and Thin Overlay treatments in the decision tree. Thick overlay was not included in this study because it was considered as a major rehabilitation treatment and its LCIs had not been developed as of the time of the study. As for Thin Overlay treatment, because its deterioration rate is faster than that of Medium Overlay it can be expected to have more frequent construction events, and therefore lower total energy savings and GHG reductions. PaveM also requires that if the overlay trigger value of one lane is reached, then all the lanes in that segment in the same direction must also receive the overlay treatment. This is because the design must maintain the same grade elevation across all lanes, which was assumed to occur in this study.

In concrete CAPM treatment, diamond-grinding was performed on a concrete pavement segment when its IRI reached the trigger value. The concrete CAPM treatment also included a slab replacement using Type III cement for those slabs showing third-stage cracking. This was also determined from the Caltrans CAPM guideline *(11)*. The reason for not including calcium sulfoaluminate (CSA) cement was the same as for RHMA. The approximate difference between Type III portland cement and CSA can be seen in the previous project-level study report *(14)*. In concrete treatment, as with asphalt treatment, it is also required that if one lane triggers grinding and slab replacement treatment, then all the lanes in the same direction must receive grinding and slab replacement treatment to maintain the same grade elevation across all lanes. In this study, this was assumed to occur.

In PaveM, when the percentage of slabs of a concrete segment with third-stage cracking reaches 10 percent, a CSOL or a concrete lane replacement treatment is performed. However, (1) because CSOL introduces a change of pavement type and (2) because the life-cycle inventory of the Material Production and Construction phases of CSOL were unavailable at the time of this study, the study assumed that concrete lane replacement was performed on that segment. The new structure consists of 0.75 ft. (225 mm) jointed plain concrete slabs using dowel bars and Type I/II cement with 25 percent fly ash, and keeps the same base. The concrete lane replacement usually requires continuous traffic closure and thus may create traffic delays in the construction work zone. The impacts from construction work zone traffic for lane replacement was ignored for this study because of the small number of lane replacements triggered and the difficulty of estimating a generic scenario for traffic delay for continuous closures.

4.4 Pavement Performance Models

To assess the GHG emissions and energy consumption in the analysis period, it was necessary to evaluate IRI and macrotexture performance with and without pavement treatment activities. Different sources were used to acquire the pavement performance models for IRI and macrotexture.

4.4.1 IRI

Asphalt Pavement

The IRI progression model for medium thickness asphalt overlays was from the study by Tseng at UCPRC *(36)*. This model used ESALs, the IRI value before overlay, overlay type, and climate region as inputs. Equation 4.1 and Equation 4.2 show the models for initial IRI after the construction and IRI progression, respectively. Figure 4.2 shows the coefficients in the model. In the model represented by Equation 4.1, the standard deviation of the residual for the Medium Overlay case, 38 inches/mile (0.6 m/km), was used later in the sensitivity analysis to develop different scenarios for constructed smoothness. Figure 4.2 shows some examples of IRI progression under different *PreviousIRI* values after medium overlay, the overlay type assumed for this study in CAPM.

$$InitialIRI = a \times PreviousIRI + b \qquad \textbf{(4.1)}$$

$$IRI_t = InitialIRI + c \times Age^d \qquad \textbf{(4.2)}$$

Where:

InitialIRI	is the IRI immediately after construction of the overlay in units of inches/mile;
PreviousIRI	is the IRI value before the overlay in units of inches/mile;
a and b	are the coefficients in the overlay progression model, different for each type of overlay defined in PaveM; For Medium Overlay considered in this study, *a* is 0.40 (no unit) and *b* is 42.23 inches/mile;
IRI_t	is the IRI value at Age t year in units of inches/mile;
Age	is the age of the pavement section after last treatment in units of years; and
c and *d*	are the coefficients in the progression model, different for each type of treatment, ESAL level (as defined by the model) and climate region group, as shown in Table 4.1.

Table 4.1: Coefficients of IRI Model for Asphalt Overlay

Overlay Type[1]	ESAL Level[2]	Climate Region Group[3]	*a*	*b*	*c*	*d*
Medium overlay (0.1~0.25 ft.)	A	Severe	0.40	42.23	6.175	1.44
		Mild			5.89	1.35
	B	Severe			6.5	1.44
		Mild			6.2	1.35
	C	Severe			6.825	1.44
		Mild			6.51	1.35

Notes:

[1]: Other overlay thicknesses are defined in the PaveM system. This study only considered a CAPM strategy where a 75 mm (0.25 ft.) overlay, which falls into the category of Medium Overlay, was used.

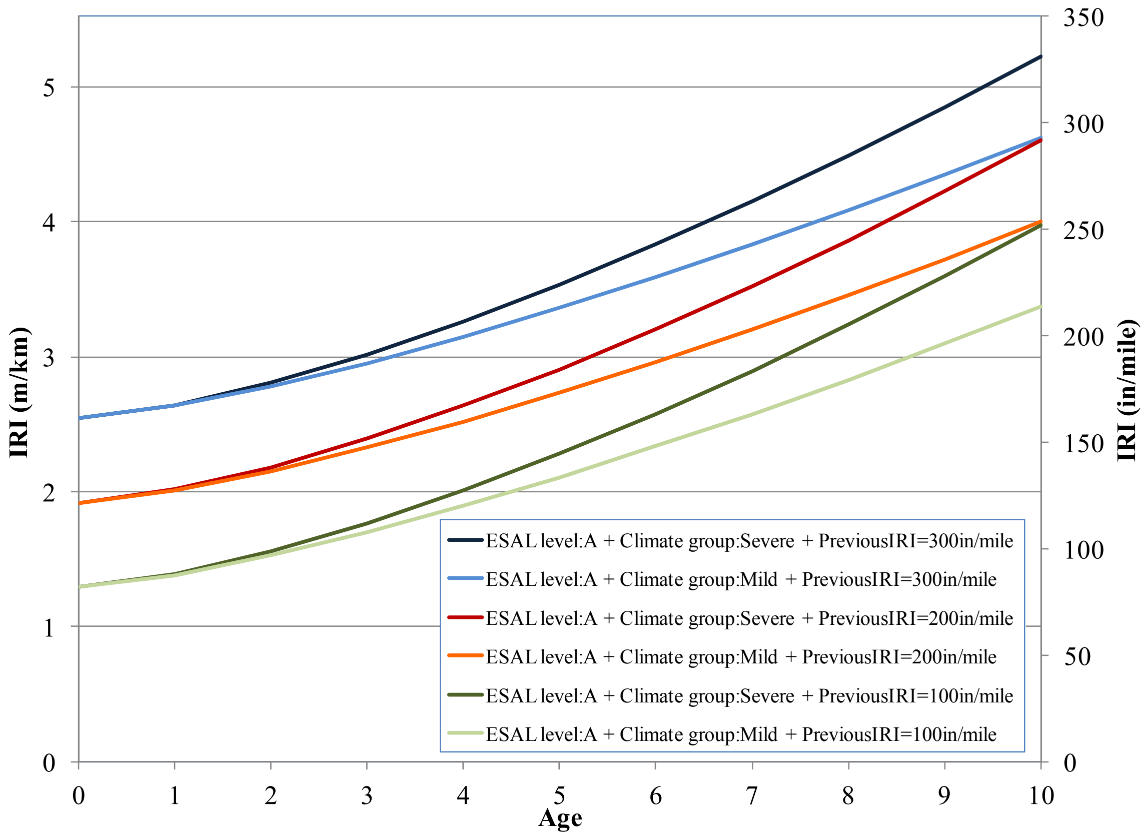
[2]: Annual ESAL level is defined in accordance with PaveM:

A: Annual ESAL ≤ 100,000;
B: 100,000 < Annual ESAL ≤ 500,000; and
C: Annual ESAL > 500,000

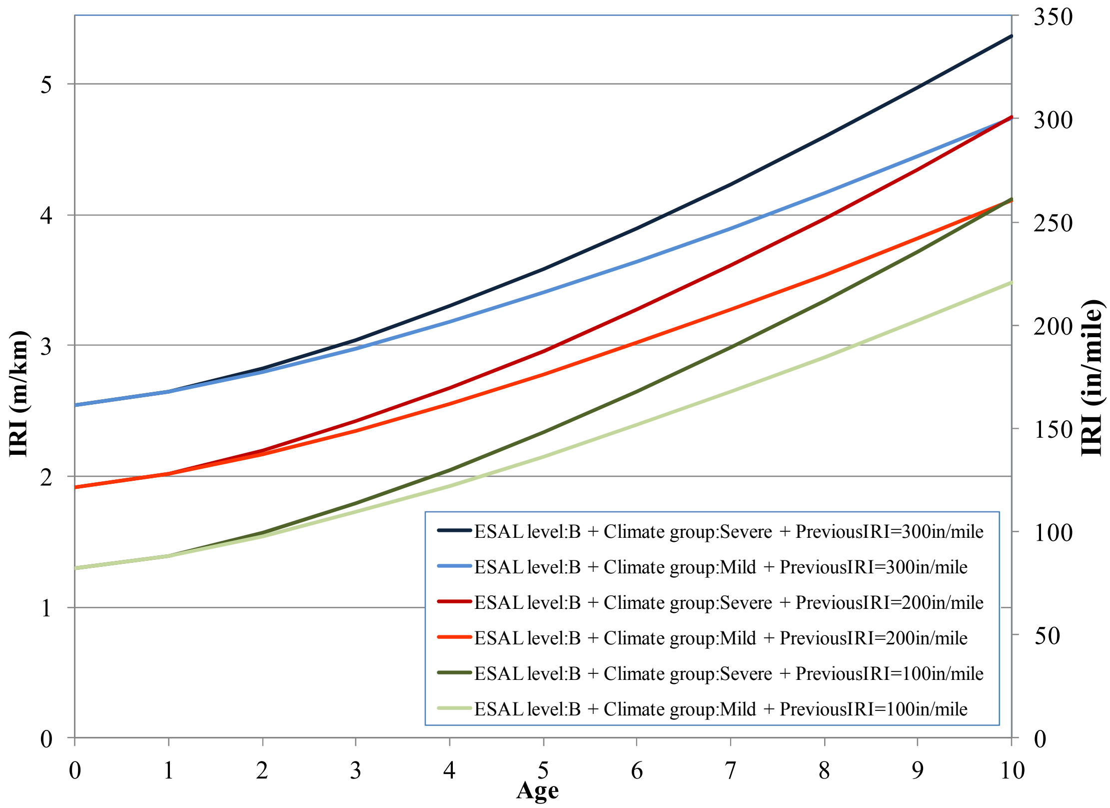
[3]: Climate region groups are defined as:

- Severe climate: Central Coast, Desert, Inland Valley, South Mountain
- Mild climate: High Desert, High Mountain, Low Mountain, North Coast, South Coast

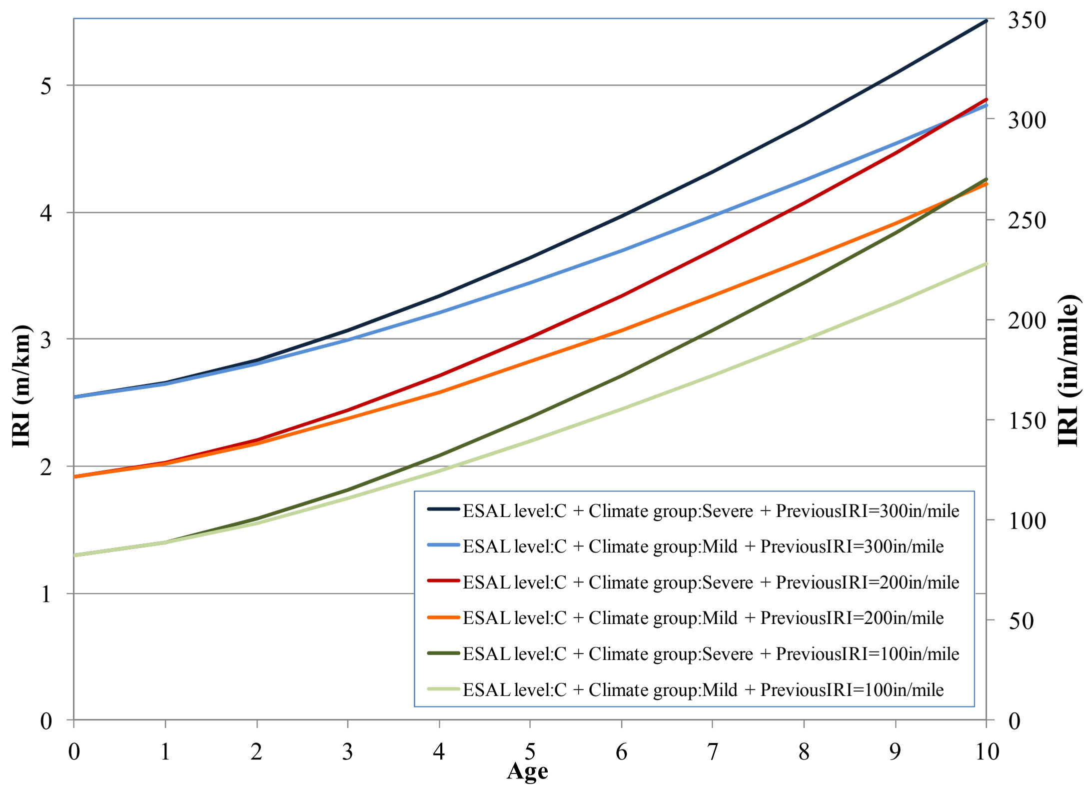
The climate regions are defined by Caltrans to show the impact of temperature, precipitation, freezing/thawing, and solar radiation on pavement *(25)*. The grouping was defined by Tseng based on the performance models for each region *(36)*, and the coefficients may reflect regional differences in addition to climate such as materials sources, underlying pavement structures, and construction quality. They will likely be revised or climate region will be eliminated as a performance model variable in the figure.



(a) a=0.40; b=42.23; c=6.175(Severe) or 5.89(Mild); d=1.44(Severe) or 1.35(Mild)



(b) a=0.40; b=42.23; c=6.5 (Severe) or 6.2 (Mild); d=1.44 (Severe) or 1.35 (Mild)



(c) a=0.40; b=42.23; c=6.825 (Severe) or 6.51 (Mild); d=1.44 (Severe) or 1.35 (Mild)

Figure 4.2: IRI progression under different *PreviousIRI* values after Medium Overlay.

For asphalt-surfaced pavement, IRI under the *Do Nothing* scenario, where no M&R treatment was performed and only a minimal level of maintenance work was carried out every year, was evaluated by first backcalculating the age of the existing pavement using Equation 4.2, and then continuing the IRI progression from that age, with an asymptote of 285 inches/mile (4.5 m/km).

When backcalculating age using Equation 4.2, the average of the thicknesses of all the overlay projects in California from 2002 to 2007 (weighted by the lane-miles of each project) were used to determine the assumed overlay type[1] *(37)* because it was impossible to collect the information about the overlay type of the existing asphalt layer and the initial IRI of existing pavement. The result, 0.162 ft. (49.4 mm), fell in the category Medium Overlay. The average IRI after Medium Overlay from Tseng's study, 108 inches/mile (1.7 m/km), was used as the initial IRI value for the existing pavement[2]. The 285 inches/mile (4.5 m/km) asymptote was set to keep the road in a usable condition under the *Do Nothing* scenario. Figure 4.3 shows the IRI progression of Medium Overlay under the *Do Nothing* scenario.

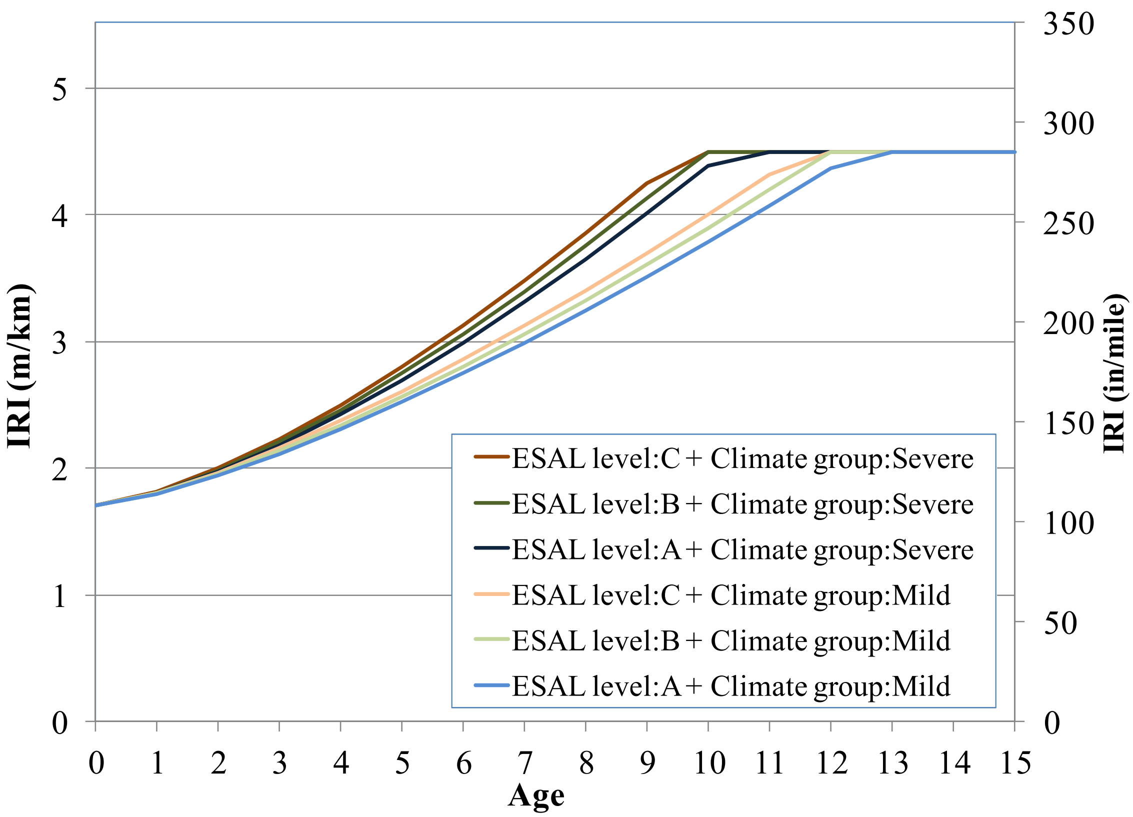


Figure 4.3: IRI progression of Medium Overlay under the *Do Nothing* scenario.

[1] All chip seal projects were assumed to have a thickness of 0.1 ft.; all CAPM projects were assumed to have a thickness of 0.2 ft.; all rehabilitation projects were assumed to have a thickness of 0.4 ft.
[2] If the current IRI of an existing pavement was smaller than this value, then backcalculation was not used to determine the age. Instead an annual increase of 3.17 inches/mile (0.05 m/km) was used, regardless of ESAL level and climate region.

Concrete Pavement

The IRI progression of concrete-surfaced pavement after grinding and slab replacement treatment was developed based on the data collected on Caltrans grinding projects *(38)* and the Caltrans PCS database, using the cumulative ESALs and IRI after the grinding as explanatory variables. The model of IRI progression for concrete pavement used in the case studies is shown in Equation 4.3.

$$\sqrt{IRI} = -1.74 \times 10^{-1} + 9.66 \times 10^{-5} \times \sqrt{CumulativeESAL} + 1.15 \times \sqrt{InitialIRI} \quad \textbf{(4.3)}$$

Where *CumulativeESAL* is the cumulative ESALs that a lane has received after a grinding project, *InitialIRI* is the IRI value right after the grinding project in units of m/km, and *IRI* is the IRI value to be estimated in the unit m/km. The statistical results of this regression are shown as follows.

	Value	Standard error	t value	P-value
(Intercept)	-1.74e-01	4.643e-02	-3.748	0.000272
Sqrt(*CumulativeESAL*)	9.657e-05	1.439e-05	6.711	6.17e-010
Sqrt(*InitialIRI*)	1.149e+00	3.515e-02	32.674	<2e-16

Residual standard error: 0.06811 on 124 degrees of freedom; Multiple R-Squared: 0.9022.

The same dataset also yielded a model for the initial IRI after grinding. It was also a linear regression model and is shown in Equation 4.4, where *IntialIRI* is the IRI right after the grinding in units of m/km, and *PreviousIRI* is the IRI value before the diamond grinding in the unit m/km.

$$InitialIRI = 0.6839 + 0.3803 \times PreviousIRI \quad \textbf{(4.4)}$$

In this model, the standard deviation of the residual is 0.285 m/km, which was used in the sensitivity analysis to develop different scenarios for constructed smoothness. The statistical results of this regression are shown as follows. Figure 4.4 shows the example of IRI progression under different *PreviousIRI* values after grinding.

	Value	Standard error	t value	P-value
(Intercept)	0.6839	0.1677	-4.078	0.000249
PreviousIRI	0.3803	0.0751	8.252	1.00e-09

Residual standard error: 0.2886 on 35 degrees of freedom; Multiple R-Squared: 0.4064.

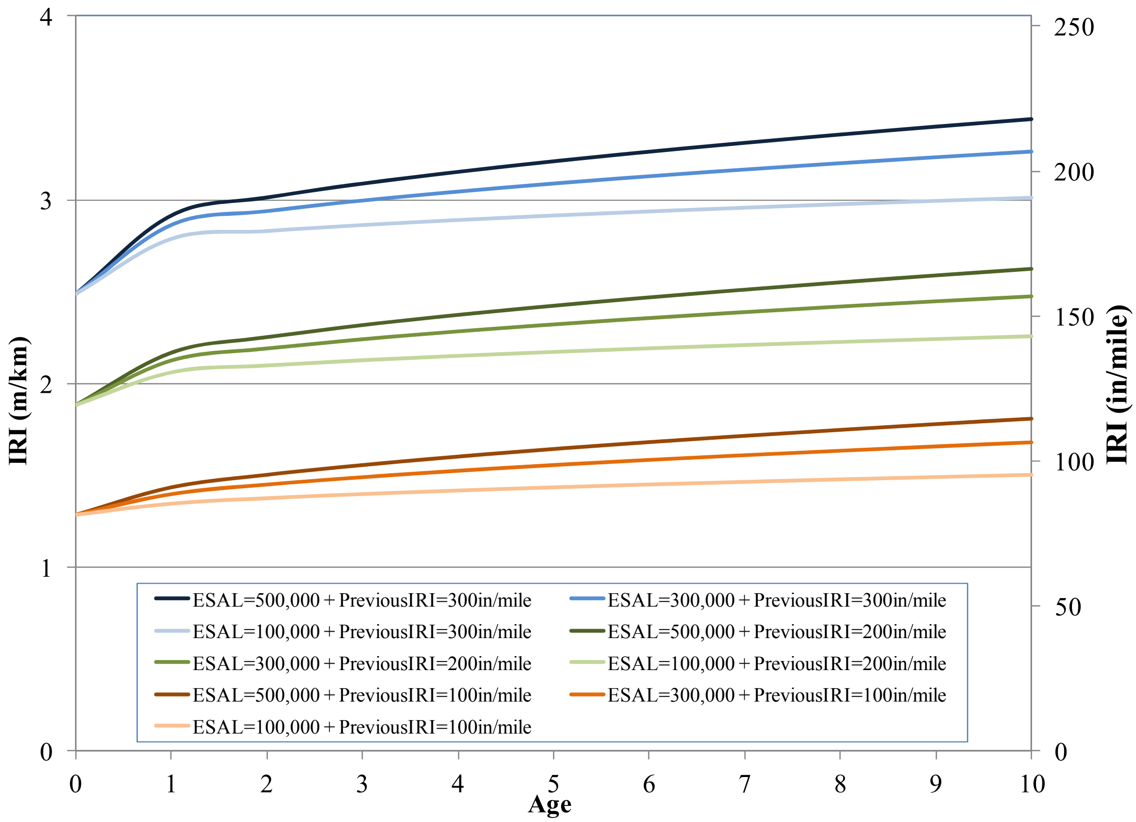


Figure 4.4: IRI progression under different *PreviousIRI* and annual ESALs after grinding.

For concrete-surfaced pavement, because the backcalculation of age required the IRI value immediately after the grinding, and the existing concrete pavement surface might have previously had a lane replacement instead of a grinding and slab replacement, this study could not locate sufficient data to perform the backcalculation of the age for the existing pavement. Therefore during the *Do Nothing* scenario, IRI was assumed to increase at a rate of 3 inches/mile (0.05 m/km) per year with an asymptote of 285 inches/mile (4.5 m/km).

4.4.2 Macrotexture

The progression of MPD over time for asphalt surfaces was taken from a previous study performed by the UCPRC *(39)*. The model of MPD progression for an HMA overlay is shown in Equation 4.5.

$$\begin{aligned} MPD(micron) = & -93.7089 - 4.2910 \times AirVoid(\%) + 47.8933 \times Age(year) \\ & + 28.2136 \times FinenessModulus - 9.9487 \times NMAS(mm) \\ & - 5.4209 \times Thickness(mm) - 0.7087 \times NumberOfDays > 30C \\ & - 0.0402 \times AADTTinLane \end{aligned} \quad \textbf{(4.5)}$$

Where *NMAS* is the nominal maximum aggregate size, and other variables are indicated by their names.

When used in the analysis, a 4 percent air void ratio, a fineness modulus of 5, a 12.5 mm nominal maximum aggregate size, and 100 days over 30°C were assumed for all HMA overlays, which were reasonable values from the UCPRC study *(39)*. The actual pavement age and AADTT (annual average daily truck traffic) of each management segment were used. Given that macrotexture only accounts for about 15 percent in the GHG benefit for asphalt pavement *(39)*, the values selected for these variables were considered reasonable.

The progression of macrotexture of concrete pavement was from a study by Rao et al. *(40),* shown in Equation 4.6. Mean texture depth (MTD) does a better job of accounting for directional texture that has been cut into the surface of the concrete, such as longitudinal tining or grooving used in California, than does MPD. MTD was then converted to MPD using Eq. 4.7 based on the *HDM-4* document.

$$MTD = -0.152 \times \left(1 + 0.233 \times Freeze\right) \times Ln\left(Age\right) + 0.887 \qquad \textbf{(4.6)}$$

$$MTD = 1.02 \times MPD + 0.28 \qquad \textbf{(4.7)}$$

Where:

MTD is the mean texture depth from sand-patch method in units of mm;
MPD is the mean profile depth from profiling method in units of mm;
Age is the age since grinding in years (0.5 to 16 years); and
Freeze is the dummy variable for freezing in a climate region: 0 is for wet non-freeze or dry non-freeze; and 1 is for wet freeze or dry freeze. In this study, the Caltrans climate regions North Coast, Low Mountain, High Desert, and High Mountain were considered freeze regions, and other regions were considered non-freeze regions.

For asphalt-surfaced pavement, the MPD under the *Do Nothing* scenario was assumed to increase at 0.05 mm per year. This value is consistent with the MPD model shown in Equation 4.5. For concrete-surfaced pavement, the macrotexture under the *Do Nothing* scenario was assumed to stay at the tenth year value shown by Equation 4.6.

4.5 Material Production and Construction Phase LCI and Cost

As discussed in Section 2.2, this study evaluated life-cycle energy consumption and GHG emissions from CAPM treatments performed on the network, and considered these life-cycle phases: the Material Production Phase, Construction Phase, and Use Phase. This section discusses the development of the life-cycle inventories for the Material Production and Construction phases.

Development of these LCIs was based on the case studies performed for all of the permutations of the variables shown in Table 2.2. When applying these principles to the network, the LCIs for these two phases of each pavement section were calculated on a prorated basis based on the size of each construction event, which was based on the dimensions of the segment. The network analysis only considered conventional HMA (with

15 percent RAP, for asphalt overlay), Type III cement (for slab replacement), and Type I/II cement (25 percent fly ash, for concrete lane replacement). Calculation of the cost-effectiveness of CAPM with respect to GHG on each set of directional segments used the estimated "unit cost" of each treatment included in PaveM *(21)*. The fuel price for the saved energy consumption was acquired from the U.S. Department of Energy's Annual Energy Outlook 2013 *(41)*.

Development of the LCI for asphalt pavement included the Material Production and Construction phases and were calculated from the flows for a normalized unit of one cubic meter of asphalt overlay material. Development of the LCI for concrete pavement included the Material Production and Construction phases and were calculated from the flows for a normalized unit of one cubic meter of concrete for the concrete slabs that were replaced and one square meter of concrete grinding. These results were considered as a "unit LCI" for each treatment. In the network-level analysis, these unit LCIs and unit costs were multiplied by the actual number of units in each segment to calculate the total material production and construction LCI and costs whenever a construction was performed. Table 4.2 and Table 4.3 show the unit LCI and unit costs for the Material Production and Construction phases of each treatment, respectively. It should be noted that these "unit LCIs" are intended to facilitate the calculation process and do not represent the actual functional units of this study.

In this study, a discount rate was used to reflect the time-value of money in the cost calculation. Theoretically, the discount rate would reflect how much future benefits would be reduced to their current value without having to consider inflation. Caltrans currently uses a discount rate of 4 percent in all life-cycle cost analysis (LCCA) practices for pavement structures *(42)*. Therefore, this study adopted a 4 percent discount rate in accordance with Caltrans practice. This study also included the salvage value for the agency cost when the next CAPM event was triggered beyond the ten-year analysis period, using linear depreciation.

Table 4.2: Unit LCI for Material Production and Construction of Each CAPM Treatment

Treatment	Unit	Energy consumption (10^6 MJ)	GHG emissions (10^3 metric ton CO_2-e)
Asphalt overlay using conventional HMA[1]	Per cubic meter asphalt mix placed	0.0031	0.000236
Slab replacement using Type III cement	Per cubic meter concrete mix placed	0.00477	0.000561
Grinding	Per square meter ground concrete	0.00162	0.000116
Concrete lane replacement using Type I/II cement with 25% fly ash	Per cubic meter concrete mix placed	0.00459	0.000486

Note:
[1]: The energy consumption and GHG from the milling process is embedded in the number shown here, based on the 75 mm overlay with 40 mm milling.

Table 4.3: Unit Cost for Each CAPM Treatment *(21)*

Treatment	Unit	Agency Cost ($)
Medium asphalt overlay	Per lane-mile	200,000
Slab replacement	Per lane-mile	1,700,000
Grinding	Per lane-mile	50,000
Concrete lane replacement	Per lane-mile	1,000,000

Because the analysis period was set to ten years, the segments where CAPM activities were performed very close to the end of the analysis period could be "penalized" unless the residual life beyond the end of analysis period was accounted for. This is because the emissions associated with the material production and construction of the CAPM activities cannot be fully paid back through the GHG reduction from vehicles on the smooth pavement after the CAPM treatments. In other words, the benefits from the construction activity would not be fully "utilized" because the analysis period is shorter than the treatment's service life.

This problem and the determination of appropriate analysis periods were subjects addressed at the 2010 Pavement LCA Workshop *(15)*. Participants in the session addressing these issues failed to reach an agreement on the specific rule for selecting the analysis period. However, the idea was generally accepted that the emissions associated with the M&R activities could be annualized/amortized *(32)*. Therefore, this study annualized the GHG and energy consumption of the last CAPM treatment performed based on the treatment's service life, and only included the parts of annualized emissions that fell within the analysis period.

In this study, the *service life* of a CAPM treatment refers to the time period between the construction of the CAPM treatment until the time that the next one is constructed based on the designated IRI trigger value[1]. Figure 4.5 demonstrates this process. In the case shown in the figure, the service life of each CAPM activity is three years and the last CAPM activity happens in Year 9. The next theoretical CAPM trigger should happen in Year 12, which is beyond the analysis period. Therefore, the GHG and energy consumption from the last CAPM event has been annualized by its service life (three years), and the emissions in Year 1 are included in this case because only the first year in its service life is within the analysis period.

[1] This study assumed there is no delay between the time that IRI reaches the trigger value and the time of the actual CAPM construction. A sensitivity analysis was later performed to estimate the effect of a delay if there is one.

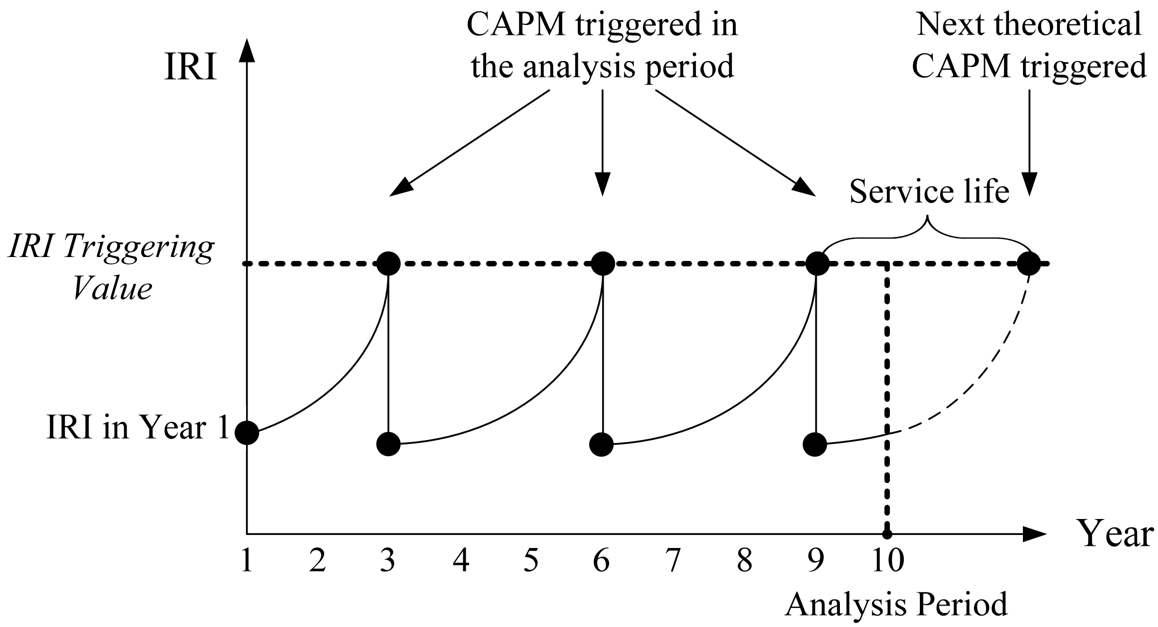


Figure 4.5: Demonstration of counting the last CAPM activity in the analysis period.

4.6 Use Phase Vehicle Emission Factors Based on Factorial Variables

As discussed in Section 2.2, each combination of factorial variables needs to be assessed to evaluate the impact of roughness on energy consumption and GHG emission in the Use Phase (using the tailpipe CO_2 emissions). However, due to the heterogeneity of the pavement network, different segments have different vehicle compositions, different IRI and MPD values, and different progression scenarios because they all have different traffic levels and climate regions. Modeling each segment individually using *MOVES* can be very time consuming.

Because the AADT and fleet compositions were readily available in the pavement management system (PMS) database, the vehicle energy consumption factor and tailpipe CO_2 emissions factor for each type of vehicle as a function of IRI and MPD under each combination of other factorial variables were developed using *MOVES* before the assessment was performed on the entire pavement network. The vehicle energy consumption factor and tailpipe CO_2 emissions factors are presented in terms of total energy consumption and tailpipe CO_2 emissions per 1,000 miles VMT for each type of vehicle. These values were then stored in a look-up table and used for every segment in the network, eliminating the need to run *MOVES* for each segment.

One sensitivity analysis was performed regarding the effect of congested traffic on flat, urban restricted-access roads and another sensitivity analysis was performed regarding the effect of different road gradients on mountainous roads, to determine if these two considerations had substantial impacts on the relationship between pavement roughness and energy consumption or tailpipe CO_2 emissions.

This section first discusses the preparation of the data required for running *MOVES* to calculate the vehicle emission factors, then discusses the sensitivity analyses, and finally develops the vehicle energy consumption and tailpipe CO_2 emission factors for each combination of the factorial variables.

4.6.1 Acquiring Data to Run Vehicle Emissions Model MOVES

There are two levels of modeling process in *MOVES*, a county level and a project level. In county level modeling, the time scale of a modeling scenario can be as long as a year, but the model assumes that the road is flat (zero grade) and therefore county-level calculations cannot address mountainous areas. In project-level modeling, the modeling resolution is more detailed (for example it can include roadway gradient or individual vehicle driving schedule) but at this level the model can only run on an hourly basis. This study used both modeling processes: the county-level modeling to address flat areas because it can provide a much faster modeling process and requires less computational intensity, and the project-level modeling to address mountainous areas because only this level can include the roadway gradient.

The following sections detail the procedures followed to develop the required inputs for *MOVES,* including the process of converting the traffic flow from *CalTruck* classifications to *MOVES* classifications because this process applies to both levels of modeling in *MOVES*.

Mapping Vehicle Classification

The traffic data that was mapped to the management segments in the network (as discussed in Section 3.2.4) was from the Caltrans traffic volume report and truck traffic report, and is referred to in this report as *CalTruck data.* However, *CalTruck* has different vehicle classifications than *MOVES* so a conversion procedure was needed to convert *CalTruck* data to *MOVES* data.

This procedure was similar to the project-level model described in the previous study report: a two-step mapping process was used to avoid severe data loss. First, the *CalTruck* data were converted to another vehicle classification method used by Caltrans (referred to as "*Caltrans* classification"), which includes thirteen vehicle types. Then, this thirteen-type classification was converted to the *MOVES* classifications.

The first step adapted the data collected from Caltrans 114 Weigh-in-Motion (WIM) stations on the California State Highway Network. At each WIM station, the number of vehicles was collected in both the *CalTruck* classification and the *Caltrans* classification. This step created a conversion matrix from the *CalTruck* classifications to the *Caltrans* classifications.

In the second step, the conversion matrix was based on engineering experience and state-average data from the *EMFAC* database, the California emissions inventory for on-road traffic. In this way, the equivalent traffic flow in the *MOVES* classification was developed for any flow in the *CalTruck* classification. Because *CalTruck* only provides the average daily traffic, this study assumed that the daily traffic amount is constant throughout the year.

Average Speed Distribution

State Average

Average speed distribution is the time fraction that the traffic has spent in each speed category[1], each hour of a day, and the type of day (weekday or weekend). This is an input required in flat-area modeling in *MOVES*. Because this is the data that characterizes traffic in terms of average-speed flow and low-speed flow, or in other words, an average traffic flow and congested traffic flow (as discussed in Section 2.3), this factor was used in a sensitivity analysis for flat, urban restricted-access roads.

This study used PeMS data to generate the average speed distribution on urban and rural freeways because the PeMS database includes data for the major freeways (restricted-access roads) in California. PeMS hourly data for the entire year of 2011 were extracted.

The first step was to select all the main-lane PeMS locations (as opposed to ramp stations) from all the stations and then identify the road type. This was done based on the location of each PeMS station, the urban/rural roads, and restricted/unrestricted-access roads (the same data source as in Section 3.2.2). Table 4.4 shows the urban PeMS stations and rural PeMS stations in Google Earth™. Table 4.4 shows the number of each type of station. Because the number of urban unrestricted-access PeMS stations was too small and the data were not representative, these stations were not analyzed. The data extraction generated a table like Table 4.5.

Table 4.4: Number of Each Type of PeMS Station

Road Type and Road Access Type	Number
Urban restricted-access	7,597
Rural restricted-access	387
Urban unrestricted-access	67
Rural unrestricted-access	129

[1] The speed category was discussed in the previous project-level study.

Table 4.5: Sample Table of PeMS Station Data Showing Three Records

Timestamp	Station	District	Route	Direction	Type	Length	Flow	Speed	Road Type	Access Type
1/1/2011 0:00	311903	3	50	E	ML	0.987	891	73.7	Urban	Restricted
1/1/2011 0:00	311974	3	50	E	ML	0.471	3309	70.3	Rural	Restricted
1/1/2011 0:00	312010	3	50	W	ML	0.77	1926	75.2	Urban	Restricted

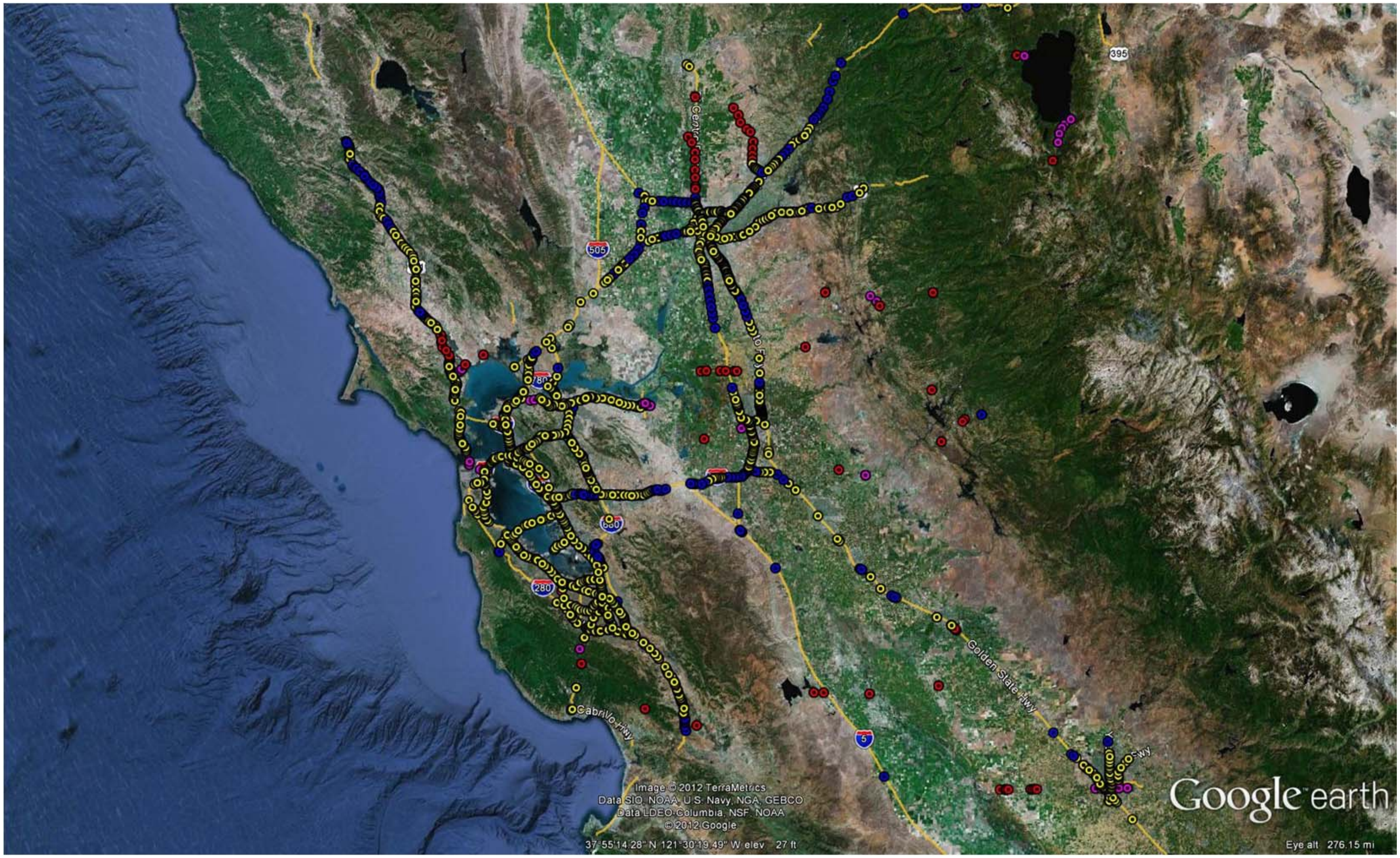
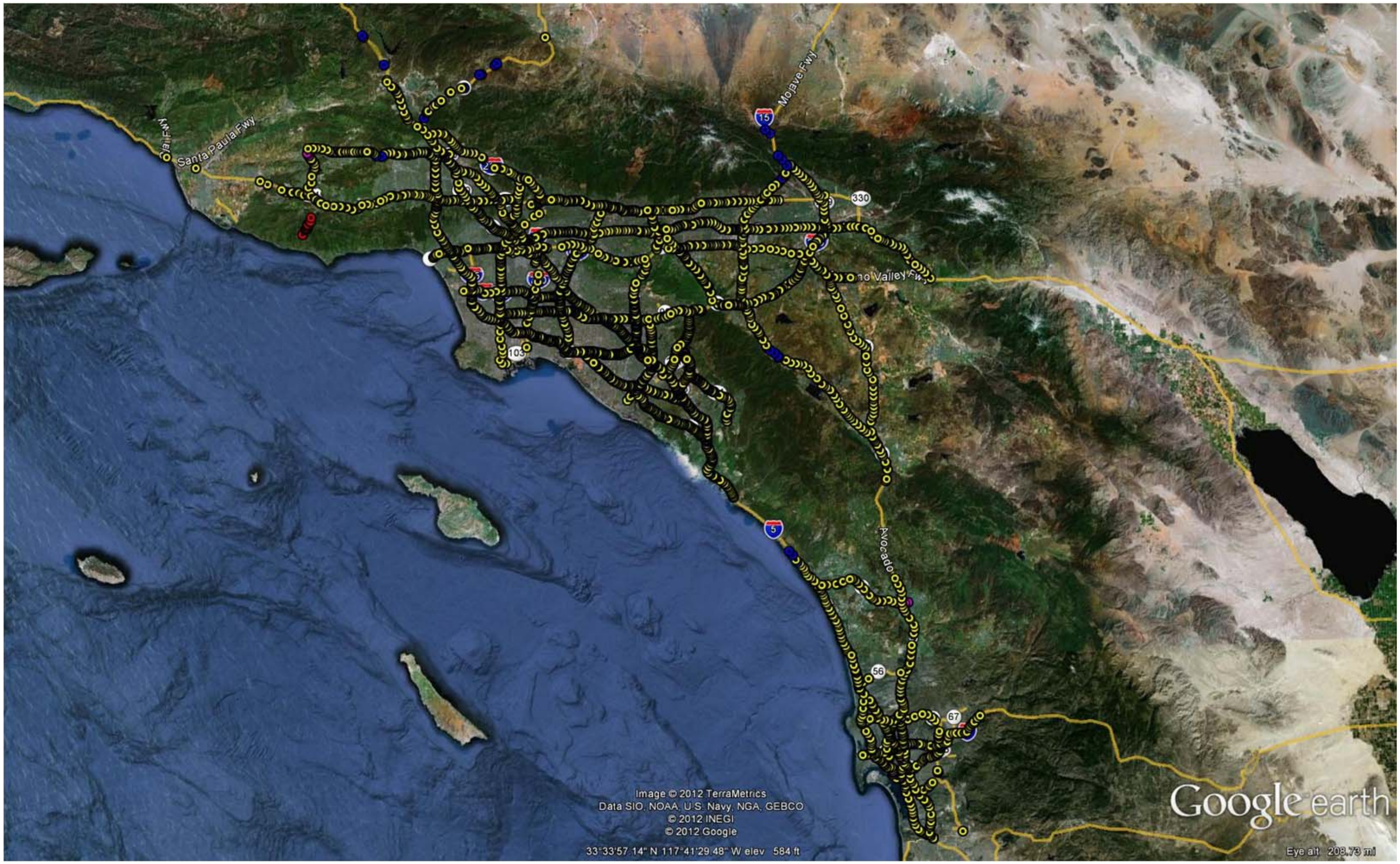


Image © 2012 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data LDEO-Columbia, NSF, NOAA
© 2012 Google
Google earth
Golden State Hwy
Cabrillo Hwy
Eye alt 276.15 mi

(a)



(b)

Figure 4.6: PeMS stations in (a) northern California and (b) southern California.
(Note: urban restricted-access stations are marked in yellow, urban unrestricted-access stations are marked in pink, rural restricted-access stations are in blue, and rural unrestricted-access stations are in red.)
(Images from Google Earth™)

The second step was to generate the total travel time in each speed category for each hour of the day and each type of day (weekday or weekend). This was done in the following substeps:

1. For each station, group the results from the data extraction by weekday/weekend, hour of the day, and average speed category. The result is shown in Table 4.6.

Table 4.6: Hourly Traffic Records Grouped by PeMS Station, Day Type, Hour of the Day, and Average Speed

Station	Day Type	Hour of the Day	Average Speed Category ID	Record in the Table Generated in Step 1
311901	Weekday	00:00-01:00	1	Record of Station 311901 at Timestamp 1/3/2011 0:00 (flow, speed, etc.)
				Record of Station 311901 at Timestamp 1/4/2011 0:00 (flow, speed, etc.)
				....
			2	Record of Station 311901 at Timestamp 1/5/2011 0:00 (flow, speed, etc.)
			...	...
		01:00-02:00	1	Record of Station 311901 at Timestamp 1/3/2011 0:00 (flow, speed, etc.)
		...	...	...
	Weekend	00:00-01:00	1	Record of Station 311901 at Timestamp 1/1/2011 0:00 (flow, speed, etc.)
		…	…	…

2. For each station, sum up all the travel time in each speed category, calculated using Equation 4.8 (this equation only shows "weekday" calculation, but the calculation for "weekend" is the same). If no record was found in a given speed category at a time of day, the total travel time was set to zero.

$$Total\ Travel\ time\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i = \sum Flow \times \frac{Length}{AvgSpeed} \quad \textbf{(4.8)}$$

3. Normalize the travel time in each speed category using Equation 4.9. This was done for each type of day (weekday or weekend) and each hour of the day combination. In other words, the sum of the time fractions should be 1 for the day type-hour of the day combination.

$$Time\ Fraction\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i$$

$$= \frac{Total\ Travel\ time\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i}{Total\ Travel\ time\ in\ Station\ k, Weekday, Hour\ \ j} \tag{4.9}$$

$$= \frac{Total\ Travel\ time\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i}{\sum_{i=1}^{n} Total\ Travel\ time\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i}$$

4. Repeat Step 1 to Step 3 for each station. The final result was a table like the one shown in Table 4.7. This result was the average speed distribution for each station, as shown in Figure 4.7

Table 4.7: Travel Time Fraction by PeMS Station, Day Type, Hour of the Day, and Average Speed

Station	Day Type	Hour of the Day	Average Speed Category ID	Travel Time Fraction
311901	Weekday	00:00-01:00	1	0
			2	0.000121
			...	...
		01:00-02:00	1	...
			...	...
		...	...	...
	Weekend	00:00-01:00	1	...
			...	...
		...	...	...
311902	Weekday	...	...	...
	Weekend	...	...	...
...	...	...	...	...

5. Average the results from last step for all the rural restricted-access road stations, rural unrestricted-access road stations, and urban restricted-access road stations, respectively. Because different stations have different traffic volumes, to calculate an overall result from all the stations the averaging process used the total travel time from all the vehicles of that station in that hour as the weighting factor. Equation 4.10 is the equation used to accomplish this.

$$Average\ Time\ Fraction\ in\ Weekday, Hour\ \ j, Speed\ Category\ i$$

$$= \frac{\sum_{k} \begin{bmatrix} Time\ Fraction\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i \\ \times Total\ Travel\ time\ in\ Station\ k, Weekday, Hour\ \ j \end{bmatrix}}{\sum_{k} Total\ Travel\ time\ in\ Station\ k, Weekday, Hour\ \ j} \tag{4.10}$$

6. The final result was the average speed distribution for urban restricted-access roads, rural restricted-access roads, and rural unrestricted-access roads, which appear in Table 4.8.

Table 4.8: Travel Time Fraction by Road Type, Road Access Type, Day Type, Hour of the Day, and Average Speed

Road Type and Road Access Type	Day Type	Hour	Average Speed Category ID	Travel Time Fraction
Urban restricted-access	Weekday	00:00-01:00	1	0
			2	0.000121
			3	0.000556
			...	...
		01:00-02:00	1	...
			...	...
		...	...	...
	Weekend	00:00-01:00	1	...
			...	...
		...	...	...
Rural restricted-access	....	...	...	...
...	...	...	...	...

A script based on MySQL was developed to perform all the procedures discussed above. This distribution was applied to all the vehicle types because PeMS does not differentiate between passenger cars and trucks. Because the WIM study showed little seasonal or monthly variations, this study assumed that the month is not an important factor for speed profiles, and therefore it was averaged in this process *(26)*.

As of the time of writing of this report, the data for flat, urban unrestricted-access road were unavailable and therefore the average speed distribution of flat, urban unrestricted-access roads in the *MOVES* default database was used.

Variance for Sensitivity Analysis

Because the average speed distribution was used in a sensitivity analysis for flat, urban restricted-access roads, the variance of this input across all the stations needed to be generated, in addition to the state-average result developed from last section. This study adopted the following method to assess the variance of the speed distribution across different stations, especially between congested areas and state-average conditions.

An average speed distribution was developed for each PeMS station based on the results from Step 4 in the previous section. However, because this distribution involved sixteen speed categories in each hour of the twenty-four hours in a day, it was difficult to directly calculate a variance among all the stations. A single number was needed to reflect the overall speed distribution, thus allowing comparison among different stations. The *average daily speed* based on the time spent in each average speed category was used as the index to reflect the overall speed. A higher average daily speed indicates that a higher portion of the total vehicle time is spent at high speed, and this segment is likely to have a high level of service (LOS) throughout the day. On the other hand, a lower result means a higher portion of low speed in that hour, indicating a higher possibility of forced flow and low LOS. The average daily speed allowed the selection of different traffic flows for the sensitivity analysis. The following steps show the procedure used to calculate the variance:

1. Based on the results such as those shown in Table 4.7 in the previous section, calculate the average daily speed using Equation 4.11. Repeat this for each station and each type of day (weekday and weekend). For this study, this generated the results shown in Table 4.9.

$$\mathit{Average\ Daily\ Speed\ in\ Station\ k, Weekday} = \frac{\sum_{i=1}^{16}\sum_{j=1}^{24}\left(\begin{array}{l}\mathit{Average\ Speed\ of\ \ Speed\ Category\ i}\\ \times \mathit{Total\ time\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i}\end{array}\right)}{\sum_{i=1}^{16}\sum_{j=1}^{24}\left(\mathit{Total\ time\ in\ Station\ k, Weekday, Hour\ \ j, Speed\ Category\ i}\right)} \quad \textbf{(4.11)}$$

Table 4.9: Average Daily Speed Grouped by PeMS Station, and Day Type

Station	Day type	Average Daily Speed
311901	Weekday	...
	Weekend	...
311902	Weekday	...
	Weekend	...
....		

2. For weekdays and weekends, calculate the standard deviation of average daily speed across all urban restricted-access stations and rural restricted-access stations[1], respectively. The results in this study for urban restricted-access roads were 6.92 mph on weekdays and 5.34 mph on weekends, while the results for rural restricted-access roads were 5.74 mph on weekdays and 5.29 mph on weekends.
3. Calculate the average daily speed based on the results such as those shown in Table 4.7 in the previous section. This generates the average daily speed for the state-average speed distribution. In

[1] The sensitivity analysis on traffic condition was not performed on rural restricted-access roads. However their data were still collected and calculated to show the difference between urban and rural roads.

this study, the results for urban restricted-access roads were 59.48 mph on weekdays and 65.91 mph on weekends, while the results for rural restricted-access roads were 61.87 mph on weekdays and 65.30 mph on weekends.

4. Based on the average daily speed from state-average data, subtract two standard deviations from the state-average daily speed to get the value at stations with low-speed traffic flow, representing the areas with frequent congested traffic. This was done for weekdays and weekends separately in this study.
5. Based on the result in Step 1 of this section, select the stations with daily speeds lower than the state-average daily speed minus two standard deviations. Then repeat Substeps 5 and 6 shown on pages 52 and 53 to calculate the average speed distribution for low-speed flow stations. This was done for weekdays and weekends separately in this study. This input was used to simulate the scenario where there is a large portion of low-speed traffic flow throughout the day in the sensitivity analysis. This average speed distribution was referred to as "low-speed" in this report, representing an area with frequent congested traffic.

Figure 4.7 to Figure 4.12 show the average speed distribution of each scenario at 7:00~8:00 a.m. (morning peak hour), 11:00 a.m. to 12:00 p.m. (nonpeak hour), and 5:00~6:00 p.m. (afternoon peak hour) on weekdays and weekends. It is clear that in the congested areas, vehicles spend more time at lower speeds compared to the average conditions on weekdays, while on weekends vehicles in all areas tend to travel at higher speeds than on weekdays. Rural areas show higher speeds compared to the urban areas.

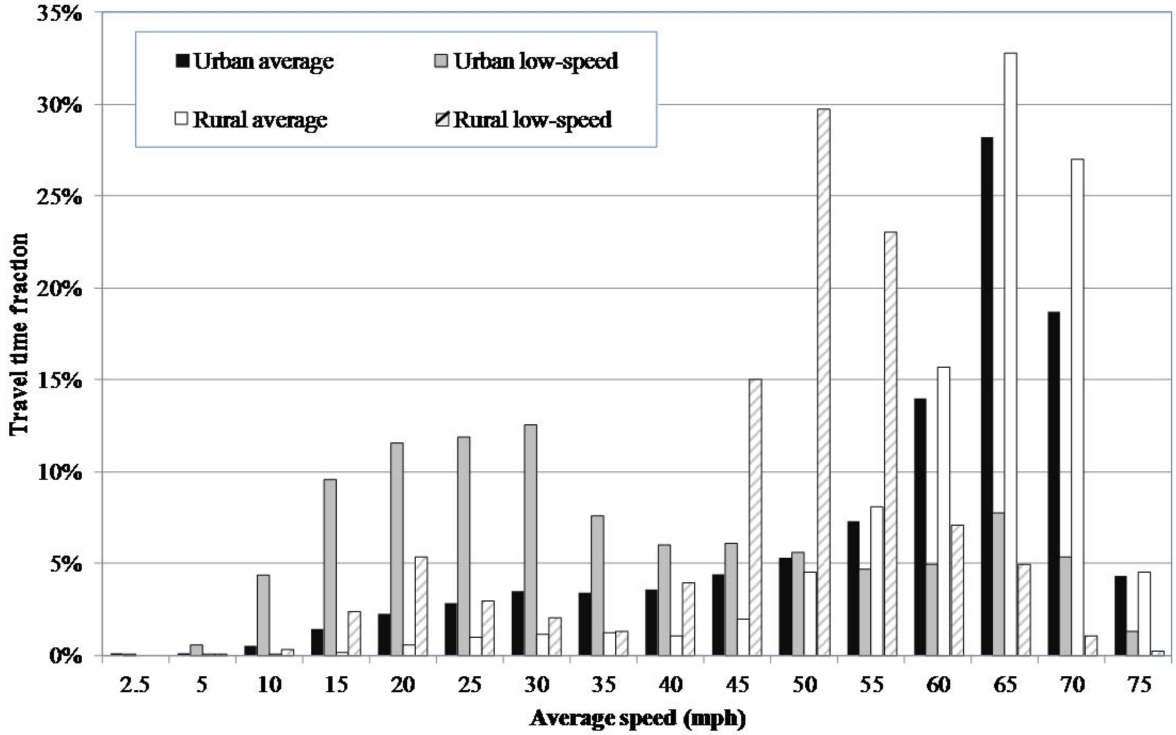


Figure 4.7: Average speed distribution from 7:00 a.m. to 8:00 a.m. on weekdays on flat restricted-access roads for rural and urban average and low-speed segments (morning peak hour).

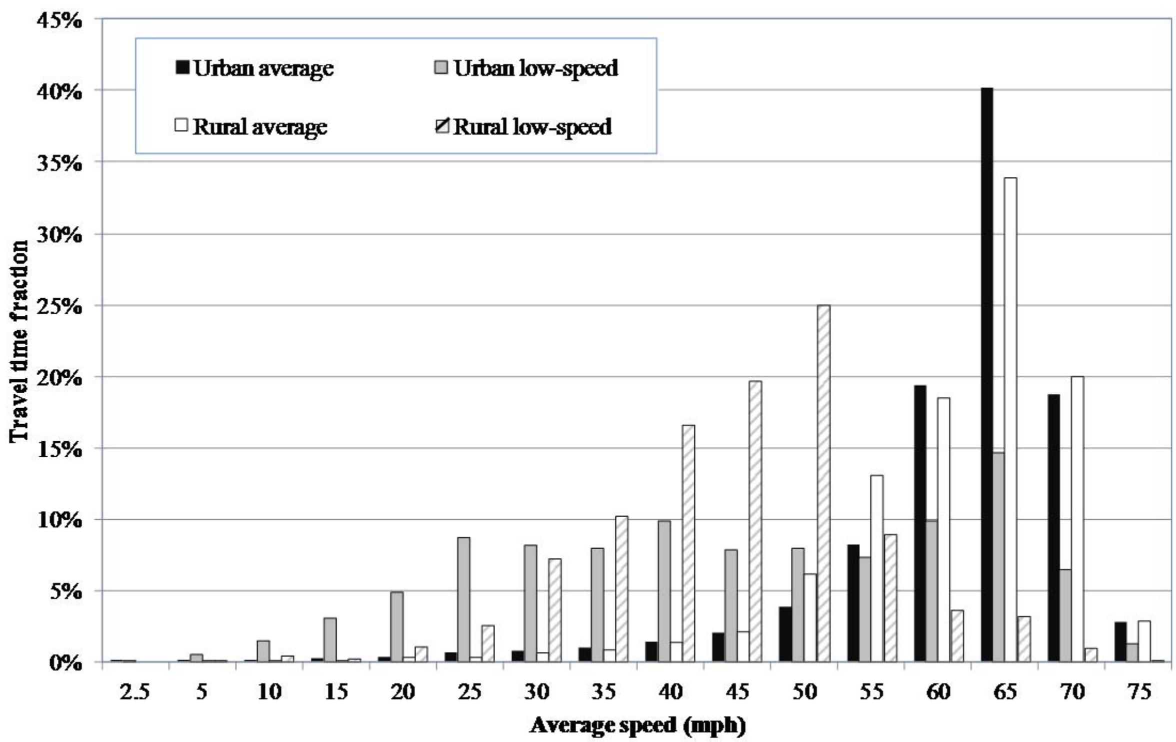


Figure 4.8: Average speed distribution from 11:00 a.m. to 12:00 p.m. on weekdays on flat restricted-access roads for rural and urban average and low-speed segments (nonpeak hour).

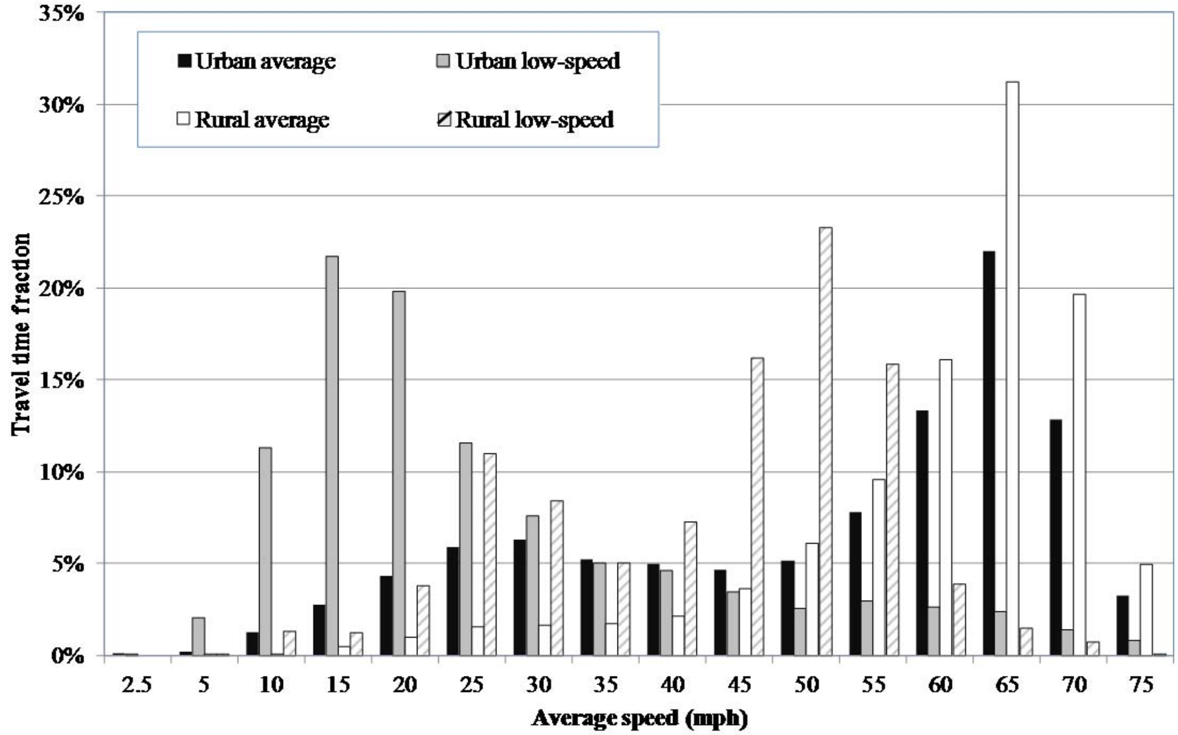


Figure 4.9: Average speed distribution from 5:00 p.m. to 6:00 p.m. on weekdays on flat restricted-access roads for rural and urban average and low-speed segments (afternoon peak hour).

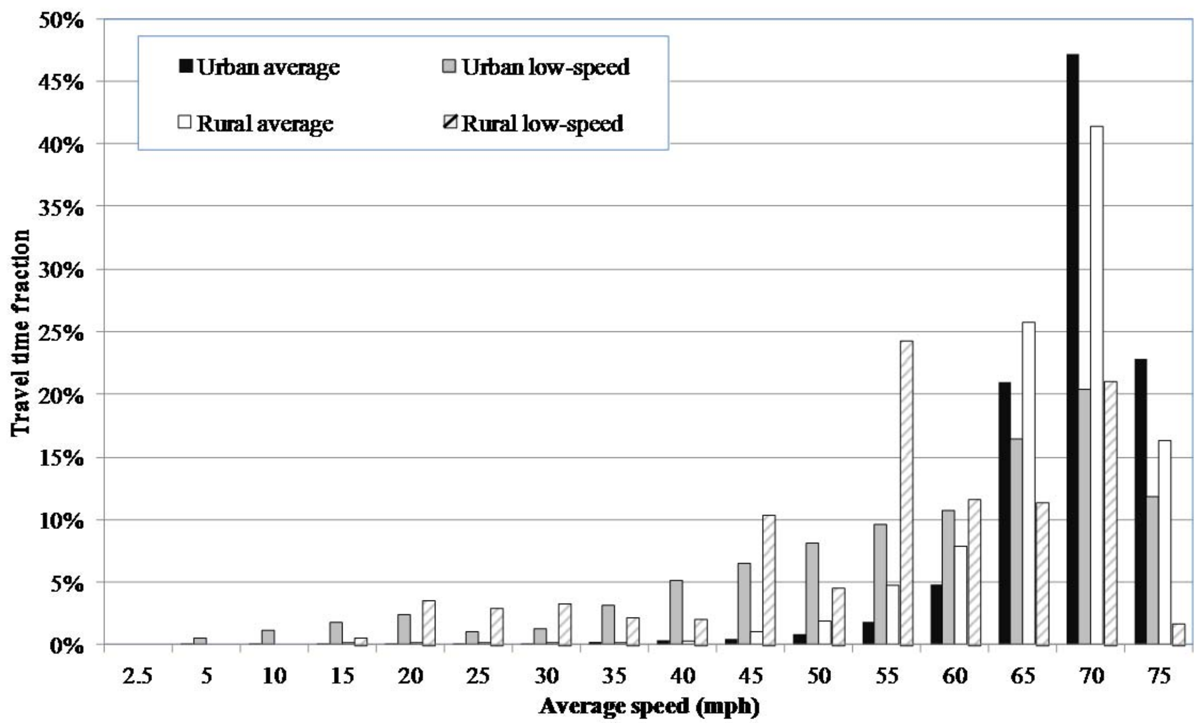


Figure 4.10: Average speed distribution from 7:00 a.m. to 8:00 a.m. on weekends on flat restricted-access roads for rural and urban average and low-speed segments (morning peak hour).

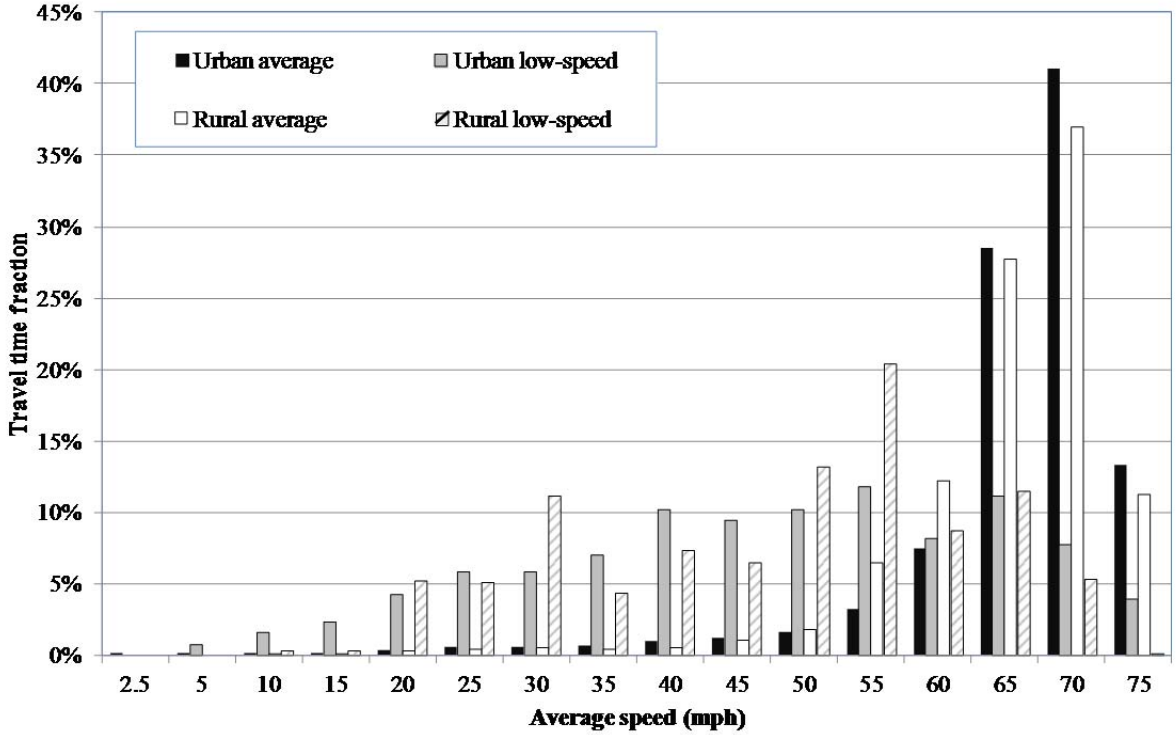


Figure 4.11: Average speed distribution from 11:00 a.m. to 12:00 p.m. on weekends on flat restricted-access roads for rural and urban average and low-speed segments (nonpeak hour).

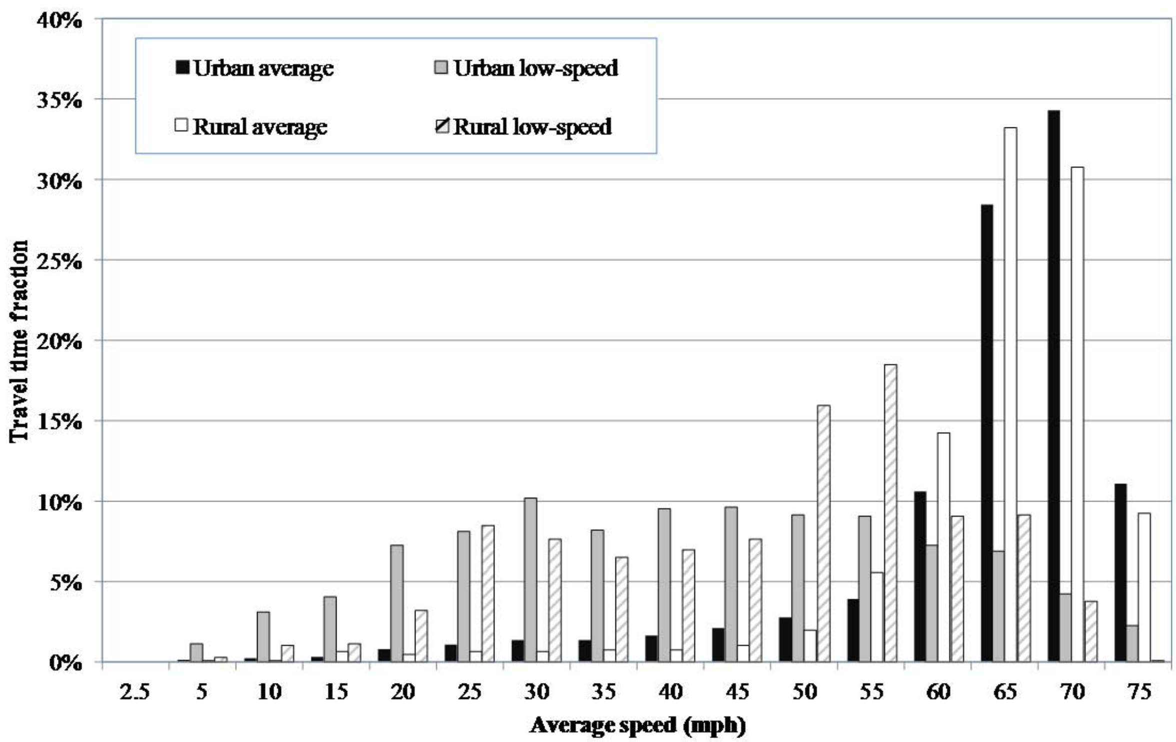


Figure 4.12: Average speed distribution from 5:00 p.m. to 6:00 p.m. on weekends on flat restricted-access roads for rural and urban average and low-speed segments (afternoon peak hour).

Other Inputs For Flat Area Modeling

Besides average speed distribution, *MOVES* required other inputs, which are discussed below.

Meteorology. Meteorology includes the average temperature and relative humidity for the location of the road segment. Because the *MOVES* default database has included this information for each county in the U.S., the default data in *MOVES* was used directly.

Vehicle Age Distribution. The vehicle age distribution was acquired from the *EMFAC* database, the California on-road vehicle inventory. However, because *EMFAC* and *MOVES* use different vehicle classifications, there was an additional mapping process. The same process that was used in the project-level model, as discussed in the previous study report *(14),* was also used for the network-level analysis.

Road Type Distribution. This input requires the VMT fractions of each road type for each vehicle type. Because this study only considered one type of road at a time, they were all set to 1.

Source Type Population. This input requires the vehicle population of each road type for each vehicle type. In this study the daily traffic flow of each vehicle type was used.

HPMS Yearly VMT. This input requires the total VMT for each vehicle type in each calendar year. In this study the yearly VMT was the sum of the daily traffic flow multiplied by the length of the segment multiplied by the number of days in a year (365 for a regular year and 366 for a leap year).

VMT Month Fraction. This input requires the total VMT monthly fraction for each vehicle type. Because this study assumed the daily VMT was the same (using AADT as input), the monthly fraction was the fraction of number of days in each month, and this was applied to all vehicle types.

VMT Day Fraction. This input requires the total VMT day fraction for each vehicle type. Again, because this study assumed the daily VMT was the same, the VMT day fraction was the fraction of the number of each type of day (weekdays and weekends) in each week, and this was applied to all vehicle types, months, and road types.

VMT Hour Fraction. This input requires the total VMT hour fraction for each vehicle type. Hourly traffic distributions were acquired from the PeMS database *(16)*. For each PeMS station, a factor for weekdays and a factor for weekends were generated separately to meet the input requirements of *MOVES*. The data from each

PeMS station was aggregated to the level of each road type and road access type, respectively. This study assumed that all vehicle types have the same VMT hour fraction.

Fuel Formulation and Fuel Supply. These two inputs provide the selections of fuels used in *MOVES* and the properties of these fuels. The default data in *MOVES* was used because fuel formulation was not the focus of this study, and no advanced fuel technology was included in this study.

Mountainous Area Modeling

To address the daily traffic in mountainous areas, the project-level modeling in *MOVES* was used. The inputs required for project-level modeling were similar to county-level modeling, and they are discussed below.

Meteorology, Vehicle Age Distribution, and Fuel Information. These inputs were the same as those in the county-level modeling process. The procedures to acquire these inputs were also the same as in the county-level modeling process.

Link Information. This input provides the segment information that is analyzed in each run of the model, including the county, the road type, the length of the road, the traffic volume on the roadway link, the average speed of all of the vehicles on the segment in that specific hour (only one hour can be analyzed in each run of the model), and the road gradient of each segment. The impact from gradient on average speed was included in this study; however, due to the lack of real-world monitoring stations in mountainous areas (no PeMS data), this study adopted the free-flow speed model in *HDM-4*. The impact from road gradient to vehicle free-flow speed from *HDM-4* is shown in Figure 4.13. This impact depends on the weight of the vehicle: the heavier the vehicle is, the more the speed is affected by the road gradient. For negative gradients (downhill), the *HDM-4* document stated that there were some discontinuity problems within the model itself and suggested mirroring the upgrade speeds with the downgrade speeds. Various studies found this to be a reasonable approximation *(43)*. In the meantime, the base speed (zero grade) was set to 65 mph on all rural restricted-access roads and 45 mph on rural unrestricted-access roads.

Vehicle Type Distribution on the Link. This input provides the fraction of the segment traffic volume by each vehicle class. This input can be acquired from the assigned traffic volume for each segment and each hour, and mapped from the *CalTruck* to the *MOVES* vehicle classifications.

Off-Network Emission. This input provides information about vehicles that are not driving on the project links but still contribute to project emissions, such as the start, idle, and parked times. Because this study only focused on emissions from running vehicles, the time fraction of off-network emissions was set to zero.

Operating Mode Distribution or *Link Drive Schedule*. Operating mode distribution is the distribution across operating modes of vehicle activity (represented by VSP in *MOVES*, as discussed in the project-level study report *[13]*) and each mode has a distinct emissions rate. The link drive schedule is the precise speed and road grade as a function of time (seconds) on a particular roadway segment. If data are available, these two inputs can provide the finest resolution of modeling at the microscopic level in *MOVES*. In each modeling instance, only one of the following inputs is required: average segment speed, operating mode distribution, or link drive schedule. In this study, because the data for VSP distribution and link drive schedule were unavailable, average segment speed was used and the default typical link drive schedule (reflecting typical driving behavior at different average speeds on different road types) in the *MOVES* database was adopted when using *MOVES* in this study.

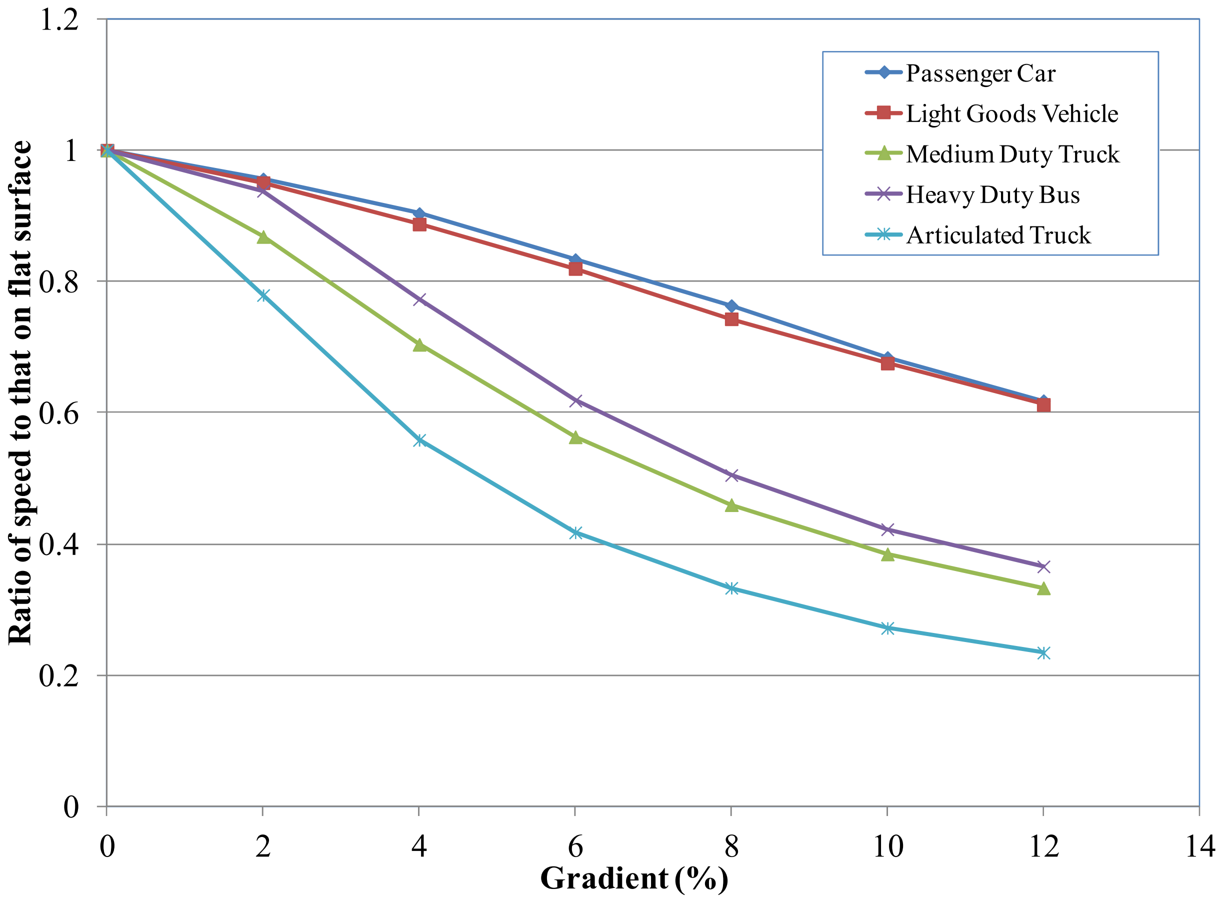


Figure 4.13: Ratio of speed with various grades and free-flow speeds on flat area.

4.6.2 Sensitivity Analyses to Evaluate Effects of Congested Traffic and Road Gradients

As discussed in Section 2.3, sensitivity analyses were performed to evaluate the impact of congested versus average traffic conditions and flat versus mountain vertical gradients and their interaction with pavement roughness on fuel savings. The purpose of the comparison was to determine whether traffic flow conditions and road gradients needed to be considered in order to answer the questions in the scope of this report. It is known that congested traffic and positive road gradients can increase fuel consumption; these sensitivity studies were to determine whether those variables have substantial interactions with pavement roughness and texture using the approach developed in the project-level LCA model.

The case studies considered for the sensitivity analyses included different traffic speed on flat, urban restricted-access roads; different grades on rural restricted-access roads; and different grades on rural unrestricted-access roads. In each case study, the material production and construction LCIs were the same among different scenarios within each case study, and only the traffic pattern was different. Therefore only the Use Phase of pavement was analyzed.

All the case studies assumed the default fuel economy improvement scenario in *MOVES*. Each case study considered a potential CAPM treatment carried out in 2012. For asphalt-surfaced pavement, the old surface layer was milled and a new medium asphalt concrete overlay was applied. For concrete-surfaced pavement, the typical concrete pavement restoration class "B" (CPR B) from Caltrans was applied. In CPR B, the slabs showing third-stage cracking were replaced using condition survey data for the segment, and all lanes were diamond ground to acquire better performance after slab replacement.

All the case studies considered two levels of smoothness achieved after the CAPM treatment: *Smooth CAPM* and *Less Smooth CAPM*. For both overlay on asphalt pavement and diamond grinding on concrete pavement the *Smooth CAPM* was calculated as the average IRI after the treatment (*InitialIRI* directly calculated from Equation 4.1 and Equation 4.4, respectively) minus one standard deviation of the residual, while *Less Smooth CAPM* was calculated as *InitialIRI* value plus one standard deviation. The asphalt overlay model had a standard deviation of 38.8 inches/mile (0.61 m/km), and the grinding model had a standard deviation of 18.06 inches/mile (0.285 m/km). The progressions of IRI and MPD of asphalt pavement were based on Equation 4.2 and Equation 4.5, respectively. The progression of IRI and MTD for concrete pavement after grinding were based on Equation 4.3 and Equation 4.6, respectively.

A *Do Nothing* scenario, in which only the minimum level of maintenance work was performed annually to keep the current pavement condition deteriorating at a very slow rate, was also modeled as a baseline for each case. The IRI and MPD progression under *Do Nothing* is described in Section 4.4.1.

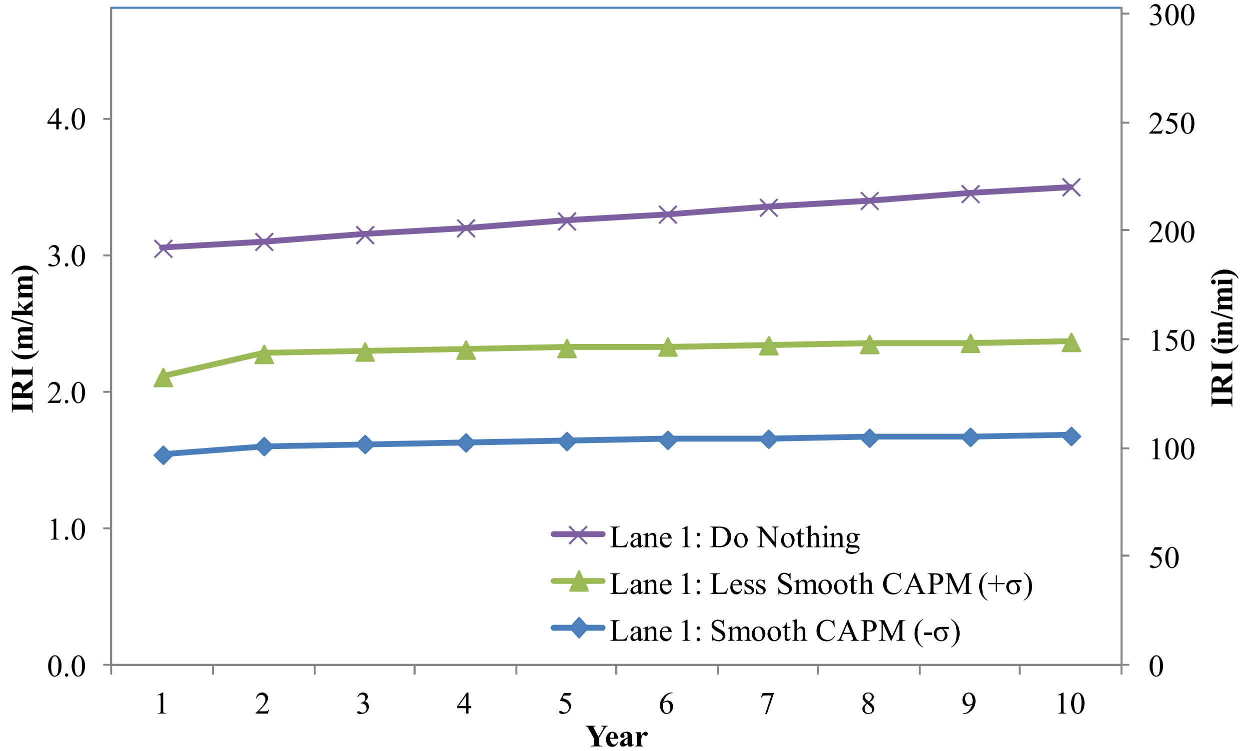
Flat, Urban Restricted-Access Roads

Using a selected segment on westbound I-80 in Solano County, this case study evaluated the impact from rolling resistance on energy saving using the state-average speed and low speed (representing congestion) traffic conditions. The segment information is shown in Table 4.10. According to the Caltrans LCCA and CAPM manual, a CPR B as a CAPM strategy has a ten-year service life. This segment was selected because the PeMS station on this segment showed up as one of the low-speed traffic flow stations. The IRI and MTD on this segment before and after CPR B are shown in Figure 4.14.

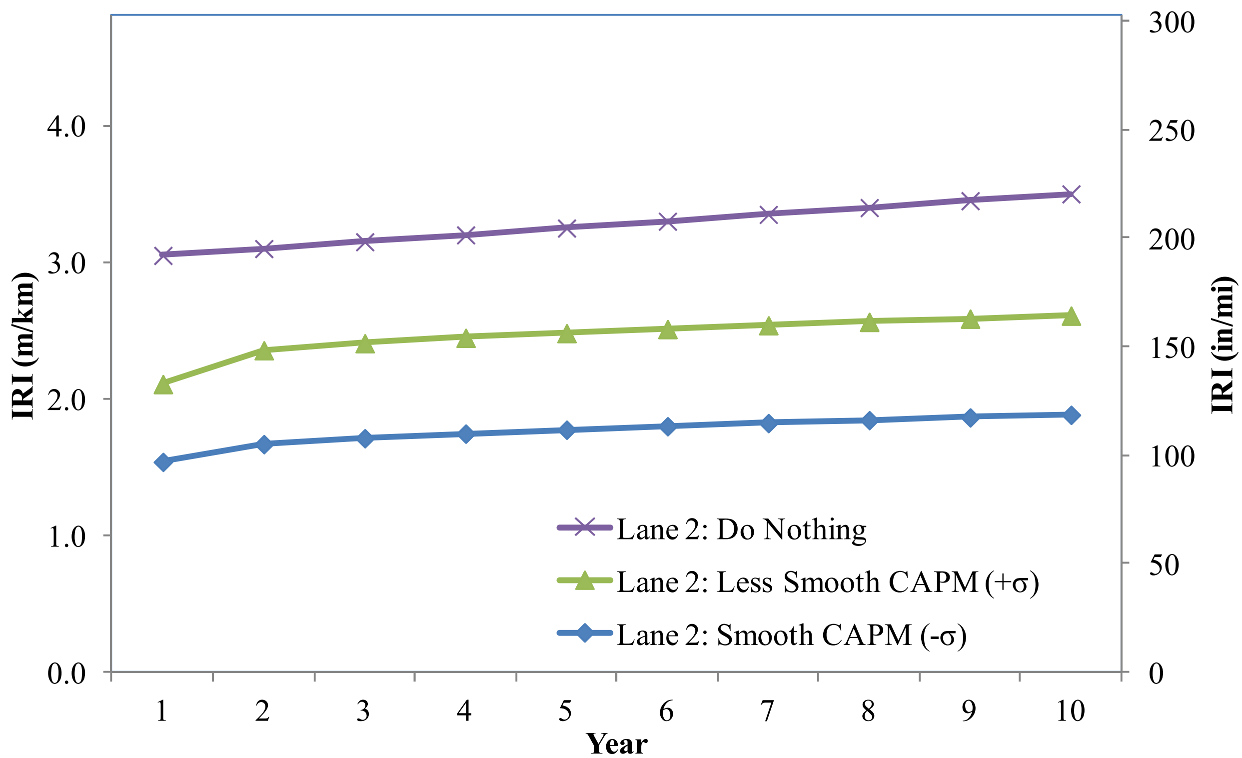
Table 4.10: Segment Information for Flat, Urban Restricted-Access Road Case Study

Case Study	County	Route	Surface	Analysis Period	Section Length	Number of Lanes	Lane Width	One-Way AADT	Truck Percentage	Initial IRI (m/km)
Flat urban restricted	Solano	I-80 westbound	Cement concrete	2012 ~ 2021 (10 years)	8,042 m (5 mi)	3	3.66 m	59,160	6.7%	3 (Lane 1) 3 (Lane 2) 3.5 (Lane 3)

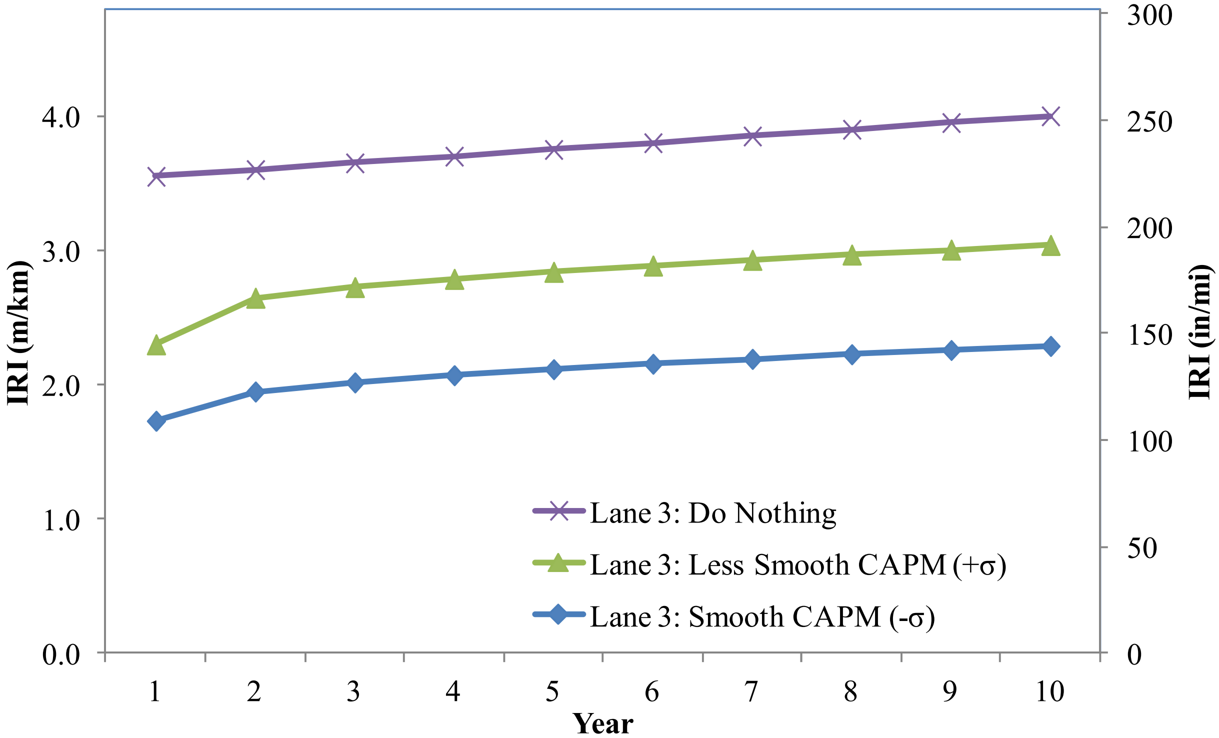
Note: 3 m/km = 190 inches/mile, 3.5 m/km = 222 inches/mile



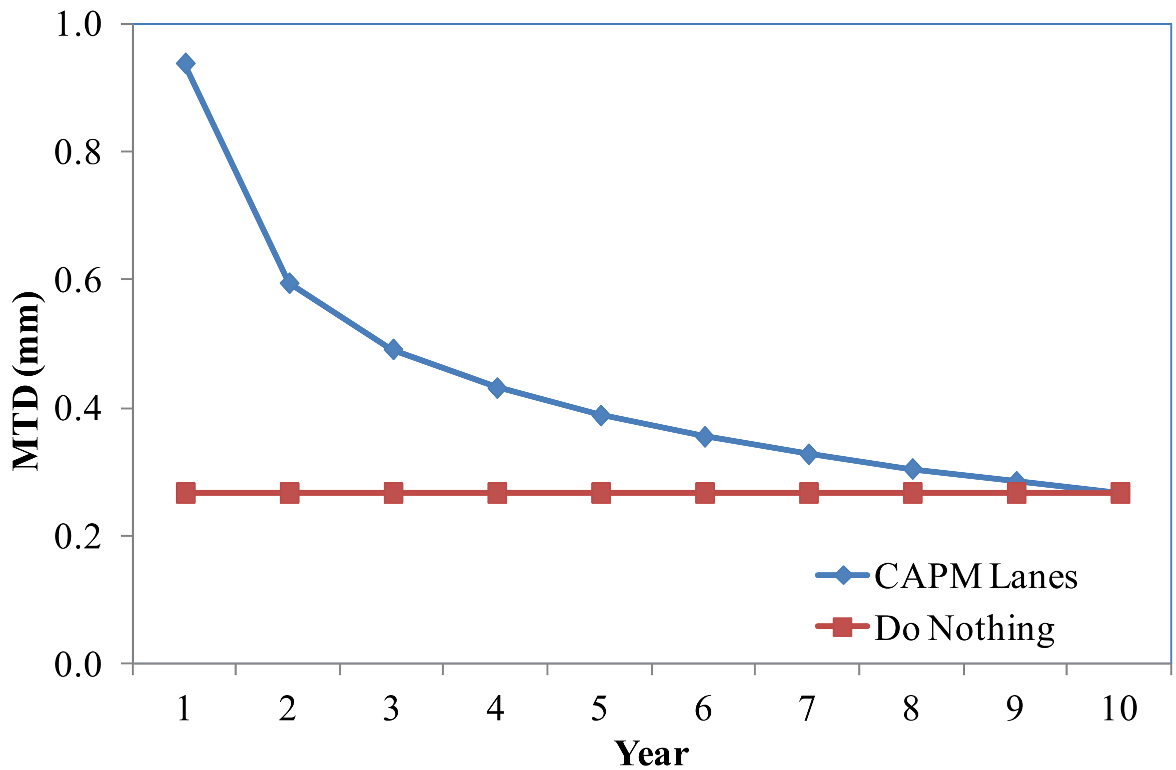
IRI in Lane 1 (inner lane)



IRI in Lane 2



IRI in Lane 3 (outer lane)



MTD in all lanes

Figure 4.14: IRI and MTD progression for flat, urban restricted-access road case study on I-80 Solano County.

The results in Figure 4.15 show the total energy consumption during the pavement Use Phase under an average-speed flow, 0 and 3 percent VMT growth, and with and without the changes in fleet fuel economy. Figure 4.16 shows the comparison of scenarios under an average-speed flow and a low-speed flow. In each scenario, the difference in energy savings due to pavement treatment between the average-speed flow and low-speed flow was about 8 percent. Considering that the energy saving from pavement CAPM was about 4 percent from the *Do Nothing* scenario (baseline), the difference that results from the speed was about 0.32 percent of the baseline. Compared to the difference resulting from the construction quality (different levels of smoothness achieved in the construction), which is about 3.0 percent of the baseline, the impact from speed was very small. Further, considering that this low-speed flow scenario was already an extreme situation (only the PeMS stations outside two standard deviations of the average traffic speed were selected when this scenario was developed, which is about 300 stations out of 7,600), it was decided that the impact from speed distribution difference on urban restricted-access roads can be neglected in the network analysis.

In addition, because the average speed of rural restricted-access roads is higher than on urban restricted-access roads and speed variance is lower than that of urban areas (as shown in Section 2.3), and because the rural restricted-access roads carry much less VMT compared to the urban restricted-access roads, this impact can be expected to be even smaller on rural roads. Therefore, the same strategy was applied to all flat rural roads. To summarize, the congested traffic driving patterns were ignored, and only state-average speeds were considered in the network analysis.

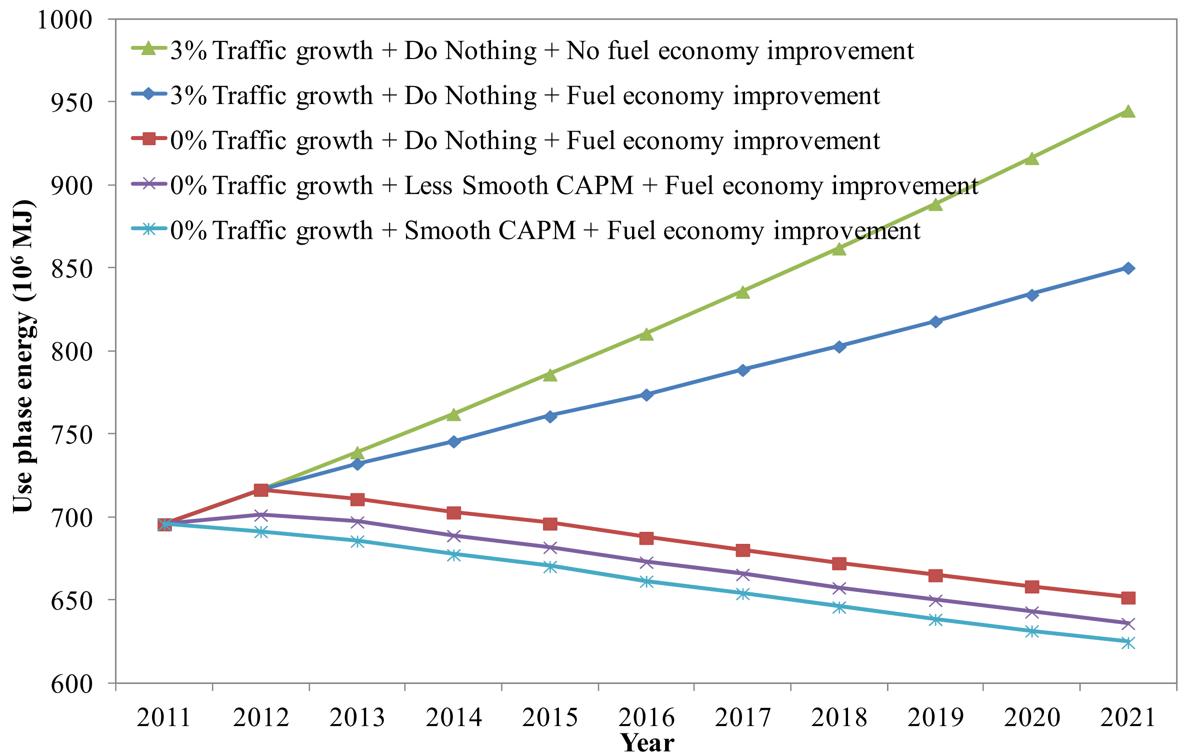


Figure 4.15: Total energy consumption in the Use Phase in the flat, urban restricted-access road case study with average-speed flow.

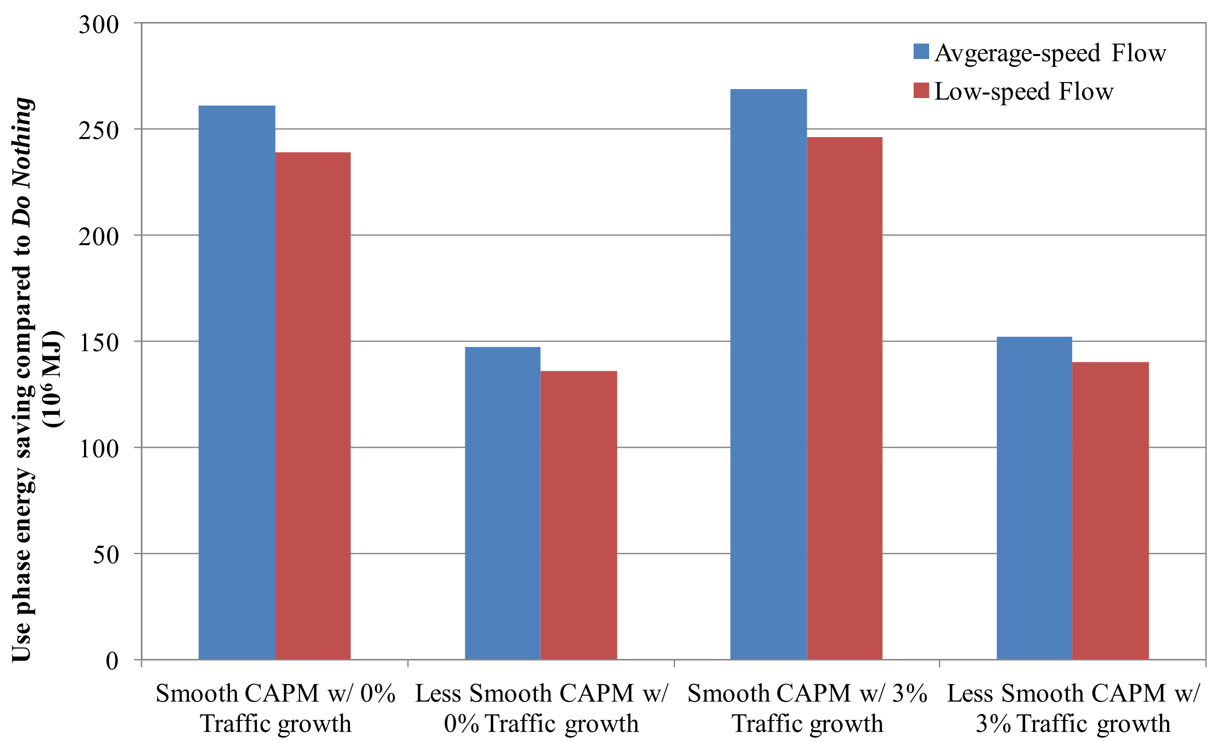


Figure 4.16: Use Phase energy saving compared to the *Do Nothing* scenario in the flat, urban restricted-access road case study.

Mountainous, Rural Restricted-Access Road

Using a selected segment on eastbound I-80 in Placer County, this case study also evaluated the impact on energy savings from rolling resistance under different gradients for rural restricted-access roads. This case study According to the Caltrans LCCA and CAPM manual, a CPR B as a CAPM strategy has a ten-year service life. The segment information is shown in Table 4.11.

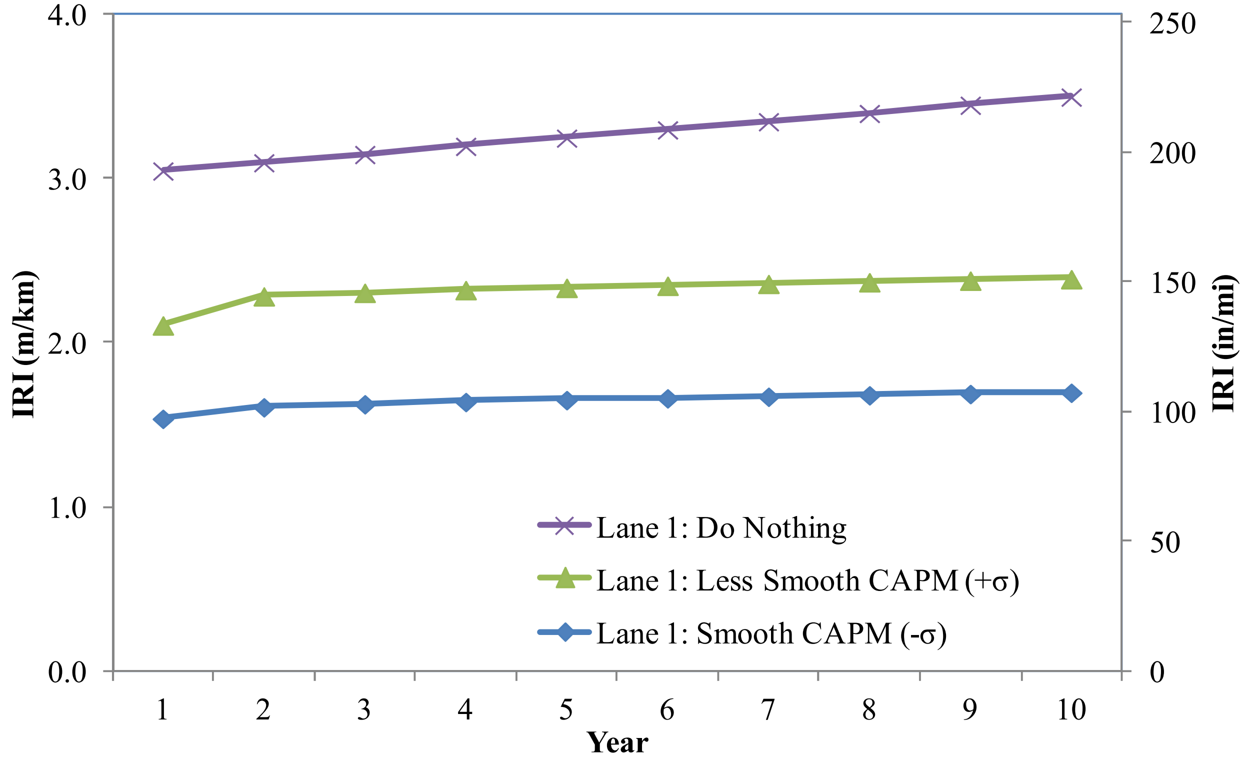
Table 4.11: Segment Information of Mountainous, Rural Restricted-Access Road Case Study

Case Study	County	Route	Surface	Analysis Period	Section Length	Number of Lanes	Lane Width	One-Way AADT	Truck Percentage	Initial IRI (m/km)
Mountainous rural restricted	Placer	I-80 eastbound	Cement concrete	2012 ~ 2021 (10 years)	8,042 m (5 mi)	3	3.66 m	5,100	29%	3 (Lane 1) 3.5 (Lane 2)

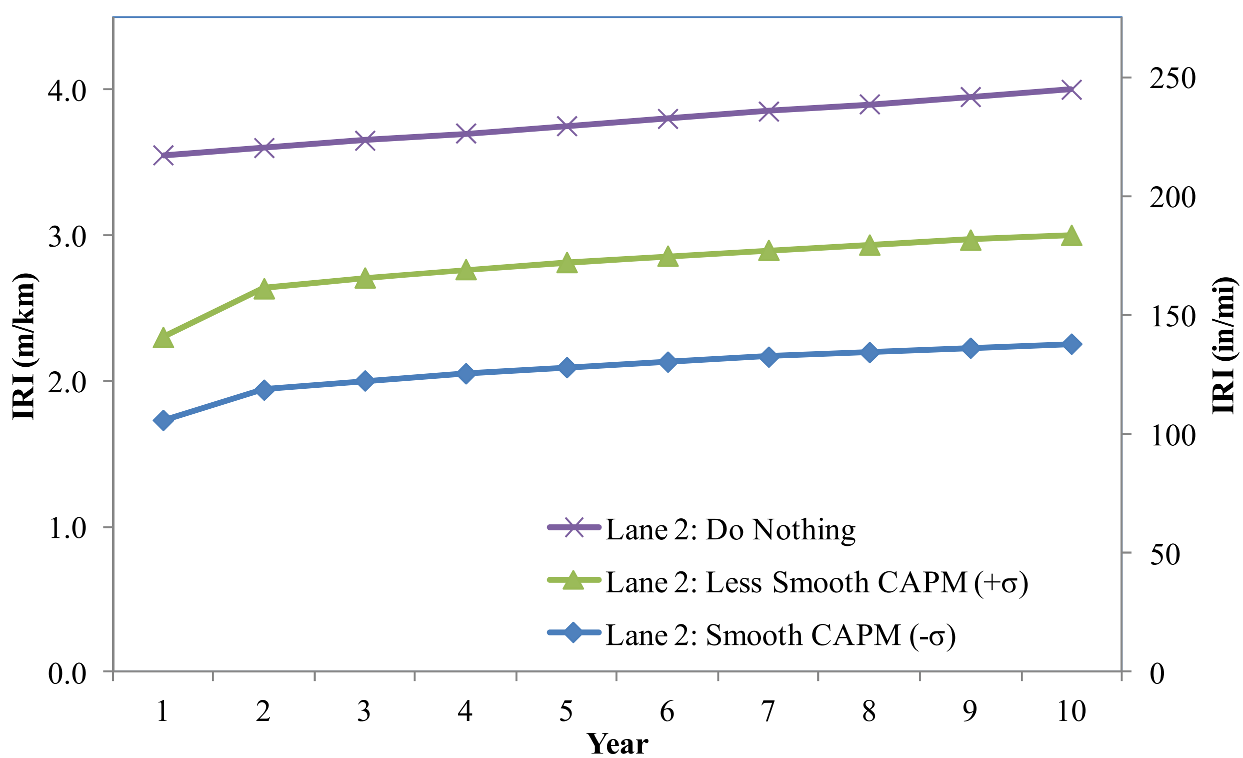
Note: 3 m/km = 190 inches/mile, 3.5 m/km = 222 inches/mile, 3.66 m = 12 ft

The IRI and MTD on this segment before and after CPR B are shown in Figure 4.17; they were developed using the model developed in previous studies and the model from Rao et al. *(40).*

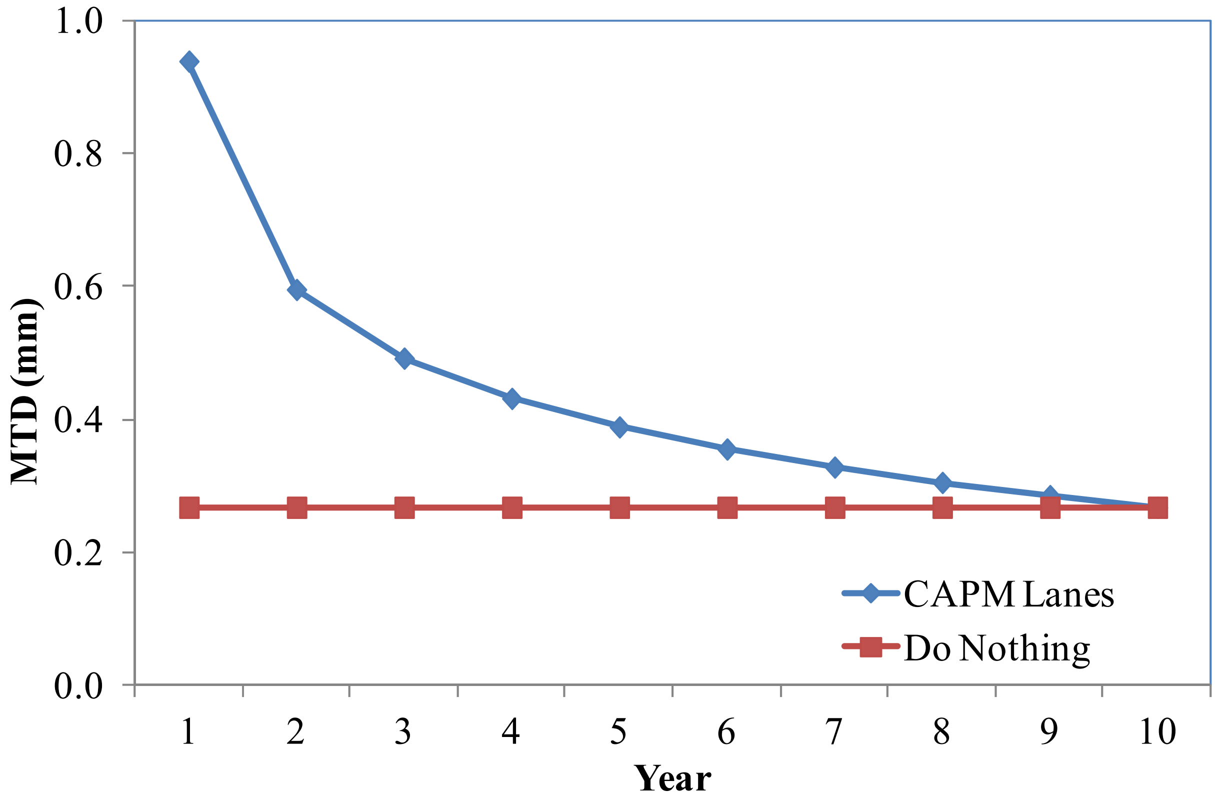
Figure 4.18 shows the total energy saving result from this case study. The result of annual total energy consumption in the Use Phase was similar to the flat, urban restricted-access road result. In this case study, the fuel saving resulting from a *Smooth CAPM* was about 3 percent of the *Do Nothing* scenario (baseline), and the saving from *Less Smooth CAPM* was about 2 percent. Within each scenario, the difference in energy saving due to different grades was about 5 percent of the zero gradient situation. Therefore, the difference that resulted from the gradient was about 0.015 percent or 0.01 percent of the baseline (depending on the smoothness achieved after the treatment). Comparing this to the difference in energy saving resulting from constructed smoothness itself (2.0 percent of the baseline), the impact from gradient was also very small. Therefore, the impact from grade difference on rural restricted-access roads can be also neglected in the network implementation.



IRI in Lane 1 (inner lane)



IRI in Lane 2 (outer lane)



MTD in all lanes

Figure 4.17: IRI and MTD progression for mountainous, rural restricted-access road case study.

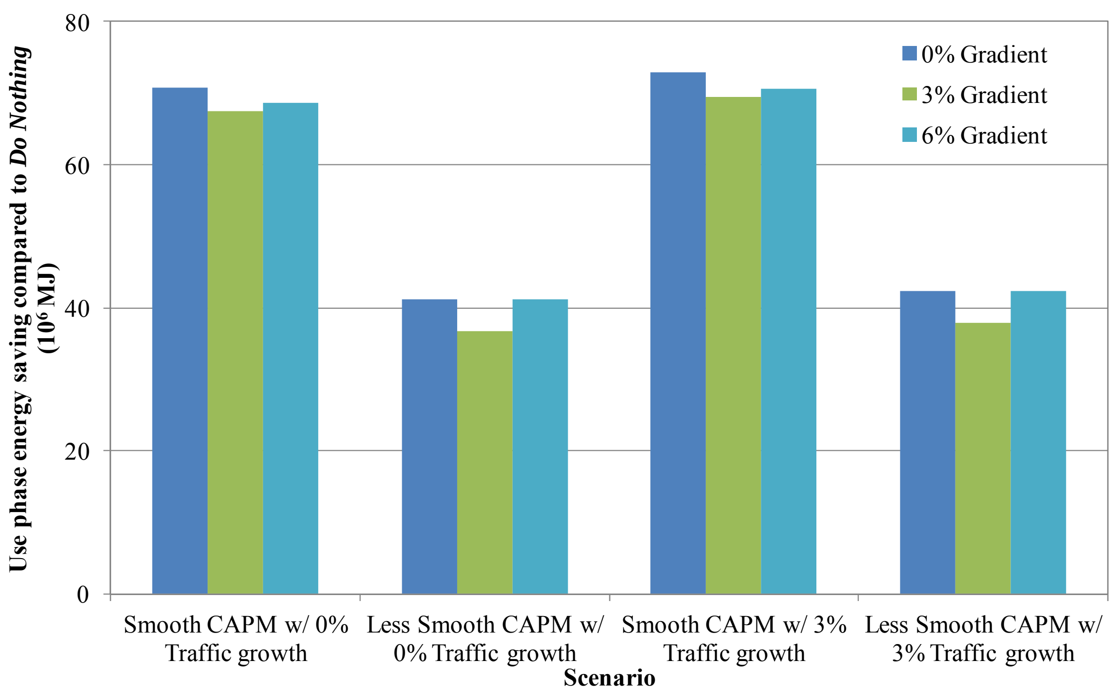


Figure 4.18: Use Phase energy saving compared to *Do Nothing* in the mountainous, rural restricted-access road case study.

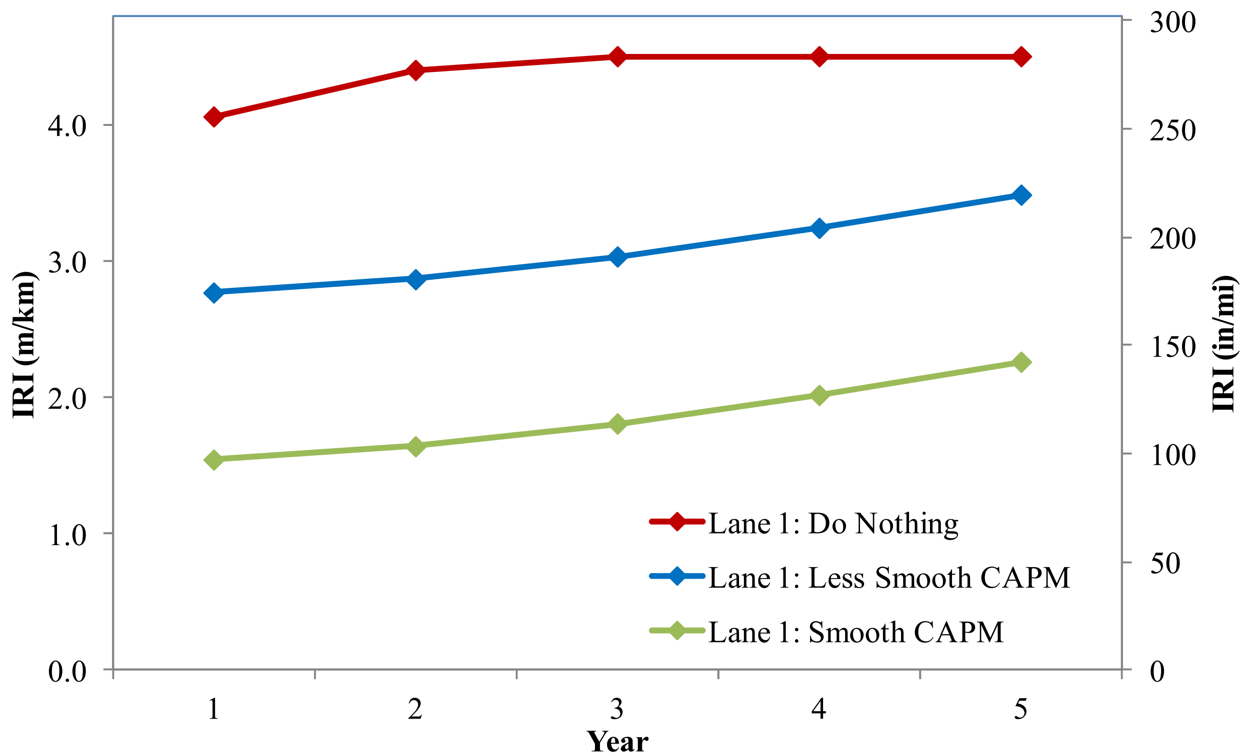
Mountainous, Rural Unrestricted-Access Road

Using a selected segment on southbound CA-70 in Butte County, this case study evaluated the impact on energy savings from rolling resistance under different gradients for rural unrestricted-access roads. The segment information is shown in Table 4.12. According to the Caltrans LCCA and CAPM manual, an asphalt overlay as a CAPM strategy has a five-year service life. Therefore in this case study, the analysis period was set to five years. The IRI and MTD on this segment before and after asphalt overlay are shown in Figure 4.19.

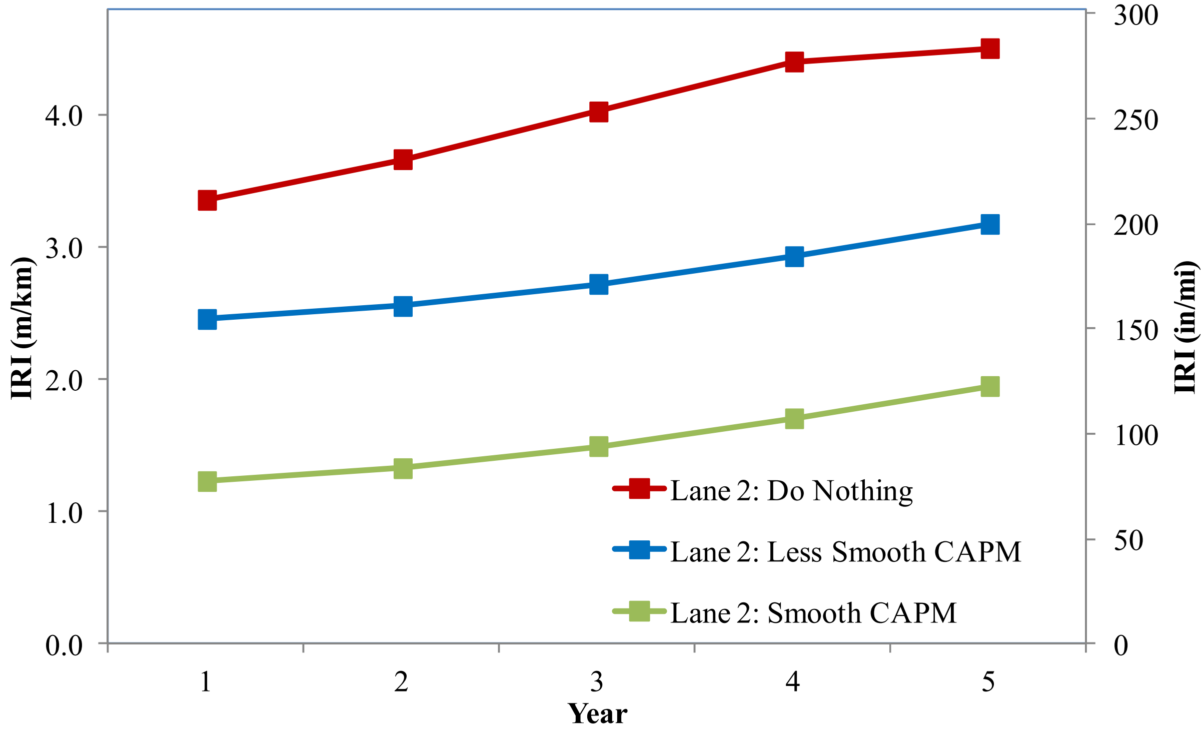
Table 4.12: Segment Information of Mountainous, Rural Unrestricted-Access Road Case Study

Case study		County	Route	Surface	Analysis Period	Section length	Number of Lanes	Lane Width	AADT	Truck percentage	Initial IRI (m/km)
Mountainous rural unrestricted		Butte	CA-70 southbound	Asphalt concrete	2012 ~ 2016 (5 years)	8,042 m (5 mi)	2	3.66 m	1,600	14.8%	3.75 (Lane 1); 3 (Lane 2)

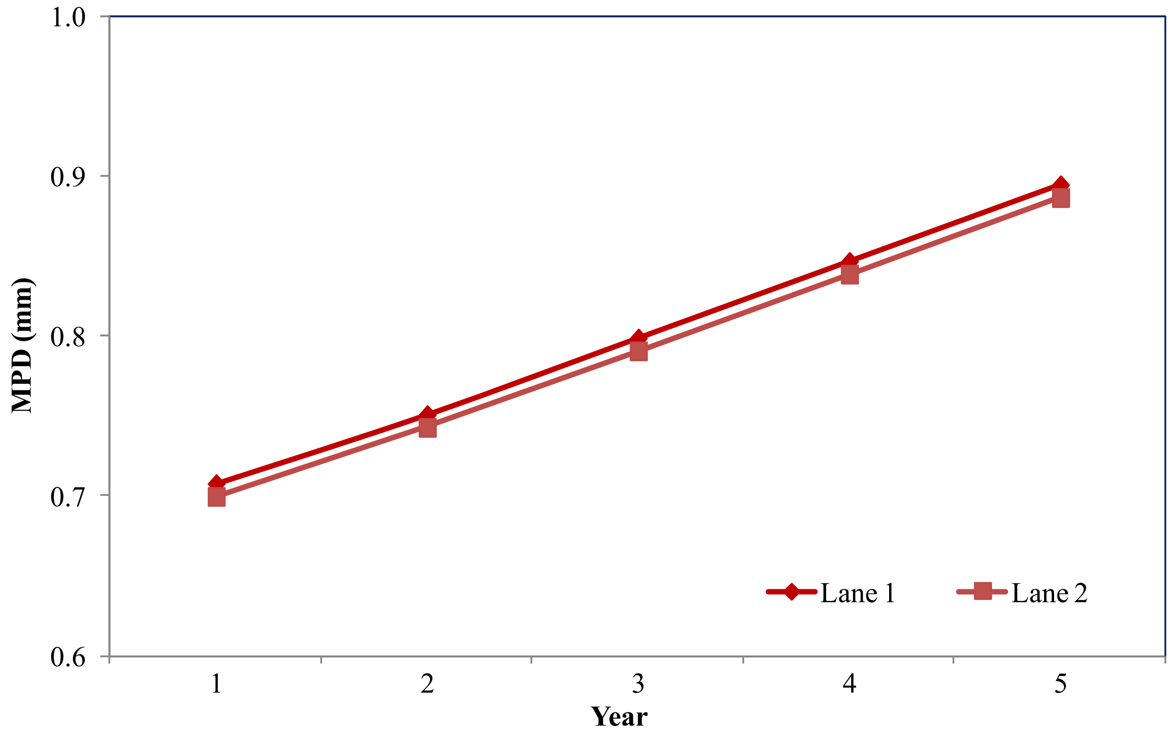
Note: 3 m/km = 190 inches/mile, 3.5 m/km = 238 inches/mile, 3.66 m = 12 ft



IRI in Lane 1



IRI in Lane 2[1]



MPD

Figure 4.19: IRI and MTD progression for mountainous, rural unrestricted-access road case study.
(Note 1: In this case study, Lane 2 (outer lane) has a lower IRI than Lane 1, which is uncommon. However because this was a direct observation from PCS database, the data were still used.)

Figure 4.20 shows the Use Phase energy saving result from this case study. The result was similar to the rural restricted-access road case study. The difference in energy saving due to the gradient was much less than the difference of smoothness variability from the construction. Therefore, the impact from grade difference on rural unrestricted-access roads can be neglected in the network implementation.

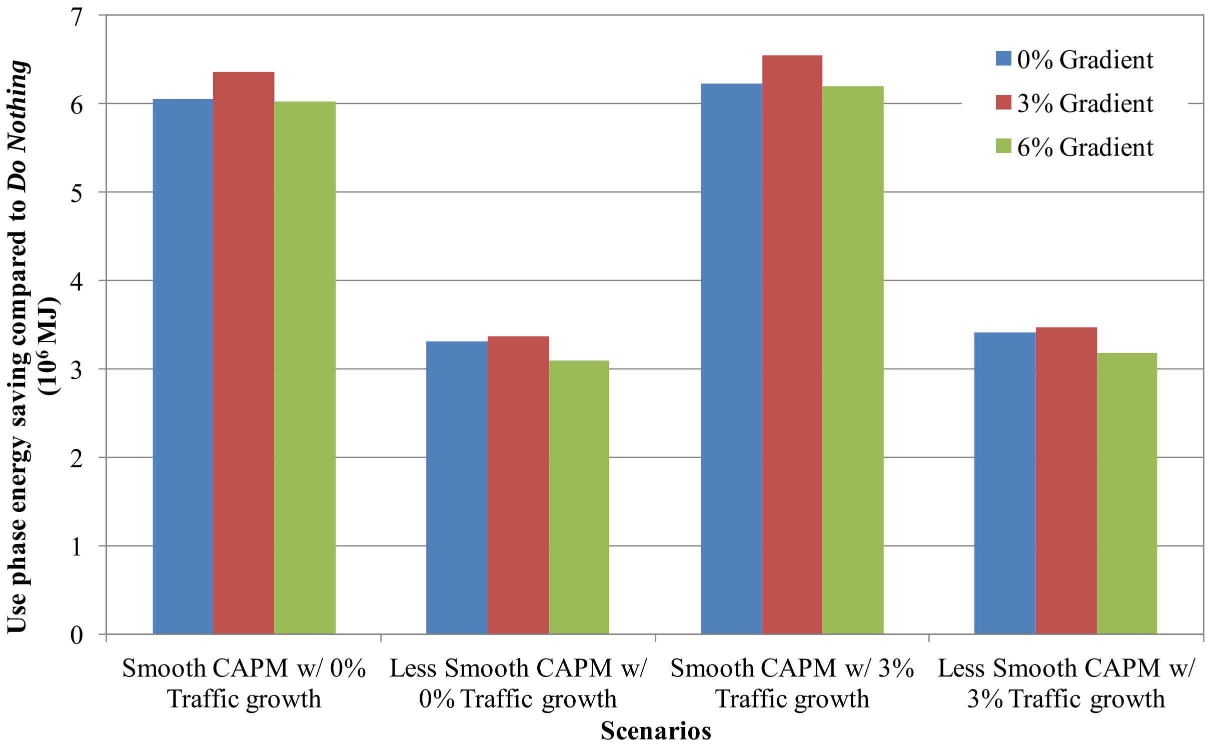


Figure 4.20: Use Phase energy saving compared to *Do Nothing* in mountainous, rural restricted-access road case study.

Conclusions from the Sensitivity Analyses

Based on the case studies performed in the previous sections, the impact from road vertical gradient and speed distribution on fuel saving (and therefore GHG reduction) due to the pavement roughness and texture can be neglected. Therefore, only road access type, road type, vehicle type, pavement surface type, IRI, and macrotexture were included in the final factorial sets for vehicle emission factors.

4.6.3 Use Phase Vehicle Energy Consumption and Tailpipe CO_2 Emissions Factor Based on Factorial Variables

As discussed in Step 4 in Section 2.2, the vehicle energy consumption and tailpipe CO_2 emission factors were developed as a function of selected pavement segment characteristics to address the Use Phase of pavement in a simplified way compared to the modeling approach presented in Chapter 3, while addressing the heterogeneity of the pavement network.

As discussed in Section 2.3, IRI and MPD[1] were treated as continuous variables while the other characteristics were treated as categorical variables when developing the vehicle emission factors. Therefore, the vehicle emissions factor was developed for each combination of variables, as a continuous function of MPD and IRI and the following categorical variables, including pavement surface type (asphalt and concrete), road access type (restricted-access and unrestricted-access), road type (urban and rural), year (from 2012 to 2021), and vehicle type (passenger car, 2-axle truck, 3-axle truck, 4-axle truck, and 5-or-more axle truck), as shown in Table 4.13 [2]. Therefore, the total number of the combinations was 2 pavement types × 2 road types × 2 road access types × 10 years × 5 vehicle types = 400.

Table 4.13: Factorial Variables Used to Develop Vehicle Tailpipe CO_2 Emissions Factors

Pavement Type	Road Type	Road Access Type	Vehicle Type Mix	Pavement Surface Characteristics
Asphalt pavement; Concrete pavement	Urban roads; Rural roads	Restricted-access road; Unrestricted-access road	Passenger cars; 2-axle truck; 3-axle truck; 4-axle truck; 5-or-more axle truck at Years 2012 to 2021 (10 years)	MPD and IRI
Categorical variable	Categorical variable	Categorical variable	Categorical variable	Continuous variable

In each combination, a series of IRI and MPD values were modeled using *MOVES* and using the project-level modeling approach described in the previous study report *(14),* and the results were used to develop the emissions factors as a function of IRI and MPD using linear regression. The IRI and MPD values were randomly paired so they were not linear-correlated (otherwise it was not possible to build a linear regression model based on these two variables). Considering the total number of modeling cases, six pairs of IRI and MPD were selected to develop the regression equation. These values were selected so they could cover a reasonable range of pavement surface characteristics. Table 4.14 shows the values of IRI and MPD in each pair. The IRI and MPD in these six pairs have an R-squared of 0.0431, indicating that the IRI and MPD selected here were poorly linear-correlated.

Table 4.14: Pavement Surface Characteristics for Building the Linear Regression model for Both Asphalt and Concrete Pavement[1]

Surface Scenario	1	2	3	4	5	6
IRI (m/km [inches/mile])	1 (63)	3.5 (222)	4 (254)	2 (127)	1.5 (95)	2.5 (159)
MPD (mm)	0.2	1	0.4	1.2	0.6	0.8

Note: For concrete pavement, MPD was converted to MTD using the equation: MTD (mm) = 1.02 × MPD(mm) + 0.28.

[1] For concrete, MTD was converted to MPD using Eq. 4.7.
[2] In these functions, IRI and MPD are independent of all other categorical variables.

The results of vehicle energy consumption and tailpipe CO_2 emissions from the *MOVES* model under the six pairs of IRI and MPD were converted to the energy consumption and tailpipe CO_2 emissions per 1,000 miles of VMT, and then analyzed using linear regression to develop a function based on MPD and IRI. The general formats of the function are shown in Equation 4.12 and Equation 4.13, where $a1$, $a2$, $b1$, $b2$, and the intercept are the coefficients derived from the linear regressions. The total number of equations is 400 for vehicle energy consumption and 400 for vehicle tailpipe CO_2 emissions, corresponding to the 400 combinations of the categorical variables used to develop the vehicle emission factors as a function of MPD and IRI. The R-squared of the linear regression was above 0.99 in all cases, indicating that the energy consumption and tailpipe CO_2 emissions were highly linear-related with IRI and MPD for each combination of the categorical variables.

$$\begin{aligned}&Energy\ Consumption\ per\ 1000\ miles\ (MJ)\ for\ each\ combination\ of\\&the\ categorical\ variables = a1 \times MPD\ (mm) + a2 \times IRI\ (m/km) + Intercept\end{aligned} \quad \textbf{(4.12)}$$

$$\begin{aligned}&Tailpipe\ CO_2\ emission\ per\ 1000\ miles\ (metric\ ton)\ for\ each\ combination\ of\\&the\ categorical\ variables = b1 \times MPD\ (mm) + b2 \times IRI\ (m/km) + Intercept\end{aligned} \quad \textbf{(4.13)}$$

The complete coefficients for each combination of the categorical variables were then stored in a look-up table and were selected according to the categorical variables when they were put to use. Table 4.15 shows an example of coefficients of energy consumption factors in this study. When put to use, these coefficients can be looked up to calculate the energy consumption and tailpipe CO_2 emissions from vehicles per 1,000 miles VMT for each combination of the categorical variables. They are then multiplied by the corresponding VMT with the WTP emissions of fuels to calculate the total emissions. The complete look-up table is provided in Appendix A.

Table 4.15: Example Coefficients of Energy Consumption Factor Function of Selected Combination of Factorial Variables

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	4	2012	1	25.89704	151.6393	5,078.736
Concrete	4	2012	2	96.42064	103.0045	10,826.86
Concrete	4	2012	3	272.7224	254.0309	16,522.89
Concrete	4	2012	4	503.809	468.2829	23,308.63
Concrete	4	2012	5	549.211	454.8151	26,300.35

Notes:
[1]: 2 represents rural restricted-access road; 3 represents rural unrestricted-access road; 4 represents urban restricted-access road; and 5 represents urban unrestricted-access road.
[2]: 1 represents passenger car; 2 represents 2-axle truck; 3 represents 3-axle truck; 4 represents 4-axle truck; 5 represents 5-or-more axle truck.

4.7 Segment-by-Segment Life-Cycle Modeling

As discussed in Step 4 in Section 2.2, with the vehicle emission factors based on the combination of the factorial variables in the pavement Use Phase, the LCIs of the Material Production and Construction phases, and the pavement performance model, the life-cycle energy consumption and GHG of the network using ten different IRI trigger values for CAPM treatments were calculated. This analysis was performed at the segment level, meaning each segment was analyzed using ten different IRI trigger values for CAPM treatments over the ten-year analysis period. The GHG reduction and energy savings that can be achieved throughout the analysis period using CAPM strategies compared to the *Do Nothing* scenario were then summed over all the segments in each group of the network. This procedure is shown in Figure 4.21, and described in detail as follows.

Each management segment in the network was evaluated through two scenarios: the *Do Nothing* scenario and the CAPM or lane replacement scenario (referred to after this simply as *CAPM* scenario). In *CAPM* scenarios, when the IRI of any management segment reached the IRI trigger value, a CAPM treatment was performed on that set of directional segments, which brought down the IRI. The energy consumption and GHG associated with the Material Production and Construction phases of the treatment were then calculated based on the material quantity and construction activity. The energy consumption and GHG emissions in the Use Phase were then calculated by plugging the corresponding coefficients for IRI and MPD into Equation 4.12 and Equation 4.13, and multiplying the result by the total VMT on that segment and then summing the WTP emissions for each year as the IRI and MPD changed following the performance equations described in Section 4.4.

In the *Do Nothing* scenarios, only routine maintenance was performed, and IRI progressed based on the pavement age backcalculation with the asymptote 285 inches/mile (4.5 m/km). In the *Do Nothing* scenarios, the environmental impacts from Material Production and Construction phases were assumed to be zero, although this is not strictly true since there will be some maintenance performed to keep the roadway safe to operate on, while the impact from the Use Phase was also calculated similarly to that in the *CAPM* scenario.

The difference of energy consumption and GHG emissions between the two scenarios were recorded and summed through the analysis period. This procedure was repeated for all the management segments in the network and the difference from each segment was summed to acquire the final result for the network.

Ten IRI trigger values were evaluated for each group in the network and the value that led to the largest GHG reduction was considered the optimal IRI trigger value, i.e., the IRI trigger value that optimizes GHG emissions reductions when all the phases of the life-cycle are taken into consideration. The agency cost associated with each CAPM event was calculated at the same time as the energy consumption and GHG emissions, and the cost from the saved fuel was calculated from the reduced energy consumption compared to the *Do Nothing* scenario.

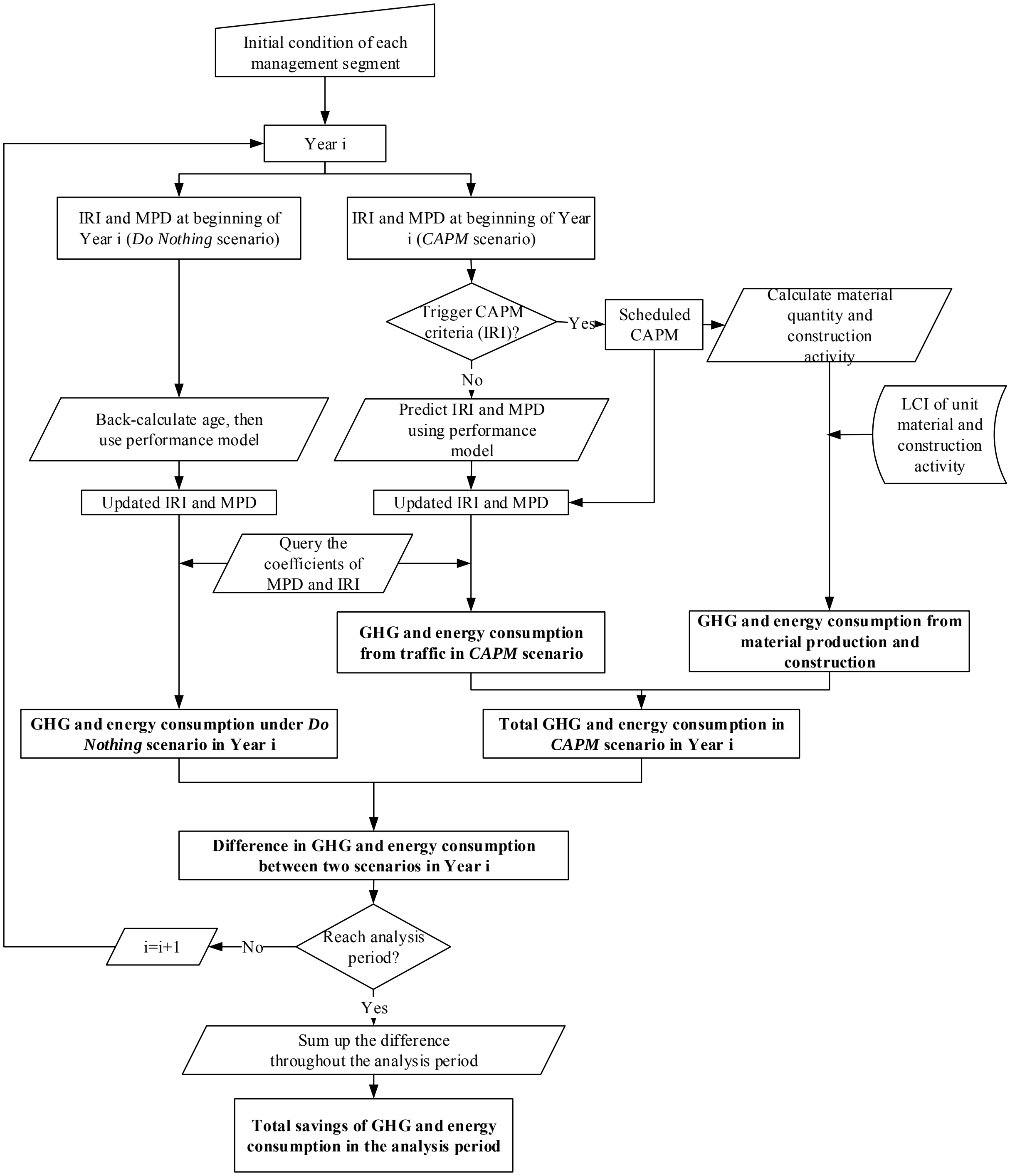


Figure 4.21: Procedure for calculating total GHG reductions for each management segment.

5 RESULTS AND DISCUSSION

5.1 Comparisons of Alternative IRI Triggers against the *Do Nothing* Scenario

5.1.1 GHG Reduction and Optimal IRI Trigger Value

The GHG reductions for each traffic group in the network (as defined in Section 3.3) resulting from CAPM scenarios with different IRI trigger values appear in Figure 5.1. The figure's x-axis shows the IRI value that triggers a CAPM treatment (asphalt overlay for an asphalt-surfaced pavement, and either grinding and slab replacement or lane reconstruction—based on the third-stage cracking—for concrete-surfaced pavement). The figure's y-axis shows the net GHG reduction from the CAPM treatments compared to the *Do Nothing* scenario. Therefore, a positive value means there is a net saving of GHG compared to the *Do Nothing* scenario over the ten-year analysis period, while a negative value indicates a net increase in GHG. The PCE values shown in the figure are the daily PCE of each set of *directional segments* as defined in Section 3.1, representing the total daily PCE of all lanes in that segment. The energy saving results have a similar trend because almost all the GHG emissions in this study were the result of energy consumption.

The result shows that the GHG reductions for CAPM and the few segments with concrete lane replacement are roughly bell-shaped or an S-shaped curve, which is understandable. If the trigger value is too low, the high GHG associated with frequent construction and material consumption can offset the GHG reductions during the Use Phase from improved pavement smoothness, even if the pavement is maintained at a very smooth level. Alternatively, if the trigger value is too high, the pavement can get very rough, which will increase the fuel use of the vehicles that use it. Therefore, an optimal IRI trigger value is the one that leads to the greatest reduction in GHG emissions compared to the *Do Nothing* scenario.

Selecting an optimal IRI trigger value for CAPM therefore involves a trade-off between the environmental impacts that occur in the Material Production and Construction phases and those that occur in the Use Phase. The results show that the largest GHG reductions that can be achieved by performing CAPM treatments come from using different IRI trigger values for different traffic level groups in the network. The higher the traffic level, the lower the IRI trigger value needed to achieve the maximum GHG reduction. Table 5.1 shows the highest GHG reduction for each group of segments in the network and its corresponding IRI trigger value. It can be seen from Table 5.1 and Figure 5.1 that the 10 percent of the network with the highest traffic (Group 7) provides nearly 35 percent of the emissions reduction despite its having similar or lower roughness (Figure 3.3) than the next-lower traffic groups.

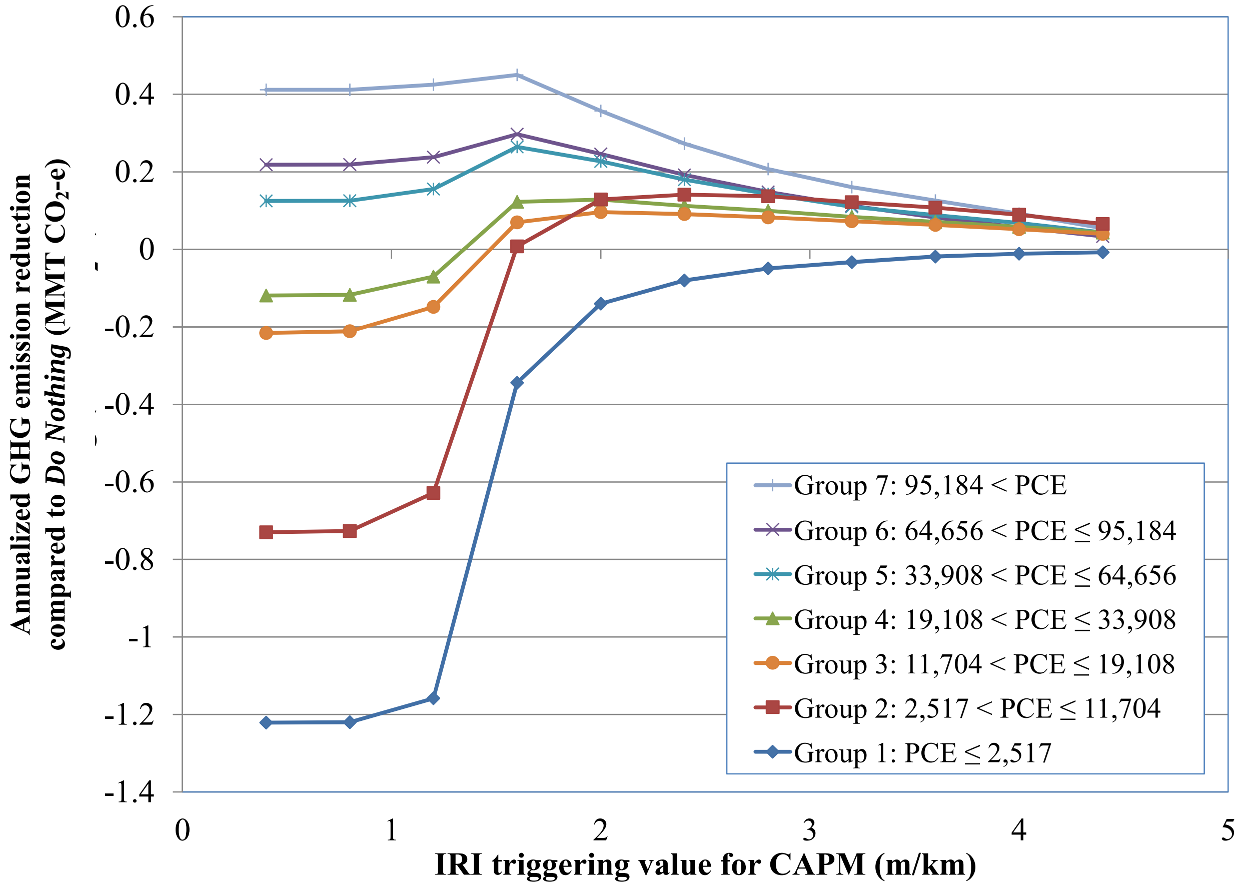


Figure 5.1: Annualized GHG reductions versus IRI trigger values for CAPM for the different traffic level groups over the ten-year analysis period for entire state network.
(1 m/km = 63.4 inches/mile)
(Note: the PCE value on a set of *directional segments* is the total PCE of all lanes in the given direction.)

Table 5.1: IRI Trigger Value for the Maximum Energy and GHG Reductions Compared to *Do Nothing* over the Ten-Year Analysis Period for the Entire Network

Traffic Group No.	Daily PCE of Directional Segments	Total Lane-Miles in the Network	Percentile Range of Lane-Mile in the Network	Optimal IRI Trigger Value (inches/mile) [m/km]	Annualized Energy Savings Compared to *Do Nothing* (million MJ)	Annualized GHG Reductions Compared to *Do Nothing* (MMT CO_2-e)
1	< 2,517	12,068	0 to 25th	—[1]	—[1]	—[1]
2	2,517 to 11,704	12,068	25th to 50th	152 [2.4]	2.04×10^3	0.141
3	11,704 to 19,108	4,827	50th to 60th	127 [2.0]	1.41×10^3	0.096
4	19,108 to 33,908	4,827	60th to 70th	127 [2.0]	1.85×10^3	0.128
5	33,908 to 64,656	4,827	70th to 80th	101 [1.6]	3.88×10^3	0.264
6	64,656 to 95,184	4,827	80th to 90th	101 [1.6]	4.26×10^3	0.297
7	> 95,184	4,827	90th to 100th	101 [1.6]	6.27×10^3	0.45
Total					**1.97×10^4**	**1.38**

Note:
[1]: Not applicable since there was no reduction in GHG.

The results shows that for directional segments with a daily PCE higher than 33,908, which accounts for the 70th percentile and higher in the traffic and cumulative lane-miles distribution plot, the largest GHG reduction comes at an IRI trigger value of 101 inches/mile (1.6 m/km), accounting for about 1.01 million metric tons (MMT) in annualized CO_2-e savings during the ten-year analysis period. For lanes with a daily PCE between 11,704 and 33,908 (from the 50^{th} to 70^{th} percentiles in the traffic and cumulative lane-mile distribution plot), the largest GHG reduction comes at an IRI trigger value of 126 inches/mile (2.0 m/km), which can achieve a total of 0.23 MMT in annualized CO_2-e savings. For segments with a daily PCE between 2,517 and 11,704 (from the 25^{th} to 50^{th} percentiles in the traffic and cumulative lane-mile distribution plot), the largest GHG savings come at a trigger value of 152 inches/mile (2.4 m/km), with a GHG reduction of 0.14 MMT CO_2-e. For segments with a daily PCE lower than 2,517, which are the directional segments with the lowest traffic and make up 25 percent of the total network lane-miles, the results show that the net GHG reductions are negative under any IRI trigger value, indicating that the GHG emissions during the Material Production and Construction phases can never be paid back during the Use Phase within the ten-year analysis period[1].

The total annualized GHG reductions that can be achieved if these optimal IRI trigger values are implemented on corresponding traffic levels is 1.38 MMT CO_2-e over the ten-year analysis period compared to the *Do Nothing* scenario. For comparison, the California Air Resources Board (CARB) has estimated that the average annual GHG from on-road vehicles will be about 168.1 MMT CO_2-e between 2006 and 2020 (*3*). Therefore, for on-road vehicles the GHG reduction estimated from this study can contribute to an approximate 0.8 percent reduction compared to the baseline over the ten-year analysis period.

Using a procedure similar to the one used above, IRI trigger values based on criteria other than GHG reduction, such as the greatest cost-effectiveness, can also be developed. Development of these alternative trigger values are discussed in the following two sections.

It should be noted that performing CAPM on all pavements that reach the designated IRI trigger in each year is unrealistic because these activities are subject to budget constraints. Actual GHG reductions under this scenario require an optimization procedure that uses the annual budget, which can change from year to year, as the constraining criterion. This was not performed in this study. Therefore, the actual amount of savings may be smaller than the values shown in Table 5.1.

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[1] It should be noted that the state would never implement a *Do Nothing* strategy on the entire network, and would only implement *Do Nothing* strategy on those sections where they do not have sufficient funding.

The results in Table 5.1 show that reducing GHG emissions by performing CAPM on rough pavements has the potential to contribute to the statewide GHG reduction target, and that traffic levels play an important role in determining appropriate roughness levels for maintenance of pavement network.

5.1.2 Determining Optimal IRI Trigger Values Based on Cost-Effectiveness

Cost-effectiveness shows the amount of money needed to achieve an amount of environmental impact (here limited to GHG) reduction over an analysis period, which is 10 years in this study. A lower cost-effectiveness value (in $/metric ton CO_2-e emissions reduced) indicates that less money is needed to achieve a particular level of GHG reduction and is therefore preferable (more cost-effective).

In order to learn whether it is more advantageous to Caltrans to implement a GHG-reducing CAPM strategy based on an IRI trigger or on cost-effectiveness, this study also examined the latter and compared it to results from the IRI trigger value investigation. In this study, two types of costs were assessed: *agency cost* and *modified total cost*. *Agency cost* reflects the expenditures required by the transportation agency (i.e., Caltrans) to perform CAPM activities, and *modified total cost* is the *agency cost* less the cost of from reduced fuel consumption by road users due to the improved fuel economy that results from use of smooth pavement. The *total road user cost* also considers vehicle maintenance, consumables in addition to fuel, vehicle life, and accidents. However, high-quality data for these costs were unavailable at the time of this study. A negative *modified total cost* indicated that in the long run this measure can both reduce GHG as well as save money for the two stakeholders (Caltrans and road users) when considered as a whole, and is therefore a “no-regrets” strategy.

In this procedure, this study discounted all costs to 2012, the starting year in the analysis period. A 4 percent annual discount rate was used in accordance with the Caltrans practice, as discussed in Section 4.5. A sensitivity analysis based on the discount rate was performed using 0 percent, 2 percent, and 4 percent, and the results showed no impacts on the relative magnitude of the cost-effectiveness. The annual fuel price for the reduced energy consumption was acquired from the U.S. Department of Energy’s Annual Energy Outlook 2013 *(41)*. Fuel prices change annually, with a ten-year average price about $3.17/gallon of gasoline. This study also considered the salvage value for the agency cost when the service life of the last CAPM event went beyond the ten-year analysis period, using the linear depreciation method. Table 5.2 and Table 5.3 show the cost-effectiveness of CAPM treatments on each group of segments and the overall cost-effectiveness on the entire network of using the optimized IRI trigger values.

Table 5.2: IRI Trigger Value for the Maximum Energy and GHG Reductions over the Ten-Year Analysis Period for the Entire Network Compared to the *Do Nothing* Scenario

Traffic Group Number	IRI Trigger Value (inches/mile) [m/km]	Total Energy Savings over 10 years[1] (million MJ)	Total GHG Reductions over 10 years[1] (MMT CO_2-e)	Total Agency Cost over 10 Years (million $)	Agency Cost-Effectiveness ($/metric ton CO_2-e)	Savings from Vehicle Fuel Consumption[2] (million $)	Modified Total Cost (million $)	Modified Total Cost-Effectiveness ($/metric ton CO_2-e)
1	–	–[3]	–[3]	–[3]	–[3]	–[3]	–[3]	–[3]
2	152 [2.4]	2.04×10^4	1.41	1,927	1,365	277	1,651	1,169
3	127 [2.0]	1.41×10^4	0.96	1,024	1,067	201	823	857
4	127 [2.0]	1.85×10^4	1.28	927	724	283	644	503
5	101 [1.6]	3.88×10^4	2.64	1,969	745	604	1,365	516
6	101 [1.6]	4.26×10^4	2.97	1,460	491	691	768	259
7	101 [1.6]	6.27×10^4	4.50	1,511	336	1,042	469	104
Total		**1.97×10^5**	**13.77**	**8,819**	**641**	**3,099**	**5,720**	**416**

Notes:

[1]: The results shown here are the total energy savings and GHG reductions over the ten-year analysis period. The reason that annualized reduction is not used here is to avoid confusion between "annualized cost" and "Equivalent Uniform Annual Cost (EUAC)," the latter of which has special meaning in life-cycle cost analysis. From here on, when GHG savings are presented along with cost, the total savings over ten years are used.

[2]: The ten-year average gasoline price is about $3.17/gal.

[3]: Not applicable since no GHG reduction.

Table 5.3: IRI Trigger Value for the Maximum Cost-Effectiveness (Based on Modified Total Cost) over the Ten-Year Analysis Period for the Entire Network Compared to the *Do Nothing* Scenario

Traffic Group Number	IRI Trigger Value (inches/mile) [m/km]	Total Energy Savings over 10 Years (million MJ)	Total GHG Reductions over 10 Years (MMT CO_2-e)	Total Agency Cost over 10 Years (million $)	Agency Cost-Effectiveness ($/metric ton CO_2-e)	Total Savings from Vehicle Fuel Consumption over 10 Years[1] (million $)	Modified Total Cost over 10 Years (million $)	Modified Total Cost-Effectiveness ($/metric ton CO_2-e)
1	–	–[2]	–[2]	–[2]	–[2]	–[2]	–[2]	–[2]
2	279 [4.4]	9.24×10^3	0.65	359	550	137	223	341
3	279 [4.4]	5.60×10^3	0.40	144	361	87	57	142
4	279 [4.4]	6.05×10^3	0.43	111	257	96	16	36
5	279 [4.4]	6.12×10^3	0.44	78	178	99	-21	-48
6	279 [4.4]	4.65×10^3	0.33	40	121	74	-34	-102
7	279 [4.4]	7.50×10^3	0.54	42	78	122	-80	-147
Total		**3.92×10^4**	**2.80**	**774**	**277**	**614**	**160**	**57**

Notes:
[1]: The ten-year average gasoline price is about $3.17/gal.
[2]: Not applicable since no GHG reduction.

It is noteworthy that the IRI trigger value for the maximum energy and GHG reductions were the not the same as those that led to the highest modified total cost-effectiveness over the ten-year analysis period. In fact, under all traffic levels, the greatest modified total cost-effectiveness level always occurred at the IRI trigger value of 279 inches/mile (4.4 m/km), which is the arbitrarily determined highest IRI trigger value analyzed in this study. Sensitivity analysis on the discount rate showed that this result stayed the same for discount rates of 0 percent and 2 percent. The reason for this phenomenon is this: with a higher IRI trigger value, the relative change in cost is always greater than the relative change in CO_2-e emissions. Figure 5.2 provides an example of this situation.

In Figure 5.2, a black line represents IRI progression under the *Do Nothing* scenario and the blue and red lines represent situations with higher and lower IRI trigger values, respectively. GHG reduction is linearly related to the area between the *Do Nothing* IRI curve and either of the IRI curves. A relatively high IRI trigger value triggers less frequent CAPM events and thus leads to lower agency cost, but whenever a treatment is triggered it also brings a relatively larger drop in IRI and thus leads to a relatively higher GHG reduction than a lower IRI trigger value. This occurs because in the performance model a drop in IRI from a treatment is linearly related to the IRI level before treatment. As a result, as an IRI trigger value increases, the cost-effectiveness becomes greater (represented by lower cost per ton of CO_2-e reduction). The same principle applies if an IRI trigger value decreases.

Therefore, the overall effect is that whenever an IRI trigger value changes, in relative terms, the resultant change in cost will always be greater than the change in GHG reduction, which means that if GHG reduction decreases, the cost will become even lower, and vice versa. However, it should be noted that this conclusion is a preliminary finding for CAPM treatments that have relatively short design lives, and only road user fuel costs have been considered. This conclusion may change if longer-lived treatments and total road user costs are evaluated.

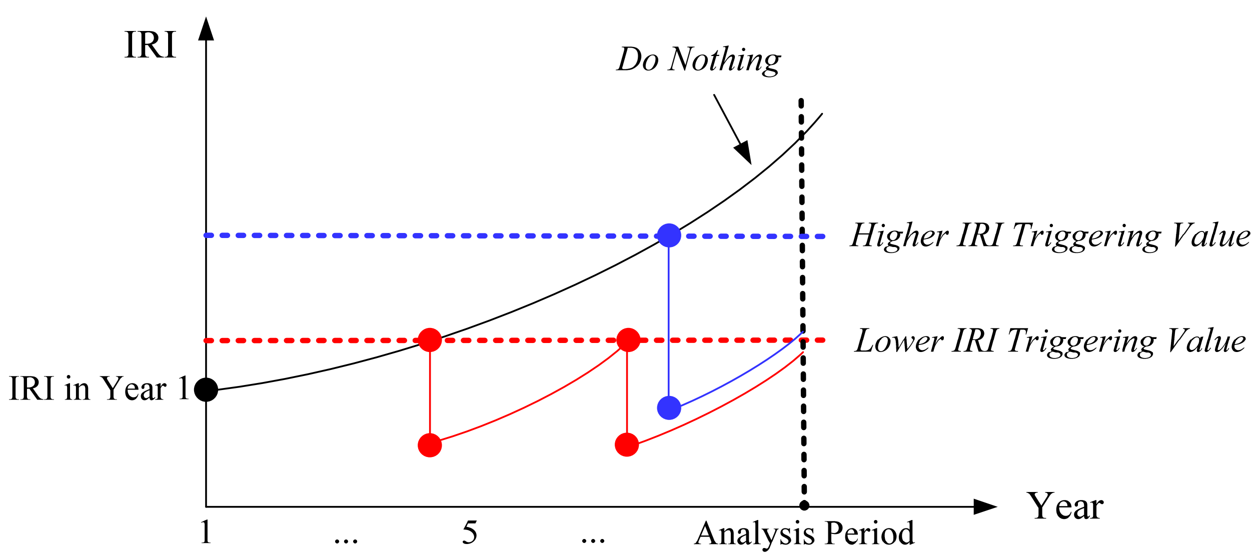

Figure 5.2: Example of the effect of different IRI trigger values on treatment timing and cost-effectiveness.

5.2 Comparison with the Existing Caltrans IRI Trigger Value

The results shown so far in this study compare the CAPM scenario with the *Do Nothing* scenario, while in reality Caltrans is not following a *Do Nothing* scenario but routinely performs M&R activities based on its existing treatment timing strategies (within annual budget constraints). Therefore, the GHG reduction shown so far may indicate an unrealistic extreme for GHG reduction. It is necessary to evaluate the marginal GHG reduction and cost compared to the existing Caltrans triggering strategies assuming Caltrans has the budget to maintain all the segments that the current strategies would identify for treatment.

Caltrans' historical PMS prioritization policies prior to the year 2011 used an IRI trigger value of 224 inches/mile (3.54 m/km) for asphalt pavement and 213 inches/mile (3.36 m/km) for concrete pavement *(44).* Since 2011, the IRI trigger value has been 170 inches/mile (2.68 m/km) on all types of pavements. Table 5.4 and Table 5.5, respectively, show the GHG reduction and cost (*agency cost* and *modified total cost*) of the *Do Nothing* scenario compared to scenarios using the historical Caltrans IRI trigger values and the current Caltrans IRI trigger value over the ten-year analysis period. As in Section 5.1, a positive value means there is a net saving of GHG compared to the historical or current Caltrans triggers over the ten-year analysis period, while a negative value indicates a net increase in GHG.

It can be seen that, using the historical Caltrans IRI trigger value[1], the annualized GHG reduction compared to *Do Nothing* was 0.56 MMT of CO_2-e, with an *agency cost-effectiveness* of \$572/metric ton CO_2-e and a *modified total cost-effectiveness* of \$355/metric ton CO_2-e. Using the current Caltrans IRI trigger value[2], the annualized GHG reduction compared to *Do Nothing* over the analysis period was 0.81 MMT of CO_2-e, with an *agency cost-effectiveness* of \$737/metric ton CO_2-e and a *modified total cost-effectiveness* of \$520/metric ton CO_2-e. Therefore, compared to the historical Caltrans IRI trigger value, the current Caltrans IRI trigger value of 170 inches/mile substantially reduces GHG, although it is less cost-effective from an agency perspective. The results are shown in Table 5.6 and Table 5.7.

Table 5.6 and Table 5.7 show comparisons of GHG reduction and cost between the optimal IRI trigger values developed in this study and the two existing IRI trigger values adopted by Caltrans (historical and current), respectively. The results show that, compared to using of the historical Caltrans IRI trigger value, the optimal IRI trigger values of this study can achieve a marginal annualized GHG reduction of 0.82 MMT CO_2-e, with a

[1] For GHG reduction and cost from using historical Caltrans IRI trigger value, 219 inches/mile (3.45 m/km) is used as the IRI trigger value (averaged from asphalt and concrete), and the results were calculated through interpolation from Figure 5.1.

[2] The GHG reduction and cost from using 170 inches/mile as the IRI trigger value were calculated through interpolation from Figure 5.1.

marginal *agency cost-effectiveness* of \$688/metric ton CO_2-e and a marginal *modified total cost-effectiveness* of \$457/metric ton CO_2-e.

Compared to the current Caltrans IRI trigger value, the optimal IRI trigger values developed in this study can achieve a marginal annualized GHG reduction of 0.57 MMT of CO_2-e, with a marginal *agency cost-effectiveness* of \$502/metric ton CO_2-e and a marginal *modified total cost-effectiveness* of \$266/metric ton CO_2-e. The reason for the increased marginal cost-effectiveness is that the current Caltrans IRI trigger value is much closer to the optimal IRI trigger values developed in this study than the historical Caltrans trigger, and this leads to a very small marginal *agency cost* and *modified total cost* when the optimal IRI trigger values developed this study were compared with the current Caltrans trigger value. As discussed in the previous section, when applying different trigger values, in relative terms the change in cost is always greater than the change in CO2-e reduction. Therefore, the marginal cost-effectiveness increases when the IRI trigger value is compared with Caltrans historical and current trigger values as opposed to *Do Nothing*.

In actual Caltrans practice, even if the IRI of a segment has reached its designated trigger value, the M&R activity might not happen for another one to three years because of project development and delivery times , and this period may be longer if there are budget constraints. Therefore it can be expected that the actual GHG reductions and the cost in the analysis period will be smaller than the values shown in Table 5.1.

The following calculation shows an example of how much GHG reduction and cost can change if the M&R activity does not occur soon after being triggered. For a two-lane (one direction) one-mile rural freeway with a one-direction AADT of 12,000 and 10 percent trucks, the daily PCE is 12,600 and therefore the CAPM on this segment should be triggered at 127 inches/mile (2 m/km). Table 5.8 shows the results when the CAPM treatment was performed with different delays. In this case, if the CAPM treatment was performed 1, 2, and 3 years after the IRI reached the trigger, the GHG reductions would drop by approximately 6 percent, 13 percent, and 18 percent respectively, compared to a situation where CAPM was performed on time. It is also evident that the cost dropped faster than the GHG reductions when CAPM was delayed and a 4 percent discount rate was used. Although the delay can lead to a better cost-effectiveness value, it considerably reduces the potential GHG reductions. These results indicate that it is important to program treatments for the time that it is predicted a segment will reach the trigger value using performance models in PaveM, as opposed to waiting until the trigger value is measured and then programming the treatment.

Table 5.4: GHG Reduction and Cost of Historical Caltrans IRI Trigger Values Compared to *Do Nothing* over the Ten-Year Analysis period for the Entire Network

Traffic Group Number	IRI Trigger Value (inches/mile) [m/km]	Total GHG Reductions over 10 Years (MMT CO_2-e)	Total Agency Cost over 10 Years (million $)	Agency Cost-Effectiveness ($/metric ton CO_2-e)	Total Savings from Vehicle Fuel Cost[1] (million $)	Modified Total Cost (million $)	Modified Total Cost-Effectiveness ($/metric ton CO_2-e)
1	219 [3.45]	-0.24	1,232	-5,127	-100	1,332	-5,541
2	219 [3.45]	1.13	853	755	233	620	549
3	219 [3.45]	0.67	320	479	147	173	258
4	219 [3.45]	0.76	259	341	171	88	116
5	219 [3.45]	0.97	242	250	224	18	19
6	219 [3.45]	0.94	163	173	218	-55	-59
7	219 [3.45]	1.39	141	101	321	-180	-130
Total		**5.61**	**3,210**	**572**	**1,215**	**1,995**	**355**

[1]: Ten-year average gasoline price = $3.17/gal.

Table 5.5: GHG Reduction and Cost of Current Caltrans IRI Trigger Values Compared to *Do Nothing* over the Ten-Year Analysis Period for the Entire Network

Traffic Group Number	IRI Trigger Value (inches/mile) [m/km]	Total GHG Reductions over 10 Years (MMT CO_2-e)	Total Agency Cost over 10 Years (million $)	Agency Cost-Effectiveness ($/metric ton CO_2-e)	Savings from Vehicle Fuel Cost[1] (million $)	Modified Total Cost (million $)	Modified Total Cost-Effectiveness ($/metric ton CO_2-e)
1	170 (2.68)	-0.58	2,100	-3,620	-207	2,308	-3,977
2	170 (2.68)	1.38	1,556	1,126	277	1,279	926
3	170 (2.68)	0.85	568	667	186	382	448
4	170 (2.68)	1.03	499	484	232	267	259
5	170 (2.68)	1.54	539	351	361	178	116
6	170 (2.68)	1.61	382	237	381	1	1
7	170 (2.68)	2.26	325	144	528	-203	-90
Total		**8.10**	**5,970**	**737**	**1,758**	**4,212**	**520**

[1]: Ten-year average gasoline price = $3.17/gal.

Table 5.6: Optimal IRI Trigger Values Compared to Historical Caltrans IRI Trigger Values over the Ten-Year Analysis Period for the Entire Network

Traffic Group Number	Marginal GHG Reduction (MMT CO_2-e)	Marginal Agency Cost (million $)	Marginal Agency Cost-Effectiveness ($/metric ton CO_2-e)	Marginal Modified Total Cost (million $)	Marginal Modified Total Cost-Effectiveness ($/metric ton CO_2-e)
1	0.24	-1,232	-5,127	-1,332	-5,541
2	0.28	1,074	3,818	1,031	3,664
3	0.29	704	2,420	650	2,234
4	0.52	669	1,283	556	1,067
5	1.68	1,727	1,030	1,348	803
6	2.03	1,297	638	824	405
7	3.11	1,370	441	649	209
Total	**8.15**	**5,609**	**688**	**3,725**	**457**

Table 5.7: Optimal IRI Trigger Values Compared to Current Caltrans IRI Trigger Value over the Ten-Year Analysis Period for the Entire Network

Traffic Group Number	Marginal GHG Reduction (MMT CO_2-e)	Marginal Agency Cost (million $)	Marginal Agency Cost-Effectiveness ($/metric ton CO_2-e)	Marginal Modified Total Cost (million $)	Marginal Modified Total Cost-Effectiveness ($/metric ton CO_2-e)
1	0.58	-2,100	-3,620	-2,308	-3,977
2	0.03	371	12,699	371	12,701
3	0.11	456	4,240	440	4,098
4	0.25	428	1,716	377	1,511
5	1.11	1,430	1,293	1,188	1,074
6	1.36	1,078	791	767	563
7	2.24	1,186	531	672	301
Total	**5.67**	**2,849**	**502**	**1,508**	**266**

Table 5.8: Example of Comparison between On-Time and Late Triggering (Ten-Year Analysis Period)

When is CAPM Performed	Agency Cost Compared to *Do Nothing* ($)	GHG Reduction Compared to *Do Nothing* (metric ton CO_2-e)	Cost Ratio (compared to on-time triggering cost)	GHG Ratio (compared to on-time triggering)
On time	8.72×10^5	6.22×10^4	1.00	1.00
1 year later	7.90×10^5	5.85×10^4	0.91	0.94
2 years later	7.16×10^5	5.39×10^4	0.82	0.87
3 years later	7.04×10^5	5.08×10^4	0.81	0.82

5.3 Comparison with Alternative GHG Mitigation Measures

Lutsey examined GHG mitigation strategies for the transportation sector and their cost-effectiveness (*5*). The cost-effectiveness of the pavement preservation treatments in this study are considerably lower than many in the alternative measures Lutsey identified, which are shown in Table 5.9 *(5)*.

Table 5.9: Comparison of Cost-Effectiveness between Reducing GHG through Optimizing Pavement Treatment and Some Alternative Measures in the Transportation Sector (*5*)

Measure	Annual CO_2-e Emissions Reduction[1]	Total Cost-Effectiveness ($2008/metric ton CO_2-e)
Light duty vehicle: Incremental efficiency	20% tailpipe reduction	-75
Light duty vehicle: Advanced hybrid vehicle	38% tailpipe reduction on new vehicles	42
Commercial trucks: Class 2b efficiency	25% tailpipe reduction	-108
Alternative refrigerant	Replacement of HFC-134a with R-744a (CO2)	67
Ethanol fuel substitution	Increase mix of cellulosic ethanol to 13% by volume	31
Biodiesel fuel substitution	Increase mix of biodiesel to 5% by volume	51
Aircraft efficiency	35% reduction in energy Intensity	-9
Use of optimized pavement roughness triggers [this study]	1.38 MMT	390[2]

Notes:

[1]: The first seven measures calculated by Lutsey are the value in 2025. The value for use of optimized pavement roughness triggers from this study is an annualized value between 2012 and 2021.

[2]: This result was calculated in 2012 dollars and is converted to 2008 dollars in this table using the consumer price index (CPI).

The high cost results for use of optimized pavement roughness triggers shown in the bottom right cell of the table occur because the construction of civil infrastructure is expensive, and more importantly, the costs evaluated in this study only include the agency and fuel cost, and exclude other road user costs. Because the main functionality of pavement is to maintain the mobility of goods and people using vehicles, one of the primary purposes for pavement management is to ensure the transportation safety and efficiency, which road users cares about most. Therefore, a more comprehensive benefit analysis would include other social benefits such as vehicle life, safety, tire consumption, goods damage, vehicle maintenance, driver comfort, and the value of time. From this point of view, the CO_2-e reduction can be considered a "co-benefit" from pavement management when used as a GHG mitigation measure, and will be more cost-effective if all road user costs reductions are included.

A preliminary study showed that while fuel consumption (and therefore fuel cost) exhibits a linear relationship with roughness, total road user cost can increase exponentially with pavement roughness *(45)*. The ratio between total road user cost and fuel cost ranges from 6 to 10, depending on the vehicle type, driving speed, and pavement condition *(45)*. A first-order estimate shows that total cost-effectiveness can range from -$710/metric ton CO_2-e to -$1,610/ metric ton CO_2-e (compared to the $416/metric ton CO_2-e as shown in Table 5.2) if all road user costs are included. This result indicates pavement management, when properly programmed as in this study, can potentially be a cost-competitive measure to reduce GHG emissions if total road user cost is considered. Once the total cost models as a function of pavement roughness for California are fully developed, the comparison with other transportation strategies should be performed again.

5.4 Sensitivity Analyses

The main input data for this study include the traffic count and IRI on the state pavement network, the emissions factors from the *MOVES* model, maintenance cost, and IRI performance.

The traffic counts used in this study were extracted from the traffic database used by the Caltrans PMS. They incorporate high-quality data from Caltrans Performance Measurement System (PeMS) and Weigh-In-Motion (WIM) stations. The IRI values on the network were collected in the 2011 Caltrans Automated Pavement Condition Survey. Because of their wide use within Caltrans, these two sources of data have gone through a number of quality control and quality assurance studies to ensure their accuracy, and should have minimal uncertainty. For emission factors, because *MOVES* itself does not provide an uncertainty analysis module, it is very difficult to perform any uncertainty analyses outside this complex model. Because this study was also focused on the emissions difference between scenarios, the uncertainty of emission factors could be expected to play a less important role. For maintenance cost, although it is averaged from historical Caltrans construction projects and there are some uncertainties associated with it, it can be predicted that the impact on the result will be completely linear because this study did not include cost in the optimization procedure.

Therefore, sensitivity analyses were performed on two variables to assess their impacts on the results: constructed smoothness and analysis period. They are discussed in the following sections.

5.4.1 Constructed Smoothness

To evaluate the influence of construction quality on modeling results, the initial smoothness after the construction of CAPM was used as a sensitivity factor. Three levels of initial smoothness after construction were considered (based on the standard deviation of residuals from Equation 4.1 and Equation 4.4, for asphalt overlay and concrete grinding, respectively): *Smooth CAPM*, which is the best estimate IRI modeling value minus one standard deviation from the initial IRI model; *Medium Smooth CAPM*, which is the value directly calculated from the model (the result shown in Section 4.4.1); and *Less Smooth CAPM*, which is the modeling value plus one standard deviation. The agency cost for *Smooth CAPM* was considered to be 15 percent higher than *Medium Smooth CAPM*, and the agency cost for *Less Smooth CAPM* was 15 percent lower, reflecting the effort and attention needed by contractors to implement each IRI specification.

The results are shown in Figure 5.3 and Figure 5.4, and are summarized in Table 5.10. It can be seen that the results are still approximately bell-shaped or S-shaped curves. However, the variability of initial constructed smoothness shown for the *Smooth CAPM* and *Less Smooth CAPM* cases greatly change the results compared to the previously shown mean (*Medium Smoothness*) results. In *Smooth CAPM*, the IRI trigger values that led to the largest GHG and energy saving was about 51 inches/mile (0.8 m/km) lower than those in *Medium Smooth CAPM*. Even the traffic group with a daily PCE less than 2,517 showed a GHG reduction at a trigger value of 254 inches/mile (4 m/km).

This is because the lower initial IRI after the treatment led to greater benefits with respect to GHG reduction when CAPM was performed. Therefore the pavement can be maintained at a smoother level. An annualized GHG reduction of 2.89 MMT CO_2-e can be achieved if *Smooth CAPM* is implemented, more than twice the result from *Medium Smooth CAPM*. Meanwhile *Smooth CAPM* achieved a modified total cost-effectiveness of \$370/metric ton CO_2-e. This is also expected because in *Smooth CAPM*, each time that CAPM was triggered, even with a 15 percent greater agency cost than the *Medium Smooth CAPM*, the IRI drop after the treatment was even bigger, which led to more GHG benefits. On the other hand, under the *Less Smooth CAPM* scenario, because the initial IRI after the treatment was higher than the *Medium Smooth CAPM*, it takes longer to accumulate enough GHG reductions to offset the emissions from material production and construction. The average IRI trigger value was about 63 inches/mile (1 m/km) higher than those in *Medium Smooth CAPM*, leading to an annualized GHG reduction of 0.47 MMT of CO_2-e compared to the *Do Nothing* scenario which had a modified total cost-effectiveness of \$731/metric ton CO_2-e, less than half of the GHG reduction achieved in *Medium Smooth CAPM*.

Constructed smoothness is primarily controlled by construction practice and quality control, the existing pavement condition, and to a lesser degree by the treatment type. Some "Best Practices" to improve the constructed smoothness include pre-paving/grinding, good planning and preparation, good mix design, grade control, equipment control, and good communication between personnel *(46, 47).* Constructed smoothness has historically not been specified in terms of IRI in California and in most other states due to technical difficulties; a specification based on a moving beam has been used to identify "bumps" which were then removed before acceptance of the completed project. However, those difficulties have recently been solved and many states are now moving to constructed smoothness specifications in terms of IRI. The new specifications are expected to reduce both the average IRI obtained from treatment as well as IRI variability. For example, California implemented an IRI-based constructed smoothness specification in July 2013. However, data are not yet available to analyze the marginal benefit from this and other specific practices to improve smoothness.

The sensitivity analysis again shows that the constructed smoothness achieved after the M&R activities is crucial to the total GHG reduction and determination of the IRI trigger value. If the construction does not result in a smooth pavement, the benefit from the treatment can be greatly reduced, and if the construction leads to a better-than-average pavement, the benefit achieved can be more than doubled.

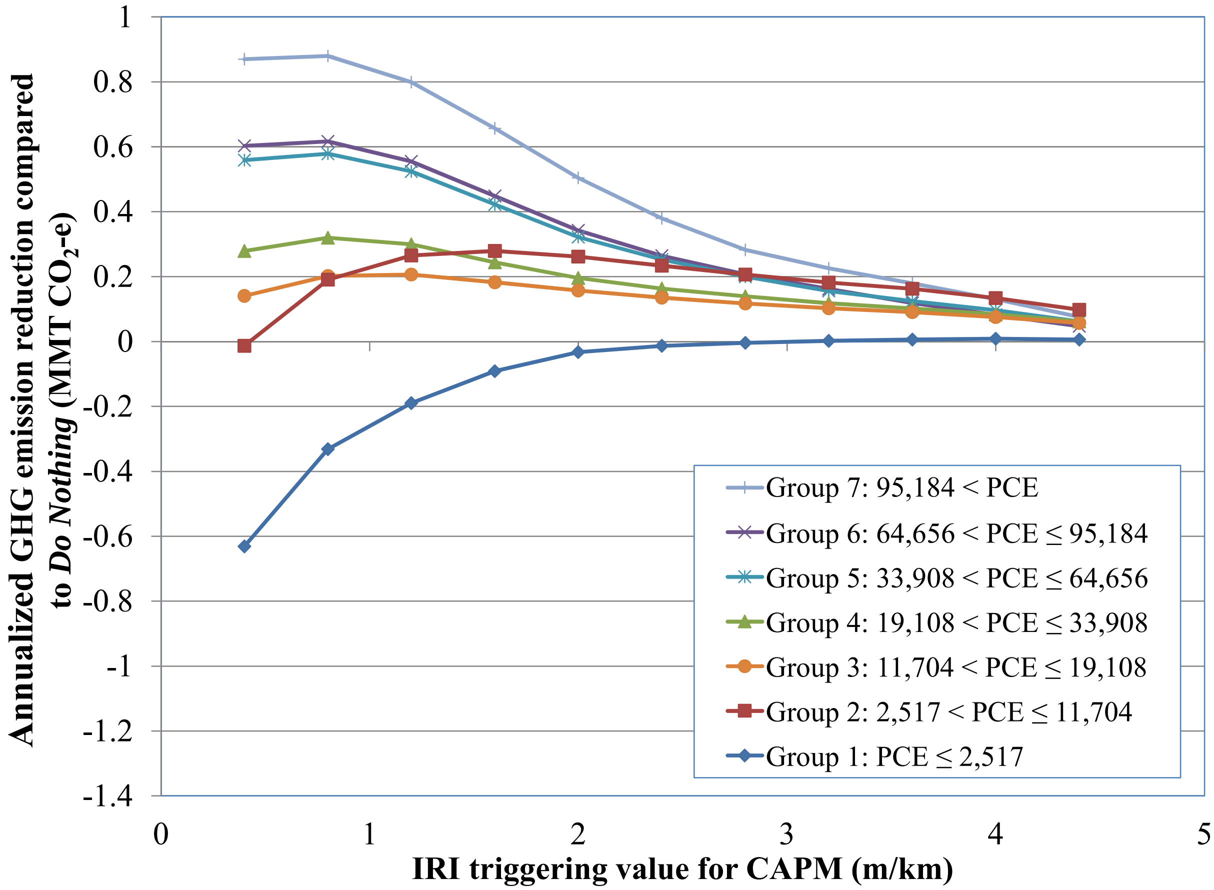

Figure 5.3: Annualized GHG reductions versus IRI trigger value under the *Smooth CAPM* scenario over a ten-year analysis period.
(1 m/km = 63.4 inches/mile)

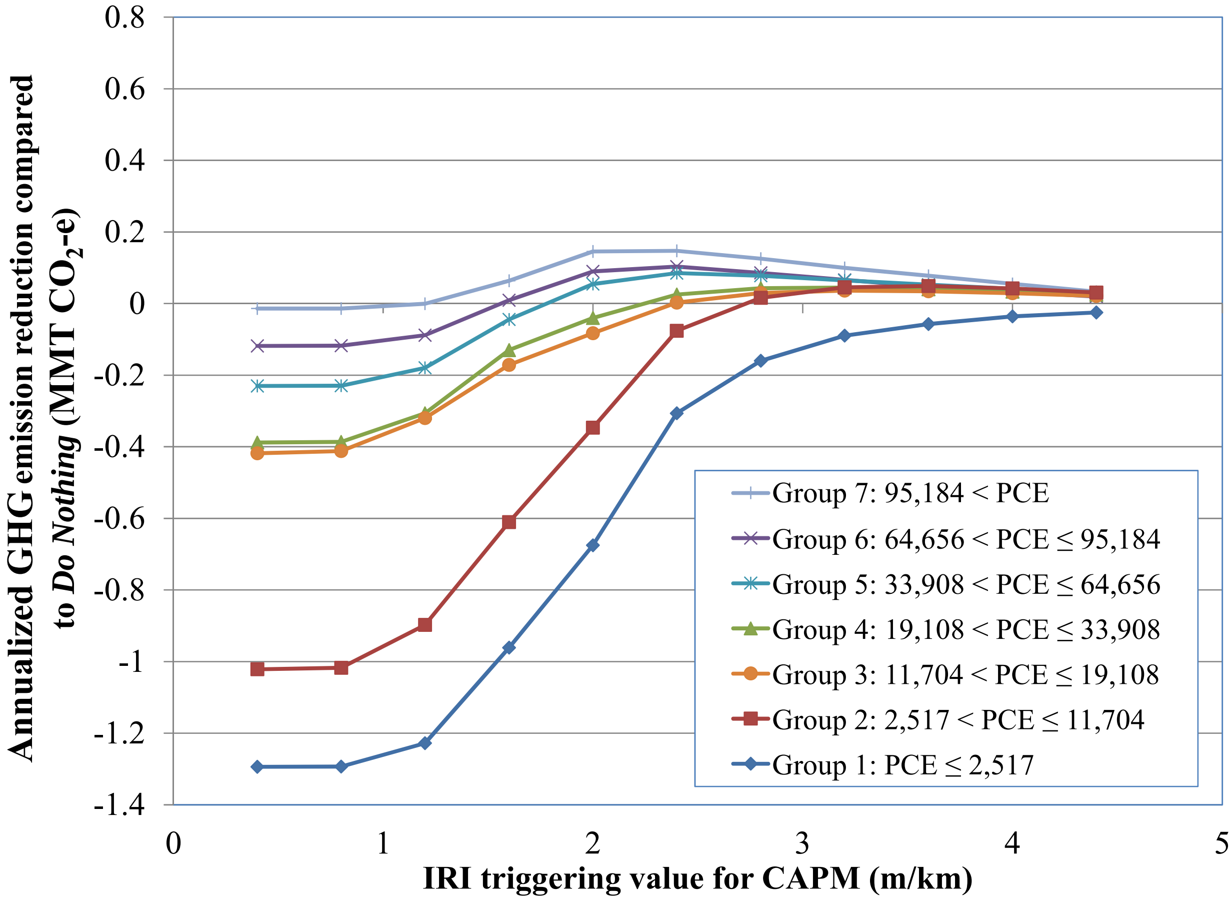

Figure 5.4: Annualized GHG reductions versus IRI trigger value under the *Less Smooth CAPM* scenario over a ten-year analysis period.
(1 m/km = 63.4 inches/mile)

Table 5.10: Sensitivity Analysis of Constructed Smoothness for the Maximum Energy and GHG Reductions over the Ten-Year Analysis Period

Traffic Group	Daily PCE of Directional Segments	*Smooth CAPM* (-σ)		*Medium Smooth CAPM* (mean)		*Less Smooth CAPM* (+σ)	
		IRI Trigger Value (inches/mile) [m/km]	GHG Reductions (MMT CO_2-e)	IRI Trigger Value (inches/mile) [m/km]	GHG Reductions (MMT CO_2-e)	IRI Trigger Value (inches/mile) [m/km]	GHG Reductions (MMT CO_2-e)
1	≤ 2,517	254 [4]	0.09	—	0	—	0
2	2,517 to 11,704	101 [1.6]	2.79	152 [2.4]	1.41	228 [3.6]	0.49
3	11,704 to 19,108	76 [1.2]	2.06	127 [2]	0.96	203 [3.2]	0.36
4	19,108 to 33,908	51 [0.8]	3.20	127 [2]	1.28	203 [3.2]	0.44
5	33,908 to 64,656	51 [0.8]	5.79	101 [1.6]	2.64	152 [2.4]	0.85
6	64,656 to 95,184	51 [0.8]	6.17	101 [1.6]	2.97	152 [2.4]	1.03
7	> 95,184	51 [0.8]	8.79	101 [1.6]	4.50	152 [2.4]	1.47
Total GHG reduction (MMT CO_2-e)			**28.89**		**13.77**		**4.66**
Annualized GHG reduction (MMT CO_2-e)			**2.89**		**1.38**		**0.47**
Modified total cost-effectiveness ($/metric ton CO_2-e)		**370**		**416**		**731**	

5.4.2 Analysis Period

The determination of analysis period was one of the topics discussed in the UCPRC Pavement LCA Workshop in 2010. The outcome of the workshop was that the *UCPRC Pavement LCA Guideline* proposed three possible ways to handle the analysis period: (1) use 1.2 to 1.5 times the longest functional design life among all the alternatives, (2) use the duration until the next major rehabilitation, or (3) use differing analysis periods for each treatment and annualize/amortize construction and M&R events and compare annual emissions *(15).*

In this study, a ten-year analysis period was used to cover the design life of CAPM treatments. This is because this study considered that the same CAPM activities (no major rehabilitation or reconstruction activities) would be repeated after the pavements reached the designated IRI trigger value beyond the analysis period. Further, this study annualized the impact from the Material Production and Construction phases of the last CAPM event to avoid the "penalty" from these phases in the situation where a CAPM treatment was very close to the end of the analysis period and the impacts from these two phases could not get fully paid back within the analysis period. Therefore, the selection of analysis period was not expected to arise as an important problem in this study. However, to evaluate the impact of the analysis period on the final result, sensitivity analysis was performed using three analysis periods: 10 years, 15 years, and 20 years. The results are summarized in Table 5.11.

It can be seen that different analysis periods did not substantially change the optimal IRI trigger values in this study, except for two groups that had slightly lower IRI optimal trigger values. The IRI trigger value of Group 4 (19,108 < Daily PCE ≤ 33,908) changed from 127 inches/mile to 101 inches/mile (2.0 m/km to 1.6 m/km) when the analysis period changed from 10 years to 15 years and 20 years. This is probably due to the fact that the IRI in the *Do Nothing* scenario was also increasing and therefore, as the analysis period grew longer, there was a small tendency for the IRI difference between the *Do Nothing* scenario and the *CAPM* scenario to also become larger. This bigger difference in IRI could result in a greater GHG benefit (compared to *Do Nothing*), which therefore made it preferable to perform CAPM at a lower IRI trigger value. However, overall the analysis period did not substantially change the results from this study.

Table 5.11: Sensitivity Analysis of Analysis Period for the Maximum Energy and GHG Reductions Using CAPM Treatments (GHG Reductions Are Results Compared to *Do Nothing*, Historical Caltrans Trigger, and Current Caltrans Trigger)

Traffic Group	Daily PCE of Directional Segments	10-Year Analysis Period				15-Year Analysis Period				20-Year Analysis Period			
		Optimal IRI Trigger Value (inches/mile) [m/km]	GHG Reductions Compared to (MMT CO_2-e)			Optimal IRI Trigger Value (inches/mile) [m/km]	GHG Reductions Compared to (MMT CO_2-e)			Optimal IRI Trigger Value (inches/mile) [m/km]	GHG Reductions Compared to (MMT CO_2-e)		
			Do Nothing	Historical Caltrans	Current Caltrans		*Do Nothing*	Historical Caltrans	Current Caltrans		*Do Nothing*	Historical Caltrans	Current Caltrans
1	≤ 2,517	—	0	0.24	0.58	—	0.00	0.30	0.69	—	0	0.28	0.73
2	2,517 to 11,704	152 [2.4]	1.41	0.28	0.03	152 [2.4]	3.03	0.70	0.14	152 [2.4]	5.13	1.33	0.32
3	11,704 to 19,108	127 [2]	0.96	0.29	0.11	127 [2]	2.02	0.68	0.30	127 [2]	3.46	1.31	0.64
4	19,108 to 33,908	127 [2]	1.28	0.52	0.25	101 [1.6]	2.72	1.22	0.67	101 [1.6]	4.96	2.52	1.54
5	33,908 to 64,656	101 [1.6]	2.64	1.68	1.11	101 [1.6]	5.58	3.62	2.43	101 [1.6]	9.80	6.46	4.33
6	64,656 to 95,184	101 [1.6]	2.97	2.03	1.36	101 [1.6]	6.10	4.17	2.84	101 [1.6]	10.60	7.23	4.91
7	> 95,184	101 [1.6]	4.50	3.11	2.24	101 [1.6]	9.06	6.31	4.49	101 [1.6]	15.50	10.81	7.45
Total GHG reduction (MMT CO_2-e)			**13.77**	**8.15**	**5.67**		**28.51**	**17.00**	**11.55**		**49.45**	**29.94**	**19.92**
Annualized GHG reduction (MMT CO_2-e)			**1.38**	**0.82**	**0.57**		**1.90**	**1.13**	**0.77**		**2.47**	**1.50**	**1.00**
Modified total cost-effectiveness ($/metric ton CO_2-e)			**416**	**457**	**266**		**273**	**300**	**249**		**162**	**171**	**153**

6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this study, a simplified version of the life-cycle assessment model developed in a previous project-level study was applied to the California state pavement network to evaluate a strategy that consists of applying CAPM maintenance treatments and a small number of concrete lane replacements to rough pavement, and the strategy's potential impact on GHG emissions. The network was broken into different groups based on their traffic levels. An IRI value for triggering a CAPM treatment that can lead to the highest energy and reduce GHG emissions was developed for each group.

Based on the analyses in this study:

- Neither the presence of congestion nor the road gradient have a substantial impact on the fuel economy change brought about by a reduction in rolling resistance due to roughness and macrotexture. This indicates that the impact of rolling resistance on the total vehicle fuel consumption is relatively robust and not strongly influenced by these factors.
- The traffic level has a substantial impact on GHG emissions reduction and the optimized IRI values that trigger CAPM treatments. Performing CAPM on segments that have very low daily passenger car equivalents (PCEs) in the network does not lead to net GHG emissions reduction or energy benefits.
- The optimal IRI trigger values for segments with higher traffic volumes vary. The higher the traffic volume, the lower the IRI trigger value needed to achieve the maximum net GHG emissions reduction benefit. An annualized GHG reduction of 1.38 MMT CO_2-e compared to the *Do Nothing* scenario (minimal maintenance of the pavement to keep the IRI at or below 279 inches/mile [4.4 m/km]) in the ten-year analysis period occurs if the optimal IRI trigger values are implemented on the network.
- Cost analysis shows that the optimal IRI trigger values from this study can achieve a cost-effectiveness of \$641/metric ton CO_2-e with *agency cost* accounting and \$416/metric ton CO_2-e with *modified total cost* accounting considering the cost of road user vehicle fuel and agency cost together, compared to the *Do Nothing* scenario over the ten-year analysis period.
- Compared to the historical Caltrans IRI trigger value, the optimal IRI trigger values from this study can achieve an annualized marginal GHG emissions reduction of 0.82 MMT CO_2-e, with a marginal *agency cost-effectiveness* of \$688/metric ton CO_2-e and a marginal *modified total cost-effectiveness* of \$457/metric ton CO_2-e.
- Compared to the current Caltrans IRI trigger value (170 inches/mile [2.68 m/km] on all pavements), the optimal IRI trigger values developed in this study can achieve an annualized marginal GHG reduction of 0.57 MMT CO_2-e over the ten-year analysis period, with a marginal *agency cost-effectiveness* of

\$502/metric ton CO_2-e and a marginal *modified total cost-effectiveness* of \$266/metric ton CO_2-e. It should be noted that this result was derived mainly considering two example CAPM treatments (asphalt overlay and concrete grinding with and slab replacement[1]).

- Compared to other measures in the transportation sector, the GHG emissions reduction achieved from roadway maintenance was relatively low in terms of cost-effectiveness. The discussion in this report showed that this was because the cost analysis in this study only included the agency cost and road user fuel cost, and under this situation cost-effectiveness may not be a good indicator for pavement-related strategies because it did not fully capture the additional costs associated with pavement roughness, such as tire wear, vehicle maintenance, reduced vehicle life, and accident costs.
- Sensitivity analysis on constructed smoothness shows that the smoothness achieved from construction has a substantial impact on the results. If poor smoothness (one standard deviation higher than the average historical IRI after the construction) occurs from an M&R activity, then the GHG reduction can be reduced by more than half of that of an average CAPM treatment, and the construction will then result in a very low modified total cost-effectiveness. On the other hand, if a very smooth pavement (one standard deviation lower than the average IRI after the construction) is achieved, then the GHG reduction can be more than twice that for the average CAPM treatment resulting in a higher modified total cost-effectiveness, even if the construction cost was also higher.
- Sensitivity analysis shows that overall the analysis period did not have a substantial impact on the IRI trigger value for each traffic group compared with longer periods. This was expected because this study only considered repeated CAPM treatments and annualized the emissions and energy consumption from the Material Production and Construction phases.

6.2 Recommendations

The following recommendations are made based on the results of this study:

- The life-cycle inventory results developed for this study should be implemented in the Caltrans pavement management system and used to provide first-order estimates of life-cycle GHG emissions from different scenarios for pavement maintenance and rehabilitation (M&R).
- If an increase in agency cost is considered acceptable after both agency and road user costs have been evaluated, then Caltrans should replace its current pavement maintenance and rehabilitation (M&R) triggers, which are based on cracking, with triggers that are based on roughness when planning work on the lane-miles in its network that have the highest 10 to 30 percent of daily directional PCE. This IRI-based trigger level should be moved closer to the optimized 101 inches/mile (1.6 m/km) value identified in this study.

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[1] Although concrete lane replacement was also included in the analysis as an M&R treatment, it was addressed in a very limited and preliminary way.

- Caltrans should continue using the recent changes made to improve smoothness at the time of construction. Among these changes are the inclusion of smoothness requirements in terms of IRI in pavement construction specifications and the development and implementation of a roughness measurement system certification process for Caltrans and contractors. Additional changes in maintenance and rehabilitation design and construction that can cost-effectively improve pavement smoothness at the time of construction should be developed.
- These recommendations should be considered within a larger pavement maintenance and rehabilitation funding level analysis that includes a comparison of the change in IRI trigger values against other alternative strategies used in the transportation sector and in other sectors. This comparison should be in terms of total GHG emissions reduction and GHG emissions reduction cost-effectiveness, and should use the values developed in this study.

6.3 Future Work

The LCA model and its application in the case studies and on the pavement network have shown that LCA can be a useful tool in pavement decision-making for assessing the impacts of pavement M&R strategies on the environment. But there are still numerous areas that can benefit from future research:

- In this study, only relatively short-lived CAPM treatments were selected as potential M&R activities. However, there are situations in which either a major rehabilitation or reconstruction or a less intensive maintenance treatment is warranted by pavement conditions. Rehabilitation followed by pavement preservation and CAPM treatments represents a more comprehensive pavement life-cycle, and studies have shown that this type of M&R strategy is both effective in reducing life-cycle costs and has the potential to reduce the environmental life-cycle impacts. Therefore, it is necessary to develop pavement performance (IRI and macrotexture) models and LCIs of the Material Production and Construction phases for these types of rehabilitation and preservation treatments, and to include these combined treatments in pavement life-cycle assessment.
- This study assumed that the treatments considered had the same life-cycle inventory for materials and construction across all statewide construction projects. Future studies need to improve the life-cycle inventories of Material Production and Construction phases so that when the inventories are applied to the network, they reflect local conditions for material production, transport, and construction.
- Because of the lack of a comprehensive model to address viscoelastic energy dissipation due to structural response in the Use Phase of pavement, this study made the assumption that the pavement surface type stayed the same when M&R activities were performed and it avoided direct comparisons between asphalt pavement and concrete pavement. However, the comparison between asphalt and concrete pavement is inevitable as the research in pavement LCA advances. UCPRC has already started a new study to verify a

number of models, such as ones from University of Lyon (ENTPE), France *(48)*, and the Massachusetts Institute of Technology *(49)*, with vehicle experiments to estimate the fuel consumption change brought by the pavement structure. After this study has been completed, any future pavement LCA study should include the energy consumption and GHG emissions due to the pavement structure in the comprehensive network analysis.

- The cost-effectiveness analysis in this study only included the agency cost and fuel cost, and the total road user cost (such as fuel cost, tire wear cost, car maintenance cost, and safety cost) was not fully evaluated. As a result, the costs in this study do not fully reflect the benefits associated with pavement roughness, and the study's "cost-effectiveness" is not a good indicator for selecting pavement strategies. Therefore, future studies should include both the agency cost and total road user cost to fully analyze the costs from the pavement M&R activities. The benefits can also potentially be expanded to consider the potential for changes in GHG emissions from vehicle replacement and vehicle maintenance as a function of pavement smoothness.

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APPENDIX A: LOOK-UP TABLE OF VEHICLE TAILPIPE CO2 EMISSIONS FACTORS AS A FUNCTION OF IRI AND MPD

As discussed in Section 4.6.3, vehicle tailpipe emissions factors and energy consumption factors of pavement Use Phase were developed for each combination of factorial variables. The vehicle tailpipe CO_2 emissions factors were in the unit metric ton per 1,000 miles of VMT, and the energy consumption factors were in the unit MJ per 1,000 miles of VMT. The equations of these factors are shown in Equation 4.12 and Equation 4.13, where $a1$, $a2$, $b1$, $b2$, and the intercept are the coefficients derived from the linear regressions. The total number of equations is 400 for vehicle energy consumption and 400 for vehicle tailpipe CO_2 emissions, corresponding to the 400 combinations of the categorical variables used to develop the vehicle emission factors as a function of MPD and IRI. Table A.1 and Table A.2 show the complete of coefficients of vehicle energy consumption and tailpipe CO_2 emissions factors, respectively.

Table A.1: Coefficients of Vehicle Energy Consumption Factors under Each Combination of Factorial Variables

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	4	2012	1	25.89704492	151.6393195	5078.736318
Concrete	4	2013	1	25.59773359	149.7918969	5017.976792
Concrete	4	2014	1	25.15742279	147.3833113	4939.417586
Concrete	4	2015	1	24.84171981	145.3985521	4871.152537
Concrete	4	2016	1	24.40878395	142.786319	4785.692132
Concrete	4	2017	1	24.06779334	140.6502405	4713.723573
Concrete	4	2018	1	23.67896531	138.2553544	4635.468493
Concrete	4	2019	1	23.33859678	136.116187	4563.73403
Concrete	4	2020	1	23.01966828	134.106004	4497.047118
Concrete	4	2021	1	22.70625645	132.3133874	4429.890649
Concrete	4	2012	2	96.42064175	103.0045493	10826.85647
Concrete	4	2013	2	96.43476411	103.0244296	10824.88515
Concrete	4	2014	2	96.4613211	103.0329161	10823.28439
Concrete	4	2015	2	96.4480657	103.0592245	10822.25747
Concrete	4	2016	2	96.47345652	103.0684338	10821.18555
Concrete	4	2017	2	96.50470014	103.0806181	10820.47681
Concrete	4	2018	2	96.50143068	103.0927955	10820.11635
Concrete	4	2019	2	96.52090825	103.1164246	10819.99511
Concrete	4	2020	2	96.53021389	103.1324198	10819.92744
Concrete	4	2021	2	96.5834683	103.141459	10819.8727
Concrete	4	2012	3	272.722395	254.0308899	16522.89369
Concrete	4	2013	3	272.71526	254.0064917	16520.34671
Concrete	4	2014	3	272.6966188	253.9848736	16518.24568

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	4	2015	3	272.7248499	253.9840929	16517.10739
Concrete	4	2016	3	272.706983	253.9836752	16515.80257
Concrete	4	2017	3	272.7363853	253.9889823	16515.0336
Concrete	4	2018	3	272.7445105	253.9968776	16514.50189
Concrete	4	2019	3	272.7508404	254.0113844	16514.46494
Concrete	4	2020	3	272.7764146	254.0307121	16514.24711
Concrete	4	2021	3	272.7616376	254.038619	16514.00412
Concrete	4	2012	4	503.8089786	468.2829173	23308.63314
Concrete	4	2013	4	503.8238545	468.2891321	23308.48846
Concrete	4	2014	4	503.8224992	468.2912359	23308.36593
Concrete	4	2015	4	503.8195085	468.29882	23308.25973
Concrete	4	2016	4	503.8266493	468.3044233	23308.35444
Concrete	4	2017	4	503.8397181	468.3119296	23308.37572
Concrete	4	2018	4	503.8397181	468.3119296	23308.32653
Concrete	4	2019	4	503.836729	468.3180208	23308.34562
Concrete	4	2020	4	503.8264389	468.3230397	23308.34535
Concrete	4	2021	4	503.8253805	468.3236	23308.36669
Concrete	4	2012	5	549.2110011	454.8150964	26300.34738
Concrete	4	2013	5	549.2311786	454.8074003	26300.40702
Concrete	4	2014	5	549.2311786	454.8074003	26300.40702
Concrete	4	2015	5	549.2327915	454.8111255	26300.39222
Concrete	4	2016	5	549.2110011	454.8150964	26300.34738
Concrete	4	2017	5	549.2327915	454.8111255	26300.39222
Concrete	4	2018	5	549.2327915	454.8111255	26300.39222
Concrete	4	2019	5	549.2110011	454.8150964	26300.34738
Concrete	4	2020	5	549.2327915	454.8111255	26300.39222
Concrete	4	2021	5	549.2311786	454.8074003	26300.40702
Concrete	2	2012	1	25.18444169	152.3472727	5047.830477
Concrete	2	2013	1	24.88067969	150.4877634	4987.315978
Concrete	2	2014	1	24.46940464	148.075952	4908.938559
Concrete	2	2015	1	24.14089974	146.0741827	4841.106896
Concrete	2	2016	1	23.74799069	143.4472644	4756.149386
Concrete	2	2017	1	23.43060069	141.310665	4684.645332
Concrete	2	2018	1	23.04482527	138.9041774	4606.810271
Concrete	2	2019	1	22.69938102	136.7602347	4535.518403
Concrete	2	2020	1	22.36762361	134.7451627	4469.217964
Concrete	2	2021	1	22.08156894	132.9335059	4402.43757
Concrete	2	2012	2	70.99840819	68.87687493	10128.58376
Concrete	2	2013	2	70.97073973	68.80999452	10123.59592

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	2	2014	2	70.9174983	68.77712742	10119.5803
Concrete	2	2015	2	70.93589723	68.75372819	10116.86127
Concrete	2	2016	2	70.88693208	68.72079425	10114.08017
Concrete	2	2017	2	70.90702981	68.71407907	10112.17361
Concrete	2	2018	2	70.91194178	68.71847838	10111.10009
Concrete	2	2019	2	70.93172732	68.74217392	10110.70489
Concrete	2	2020	2	70.96305841	68.7543	10110.59889
Concrete	2	2021	2	70.93731312	68.76956649	10110.54337
Concrete	2	2012	3	293.180957	272.1343313	17066.94386
Concrete	2	2013	3	293.1659353	272.1009653	17064.7202
Concrete	2	2014	3	293.1649038	272.0893802	17062.77452
Concrete	2	2015	3	293.1878468	272.1001762	17061.85572
Concrete	2	2016	3	293.2132578	272.1090814	17060.67805
Concrete	2	2017	3	293.2233134	272.1181041	17060.07155
Concrete	2	2018	3	293.2194301	272.1217484	17059.58421
Concrete	2	2019	3	293.2345447	272.1379812	17059.57415
Concrete	2	2020	3	293.2518523	272.1614792	17059.23396
Concrete	2	2021	3	293.2799129	272.1747569	17058.82164
Concrete	2	2012	4	540.4568863	499.0666712	24150.32403
Concrete	2	2013	4	540.4507888	499.0712466	24150.34052
Concrete	2	2014	4	540.4470575	499.0757964	24150.38216
Concrete	2	2015	4	540.4527126	499.0759011	24150.31998
Concrete	2	2016	4	540.4732663	499.0840868	24150.52029
Concrete	2	2017	4	540.4793803	499.088214	24150.61733
Concrete	2	2018	4	540.4791167	499.0915682	24150.58158
Concrete	2	2019	4	540.4627915	499.0898948	24150.66153
Concrete	2	2020	4	540.4768121	499.0944493	24150.64628
Concrete	2	2021	4	540.4781827	499.0932279	24150.63002
Concrete	2	2012	5	553.5144932	457.8869611	26054.64141
Concrete	2	2013	5	553.4975312	457.8821745	26054.66953
Concrete	2	2014	5	553.4975312	457.8821745	26054.66953
Concrete	2	2015	5	553.4975312	457.8821745	26054.66953
Concrete	2	2016	5	553.3291816	457.9545258	26054.66302
Concrete	2	2017	5	553.5144932	457.8869611	26054.64141
Concrete	2	2018	5	553.4959184	457.878449	26054.68434
Concrete	2	2019	5	553.4959184	457.878449	26054.68434
Concrete	2	2020	5	553.4975312	457.8821745	26054.66953
Concrete	2	2021	5	553.4975312	457.8821745	26054.66953
Concrete	3	2012	1	25.16631033	149.3280956	5029.365274

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	3	2013	1	24.83685464	147.4933896	4969.05526
Concrete	3	2014	1	24.43280222	145.1041695	4891.000458
Concrete	3	2015	1	24.10433509	143.1362727	4823.265981
Concrete	3	2016	1	23.68593198	140.5588188	4738.486559
Concrete	3	2017	1	23.33626751	138.4520575	4667.139636
Concrete	3	2018	1	22.95269075	136.0763076	4589.56169
Concrete	3	2019	1	22.62373719	133.9715333	4518.374562
Concrete	3	2020	1	22.29971361	131.9910501	4452.269241
Concrete	3	2021	1	22.00764701	130.2178325	4385.632055
Concrete	3	2012	2	63.41877973	61.33005649	10113.50651
Concrete	3	2013	2	63.39463762	61.27039323	10108.4897
Concrete	3	2014	2	63.3653666	61.21866929	10104.46169
Concrete	3	2015	2	63.37879142	61.19147392	10101.70079
Concrete	3	2016	2	63.3425129	61.16350899	10098.86221
Concrete	3	2017	2	63.31612112	61.15480458	10096.95639
Concrete	3	2018	2	63.34937573	61.1518594	10095.8351
Concrete	3	2019	2	63.36876551	61.16405247	10095.42235
Concrete	3	2020	2	63.37488134	61.19159463	10095.23278
Concrete	3	2021	2	63.41297932	61.19311652	10095.12019
Concrete	3	2012	3	296.0145948	269.3744939	16878.21951
Concrete	3	2013	3	295.9986082	269.3467785	16876.00381
Concrete	3	2014	3	296.0052636	269.3255937	16874.05901
Concrete	3	2015	3	296.00456	269.3288896	16873.18869
Concrete	3	2016	3	296.0216252	269.3282361	16872.02371
Concrete	3	2017	3	296.0185178	269.3346284	16871.44017
Concrete	3	2018	3	296.0294233	269.3294316	16870.97471
Concrete	3	2019	3	296.0404959	269.3460292	16870.96705
Concrete	3	2020	3	296.0486334	269.3672901	16870.5942
Concrete	3	2021	3	296.0696833	269.3644709	16870.24661
Concrete	3	2012	4	556.4523452	502.1982307	23811.56881
Concrete	3	2013	4	556.4606682	502.1935737	23811.61534
Concrete	3	2014	4	556.4433068	502.2034967	23811.62099
Concrete	3	2015	4	556.4612444	502.2008115	23811.58141
Concrete	3	2016	4	556.4613542	502.2153742	23811.77321
Concrete	3	2017	4	556.4731118	502.2196329	23811.8569
Concrete	3	2018	4	556.4686438	502.2197351	23811.80205
Concrete	3	2019	4	556.4786085	502.2166255	23811.88788
Concrete	3	2020	4	556.481357	502.2188866	23811.88532
Concrete	3	2021	4	556.4807099	502.2195422	23811.86658

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	3	2012	5	569.9077132	463.4960471	25685.26445
Concrete	3	2013	5	569.9041751	463.5077852	25685.22453
Concrete	3	2014	5	569.9041751	463.5077852	25685.22453
Concrete	3	2015	5	569.9025619	463.5040597	25685.23934
Concrete	3	2016	5	569.9041751	463.5077852	25685.22453
Concrete	3	2017	5	569.9041751	463.5077852	25685.22453
Concrete	3	2018	5	569.8992893	463.5191258	25685.18278
Concrete	3	2019	5	569.9116674	463.4961301	25685.26616
Concrete	3	2020	5	569.9041751	463.5077852	25685.22453
Concrete	3	2021	5	569.9041751	463.5077852	25685.22453
Concrete	5	2012	1	15.46206599	128.5690797	6393.985156
Concrete	5	2013	1	15.26467201	126.8934302	6322.328655
Concrete	5	2014	1	14.97417337	124.8326496	6234.534748
Concrete	5	2015	1	14.74166109	122.974249	6147.123866
Concrete	5	2016	1	14.46741604	120.6775744	6038.282934
Concrete	5	2017	1	14.25195419	118.7001675	5943.610688
Concrete	5	2018	1	13.97458467	116.6030978	5847.192115
Concrete	5	2019	1	13.73108867	114.6624417	5755.386019
Concrete	5	2020	1	13.56646299	112.9173352	5671.265384
Concrete	5	2021	1	13.35138366	111.3798714	5587.032326
Concrete	5	2012	2	155.0261736	131.1352198	16996.15119
Concrete	5	2013	2	155.0566309	131.1245468	16997.21538
Concrete	5	2014	2	155.0577612	131.1093066	16998.22837
Concrete	5	2015	2	155.0706433	131.1015028	16999.59939
Concrete	5	2016	2	155.1206796	131.1033129	17000.45027
Concrete	5	2017	2	155.1496346	131.0924053	17001.54278
Concrete	5	2018	2	155.1335611	131.1005756	17002.6075
Concrete	5	2019	2	155.1528949	131.1083747	17003.71695
Concrete	5	2020	2	155.2133464	131.1061405	17004.74354
Concrete	5	2021	2	155.1998472	131.125347	17005.50093
Concrete	5	2012	3	197.7876012	228.9113468	22526.32772
Concrete	5	2013	3	197.7909139	228.8789182	22527.29848
Concrete	5	2014	3	197.7956051	228.8503069	22527.90559
Concrete	5	2015	3	197.8290193	228.8516333	22530.04711
Concrete	5	2016	3	197.8289715	228.8326538	22531.21178
Concrete	5	2017	3	197.8746851	228.8264594	22533.04754
Concrete	5	2018	3	197.8888341	228.8346477	22534.57614
Concrete	5	2019	3	197.9091783	228.8505384	22536.28189
Concrete	5	2020	3	197.9433789	228.8624481	22537.73779

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	5	2021	3	197.957898	228.8743079	22539.04296
Concrete	5	2012	4	320.4367655	415.4505644	29959.11967
Concrete	5	2013	4	320.6705551	415.5087074	29958.88797
Concrete	5	2014	4	320.5528545	415.4464052	29959.23978
Concrete	5	2015	4	320.631766	415.4703767	29959.19723
Concrete	5	2016	4	320.4622381	415.4981052	29959.29397
Concrete	5	2017	4	320.5305562	415.5062825	29959.32592
Concrete	5	2018	4	320.5574992	415.3898214	29959.67123
Concrete	5	2019	4	320.4712471	415.4857082	29959.61132
Concrete	5	2020	4	320.5031608	415.4812638	29959.73603
Concrete	5	2021	4	320.4628266	415.4768792	29959.7994
Concrete	5	2012	5	418.8340389	358.341391	33090.73249
Concrete	5	2013	5	418.9273501	358.3795312	33090.62082
Concrete	5	2014	5	418.8340389	358.341391	33090.73249
Concrete	5	2015	5	418.9273501	358.3795312	33090.62082
Concrete	5	2016	5	418.9273501	358.3795312	33090.62082
Concrete	5	2017	5	418.8340389	358.341391	33090.73249
Concrete	5	2018	5	418.8340389	358.341391	33090.73249
Concrete	5	2019	5	418.8340389	358.341391	33090.73249
Concrete	5	2020	5	418.8340389	358.341391	33090.73249
Concrete	5	2021	5	418.9273501	358.3795312	33090.62082
Asphalt	2	2012	1	25.47551949	152.600633	5101.312904
Asphalt	2	2013	1	25.16327168	150.7487786	5041.130425
Asphalt	2	2014	1	24.73121489	148.3327549	4963.101277
Asphalt	2	2015	1	24.42861733	146.3316473	4895.537789
Asphalt	2	2016	1	24.03268418	143.7199293	4810.83366
Asphalt	2	2017	1	23.70886592	141.5670962	4739.638792
Asphalt	2	2018	1	23.3297295	139.1605097	4662.061789
Asphalt	2	2019	1	22.98808829	137.0198005	4590.996323
Asphalt	2	2020	1	22.67719434	135.0044179	4524.917449
Asphalt	2	2021	1	22.38197234	133.190924	4458.354532
Asphalt	2	2012	2	141.3334378	150.010785	14159.91957
Asphalt	2	2013	2	141.3835067	150.0124666	14154.30486
Asphalt	2	2014	2	141.3785684	150.0203823	14150.06104
Asphalt	2	2015	2	141.3922842	150.0408169	14147.74189
Asphalt	2	2016	2	141.4287679	150.0452395	14144.94747
Asphalt	2	2017	2	141.4674831	150.0704272	14143.45325
Asphalt	2	2018	2	141.4735863	150.0978722	14143.12688
Asphalt	2	2019	2	141.49532	150.1496313	14143.78124

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	2	2020	2	141.5519792	150.182598	14144.86744
Asphalt	2	2021	2	141.5551589	150.2138113	14145.56597
Asphalt	2	2012	3	292.8215685	296.5529304	26305.40245
Asphalt	2	2013	3	292.8306652	296.5709655	26303.24027
Asphalt	2	2014	3	292.8581915	296.5851523	26301.54635
Asphalt	2	2015	3	292.9068767	296.6270553	26301.52519
Asphalt	2	2016	3	292.9582104	296.6448488	26301.04051
Asphalt	2	2017	3	292.9786419	296.6853079	26301.1451
Asphalt	2	2018	3	293.0152444	296.7017808	26301.24156
Asphalt	2	2019	3	293.0336753	296.7368959	26302.05023
Asphalt	2	2020	3	293.081091	296.7729025	26302.71705
Asphalt	2	2021	3	293.0867542	296.7970575	26302.84239
Asphalt	2	2012	4	464.2227474	465.6754534	39340.31781
Asphalt	2	2013	4	464.2035129	465.6566386	39340.52499
Asphalt	2	2014	4	464.2794367	465.6783121	39340.56162
Asphalt	2	2015	4	464.2762827	465.67288	39340.54836
Asphalt	2	2016	4	464.2283375	465.6266553	39341.13214
Asphalt	2	2017	4	464.0376721	465.6773211	39341.40449
Asphalt	2	2018	4	464.3325364	465.6506019	39341.268
Asphalt	2	2019	4	464.1019455	465.6687767	39341.50381
Asphalt	2	2020	4	464.1182159	465.7031005	39341.43501
Asphalt	2	2021	4	464.3568249	465.6351173	39341.4377
Asphalt	2	2012	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2013	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2014	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2015	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2016	5	518.1318666	509.573743	42015.24471
Asphalt	2	2017	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2018	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2019	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2020	5	518.2969016	509.4984427	42015.26581
Asphalt	2	2021	5	518.2969016	509.4984427	42015.26581
Asphalt	3	2012	1	25.67125907	149.9140317	5083.537641
Asphalt	3	2013	1	25.3590602	148.0786686	5023.553222
Asphalt	3	2014	1	24.94772584	145.7073099	4945.792047
Asphalt	3	2015	1	24.64277507	143.7379517	4878.356896
Asphalt	3	2016	1	24.21851614	141.1614802	4793.871888
Asphalt	3	2017	1	23.9012893	139.0488242	4722.799551
Asphalt	3	2018	1	23.50383505	136.6845427	4645.477488

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	3	2019	1	23.16084604	134.5786194	4574.559208
Asphalt	3	2020	1	22.85148468	132.5982908	4508.668526
Asphalt	3	2021	1	22.5641557	130.8282631	4442.243014
Asphalt	3	2012	2	133.7472831	146.097668	13756.17953
Asphalt	3	2013	2	133.7637937	146.0899867	13750.23699
Asphalt	3	2014	2	133.7661441	146.0988772	13745.675
Asphalt	3	2015	2	133.7984693	146.1153016	13743.09664
Asphalt	3	2016	2	133.8227181	146.120131	13740.05876
Asphalt	3	2017	2	133.8243493	146.1482202	13738.39617
Asphalt	3	2018	2	133.8649239	146.1765939	13737.89299
Asphalt	3	2019	2	133.8715909	146.2083052	13738.46442
Asphalt	3	2020	2	133.939263	146.249468	13739.39541
Asphalt	3	2021	2	133.9720343	146.2775113	13739.98502
Asphalt	3	2012	3	287.8146556	294.4074537	25925.87103
Asphalt	3	2013	3	287.8421416	294.4254052	25923.63533
Asphalt	3	2014	3	287.8619411	294.4373115	25921.84605
Asphalt	3	2015	3	287.9025959	294.4768997	25921.83902
Asphalt	3	2016	3	287.9297249	294.502771	25921.29773
Asphalt	3	2017	3	287.9824496	294.5389356	25921.4201
Asphalt	3	2018	3	288.008289	294.5679033	25921.48984
Asphalt	3	2019	3	288.0353942	294.6054622	25922.29978
Asphalt	3	2020	3	288.0513592	294.6326071	25922.99749
Asphalt	3	2021	3	288.1058293	294.6626668	25923.15405
Asphalt	3	2012	4	461.1156397	464.9129211	39030.38737
Asphalt	3	2013	4	461.0985304	464.8939923	39030.61063
Asphalt	3	2014	4	461.0810847	464.8773729	39030.77449
Asphalt	3	2015	4	461.1132715	464.8735921	39030.78649
Asphalt	3	2016	4	461.1606742	464.9868452	39030.99737
Asphalt	3	2017	4	461.1348948	464.9616364	39031.31258
Asphalt	3	2018	4	461.1371041	464.9644096	39031.174
Asphalt	3	2019	4	461.3382093	464.920097	39031.35893
Asphalt	3	2020	4	461.1197537	464.9499868	39031.46978
Asphalt	3	2021	4	461.1550077	464.8343058	39031.73214
Asphalt	3	2012	5	526.6606282	522.3640737	41680.37312
Asphalt	3	2013	5	526.6606282	522.3640737	41680.37312
Asphalt	3	2014	5	526.6606282	522.3640737	41680.37312
Asphalt	3	2015	5	526.6606282	522.3640737	41680.37312
Asphalt	3	2016	5	526.6606282	522.3640737	41680.37312
Asphalt	3	2017	5	526.6606282	522.3640737	41680.37312

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	3	2018	5	526.8273647	522.287997	41680.39444
Asphalt	3	2019	5	526.6606282	522.3640737	41680.37312
Asphalt	3	2020	5	526.6606282	522.3640737	41680.37312
Asphalt	3	2021	5	526.6606282	522.3640737	41680.37312
Asphalt	4	2012	1	26.10875208	151.82594	5132.240888
Asphalt	4	2013	1	25.76194413	149.9760516	5071.841
Asphalt	4	2014	1	25.33776924	147.5747943	4993.557227
Asphalt	4	2015	1	25.01229478	145.5880102	4925.587263
Asphalt	4	2016	1	24.60635621	142.9715409	4840.401285
Asphalt	4	2017	1	24.25720272	140.8368749	4768.696781
Asphalt	4	2018	1	23.85986852	138.4369509	4690.704899
Asphalt	4	2019	1	23.53567384	136.3038328	4619.182852
Asphalt	4	2020	1	23.21535291	134.2953213	4552.716822
Asphalt	4	2021	1	22.90234263	132.5009526	4485.759507
Asphalt	4	2012	2	171.8830318	158.2942331	15589.00986
Asphalt	4	2013	2	171.9542698	158.3232247	15588.16366
Asphalt	4	2014	2	171.9909415	158.351747	15587.6673
Asphalt	4	2015	2	172.0377988	158.400039	15587.76426
Asphalt	4	2016	2	172.0619936	158.4354231	15587.56146
Asphalt	4	2017	2	172.1282504	158.4490181	15587.75161
Asphalt	4	2018	2	172.1620474	158.4807652	15588.24471
Asphalt	4	2019	2	172.193998	158.5174108	15589.01049
Asphalt	4	2020	2	172.2298352	158.5459063	15589.82102
Asphalt	4	2021	2	172.2335781	158.5654112	15590.39192
Asphalt	4	2012	3	277.5615877	281.7313118	25307.62406
Asphalt	4	2013	3	277.5994871	281.7463126	25305.02167
Asphalt	4	2014	3	277.5892129	281.7598789	25303.04545
Asphalt	4	2015	3	277.6450989	281.7846575	25302.62169
Asphalt	4	2016	3	277.6623307	281.8081564	25301.76827
Asphalt	4	2017	3	277.6901132	281.832154	25301.59769
Asphalt	4	2018	3	277.7151967	281.8586742	25301.6116
Asphalt	4	2019	3	277.7645326	281.8898627	25302.33627
Asphalt	4	2020	3	277.7740997	281.9146858	25303.09465
Asphalt	4	2021	3	277.8115134	281.9367545	25303.31351
Asphalt	4	2012	4	437.7838079	437.5564775	37622.96877
Asphalt	4	2013	4	437.7562359	437.5299419	37623.17214
Asphalt	4	2014	4	437.6959455	437.6208532	37623.06523
Asphalt	4	2015	4	437.9745811	437.579057	37622.97959
Asphalt	4	2016	4	437.7257367	437.598251	37623.50351

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	4	2017	4	437.8621866	437.6165318	37623.54252
Asphalt	4	2018	4	437.8594353	437.6141195	37623.62384
Asphalt	4	2019	4	437.7492	437.5603299	37624.05707
Asphalt	4	2020	4	437.8711893	437.6015438	37623.93762
Asphalt	4	2021	4	437.8814871	437.6344066	37623.92027
Asphalt	4	2012	5	517.0185512	508.6278929	42164.33644
Asphalt	4	2013	5	516.8360077	508.6674608	42164.46025
Asphalt	4	2014	5	516.8360077	508.6674608	42164.46025
Asphalt	4	2015	5	517.0185512	508.6278929	42164.33644
Asphalt	4	2016	5	517.0185512	508.6278929	42164.33644
Asphalt	4	2017	5	516.8518145	508.7039696	42164.31512
Asphalt	4	2018	5	516.8518145	508.7039696	42164.31512
Asphalt	4	2019	5	517.0185512	508.6278929	42164.33644
Asphalt	4	2020	5	516.8518145	508.7039696	42164.31512
Asphalt	4	2021	5	516.8360077	508.6674608	42164.46025
Asphalt	5	2012	1	15.61536675	129.2354569	6444.731992
Asphalt	5	2013	1	15.39520048	127.5616333	6373.101271
Asphalt	5	2014	1	15.1014123	125.4911998	6285.346526
Asphalt	5	2015	1	14.87968278	123.6467279	6197.89357
Asphalt	5	2016	1	14.60719536	121.3429673	6089.088775
Asphalt	5	2017	1	14.3720339	119.3773135	5994.409622
Asphalt	5	2018	1	14.12185541	117.2737677	5897.988496
Asphalt	5	2019	1	13.88454998	115.3406385	5806.168142
Asphalt	5	2020	1	13.67972989	113.6011946	5722.074129
Asphalt	5	2021	1	13.5027996	112.0566813	5637.832548
Asphalt	5	2012	2	144.8741264	153.325267	21019.82858
Asphalt	5	2013	2	144.8598311	153.336594	21020.41357
Asphalt	5	2014	2	144.884792	153.3449915	21020.97839
Asphalt	5	2015	2	144.9020349	153.3535494	21022.25183
Asphalt	5	2016	2	144.8720452	153.3650536	21022.9482
Asphalt	5	2017	2	144.9138035	153.3730387	21024.00456
Asphalt	5	2018	2	144.9008401	153.3815144	21025.18934
Asphalt	5	2019	2	144.9417002	153.3971311	21026.4978
Asphalt	5	2020	2	144.9065596	153.4089329	21027.76768
Asphalt	5	2021	2	144.915555	153.412786	21028.77029
Asphalt	5	2012	3	197.6853403	242.4645185	29820.3171
Asphalt	5	2013	3	197.6164644	242.3774183	29821.01463
Asphalt	5	2014	3	197.5322298	242.4252207	29821.06266
Asphalt	5	2015	3	197.6508126	242.4291153	29823.5591

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	5	2016	3	197.6663579	242.3778919	29824.73921
Asphalt	5	2017	3	197.6963844	242.3610313	29826.99981
Asphalt	5	2018	3	197.5442553	242.3985265	29828.97463
Asphalt	5	2019	3	197.7465784	242.3177864	29831.37219
Asphalt	5	2020	3	197.6677758	242.382739	29833.29797
Asphalt	5	2021	3	197.6453676	242.3551353	29835.28104
Asphalt	5	2012	4	333.2812674	414.8436904	41779.2043
Asphalt	5	2013	4	333.4338742	414.8962112	41778.91679
Asphalt	5	2014	4	333.7008282	414.8397003	41778.96364
Asphalt	5	2015	4	333.489531	414.8923764	41779.06455
Asphalt	5	2016	4	333.6127249	414.8837989	41778.99356
Asphalt	5	2017	4	333.5864211	414.8523192	41779.07334
Asphalt	5	2018	4	333.5818929	414.8490468	41779.21466
Asphalt	5	2019	4	333.5653068	414.8310411	41779.32753
Asphalt	5	2020	4	333.5571699	414.8253362	41779.538
Asphalt	5	2021	4	333.6960781	414.9031504	41779.34868
Asphalt	5	2012	5	418.9725595	436.728591	46343.98611
Asphalt	5	2013	5	418.9725595	436.728591	46343.98611
Asphalt	5	2014	5	418.9725595	436.728591	46343.98611
Asphalt	5	2015	5	418.9725595	436.728591	46343.98611
Asphalt	5	2016	5	418.9725595	436.728591	46343.98611
Asphalt	5	2017	5	418.9725595	436.728591	46343.98611
Asphalt	5	2018	5	418.9725595	436.728591	46343.98611
Asphalt	5	2019	5	418.9725595	436.728591	46343.98611
Asphalt	5	2020	5	418.9725595	436.728591	46343.98611
Asphalt	5	2021	5	418.9725595	436.728591	46343.98611

Notes:

[1]: 2 represents rural restricted-access road; 3 represents rural unrestricted-access road; 4 represents urban restrictedaccess road; and 5 represents urban unrestricted-access road.

[2]: 1 represents passenger car; 2 represents 2-axle truck; 3 represents 3-axle truck; 4 represents 4-axle truck; 5 represents 5 or more axle truck.

Table A.2: Coefficients of Vehicle Tailpipe CO_2 Emission Factors under Each Combination of Factorial Variables

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	4	2012	1	0.00186234	0.010901681	0.365156925
Concrete	4	2013	1	0.00183923	0.010768549	0.360795753
Concrete	4	2014	1	0.001809549	0.010595624	0.355151673
Concrete	4	2015	1	0.001784944	0.010452766	0.350250886
Concrete	4	2016	1	0.00175569	0.010266135	0.344108498
Concrete	4	2017	1	0.001732617	0.010111488	0.338942119
Concrete	4	2018	1	0.001704418	0.009940026	0.333318922
Concrete	4	2019	1	0.001678917	0.009786416	0.328166875
Concrete	4	2020	1	0.001654821	0.009642668	0.323377026
Concrete	4	2021	1	0.00163416	0.009513511	0.318552218
Concrete	4	2012	2	0.007041738	0.007525153	0.789449196
Concrete	4	2013	2	0.00704444	0.007526519	0.789321739
Concrete	4	2014	2	0.007046684	0.007527652	0.78921997
Concrete	4	2015	2	0.007046656	0.007528808	0.789159611
Concrete	4	2016	2	0.007048757	0.007530301	0.789090602
Concrete	4	2017	2	0.007049303	0.00753116	0.789050413
Concrete	4	2018	2	0.007048915	0.007532414	0.789030847
Concrete	4	2019	2	0.007052657	0.00753378	0.789028989
Concrete	4	2020	2	0.007053489	0.007535365	0.789029997
Concrete	4	2021	2	0.007055079	0.007536587	0.789031776
Concrete	4	2012	3	0.019990049	0.018618398	1.209320269
Concrete	4	2013	3	0.019987961	0.018617165	1.209144463
Concrete	4	2014	3	0.019987179	0.01861627	1.209001329
Concrete	4	2015	3	0.019988128	0.018616189	1.208930039
Concrete	4	2016	3	0.019988352	0.01861665	1.208843841
Concrete	4	2017	3	0.019989632	0.018616982	1.208796478
Concrete	4	2018	3	0.019989874	0.018617611	1.208764286
Concrete	4	2019	3	0.019992327	0.018617796	1.208768771
Concrete	4	2020	3	0.019994431	0.01861979	1.208759569
Concrete	4	2021	3	0.019993917	0.018620424	1.20874638
Concrete	4	2012	4	0.036941639	0.034338038	1.708793432
Concrete	4	2013	4	0.036940731	0.034338167	1.708788292
Concrete	4	2014	4	0.036943184	0.03433842	1.708780238
Concrete	4	2015	4	0.036944165	0.034338279	1.708775541
Concrete	4	2016	4	0.036942764	0.034338902	1.708786152
Concrete	4	2017	4	0.036945296	0.034340007	1.708789071
Concrete	4	2018	4	0.036943653	0.034339511	1.70878737
Concrete	4	2019	4	0.036947011	0.034340221	1.708787692

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	4	2020	4	0.036946599	0.034340019	1.708790445
Concrete	4	2021	4	0.03694499	0.034340613	1.708791574
Concrete	4	2012	5	0.040275156	0.033352801	1.928694743
Concrete	4	2013	5	0.040275156	0.033352801	1.928697483
Concrete	4	2014	5	0.040275156	0.033352801	1.928697483
Concrete	4	2015	5	0.040273724	0.033353203	1.928696144
Concrete	4	2016	5	0.040275156	0.033352801	1.928694743
Concrete	4	2017	5	0.040274227	0.033352421	1.928698596
Concrete	4	2018	5	0.040274227	0.033352421	1.928698596
Concrete	4	2019	5	0.040275156	0.033352801	1.928694743
Concrete	4	2020	5	0.040272067	0.033352736	1.928698889
Concrete	4	2021	5	0.040275156	0.033352801	1.928697483
Concrete	2	2012	1	0.001811936	0.010952421	0.362933234
Concrete	2	2013	1	0.001790539	0.01081886	0.358587321
Concrete	2	2014	1	0.001759034	0.010645112	0.352961078
Concrete	2	2015	1	0.001736881	0.01050191	0.348087716
Concrete	2	2016	1	0.001706751	0.01031357	0.341984559
Concrete	2	2017	1	0.001684582	0.010159302	0.336850388
Concrete	2	2018	1	0.0016571	0.009986673	0.331259233
Concrete	2	2019	1	0.001632321	0.009831908	0.326139291
Concrete	2	2020	1	0.001609638	0.009687735	0.321376273
Concrete	2	2021	1	0.001588325	0.009557759	0.316578989
Concrete	2	2012	2	0.005187361	0.005034805	0.738522149
Concrete	2	2013	2	0.005183996	0.00502987	0.738177976
Concrete	2	2014	2	0.005182561	0.005027365	0.737898762
Concrete	2	2015	2	0.005181974	0.00502532	0.737717464
Concrete	2	2016	2	0.005182473	0.005024134	0.737521765
Concrete	2	2017	2	0.005183112	0.005023007	0.737396679
Concrete	2	2018	2	0.005181748	0.005023054	0.737330039
Concrete	2	2019	2	0.005185441	0.00502485	0.737309492
Concrete	2	2020	2	0.005186556	0.005026859	0.737309126
Concrete	2	2021	2	0.005187026	0.005027693	0.737310431
Concrete	2	2012	3	0.021491208	0.019947183	1.249476719
Concrete	2	2013	3	0.02149089	0.019946431	1.249320814
Concrete	2	2014	3	0.021489268	0.019945607	1.24919068
Concrete	2	2015	3	0.021489755	0.019946412	1.249135613
Concrete	2	2016	3	0.021492308	0.019946498	1.249061883
Concrete	2	2017	3	0.021494184	0.019946699	1.249026061
Concrete	2	2018	3	0.021495398	0.019947468	1.248994784

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	2	2019	3	0.021497061	0.019948861	1.248999527
Concrete	2	2020	3	0.021497196	0.019950906	1.248983254
Concrete	2	2021	3	0.021499987	0.019951375	1.248958843
Concrete	2	2012	4	0.039632488	0.036597189	1.770864183
Concrete	2	2013	4	0.039632602	0.036597629	1.770865624
Concrete	2	2014	4	0.039632778	0.036597358	1.770871866
Concrete	2	2015	4	0.039634178	0.036597575	1.77086717
Concrete	2	2016	4	0.039633077	0.036598216	1.770886582
Concrete	2	2017	4	0.03963396	0.036598948	1.770895664
Concrete	2	2018	4	0.039634506	0.036598033	1.770894836
Concrete	2	2019	4	0.039634859	0.036599186	1.770897441
Concrete	2	2020	4	0.03963461	0.036598694	1.770899164
Concrete	2	2021	4	0.039634074	0.036599811	1.770896435
Concrete	2	2012	5	0.040583594	0.033580392	1.910673118
Concrete	2	2013	5	0.040584351	0.033580507	1.910674193
Concrete	2	2014	5	0.040584351	0.033580507	1.910674193
Concrete	2	2015	5	0.040584351	0.033580507	1.910674193
Concrete	2	2016	5	0.04058367	0.033580425	1.910675724
Concrete	2	2017	5	0.04058525	0.033580859	1.910670372
Concrete	2	2018	5	0.040584351	0.033580507	1.910674193
Concrete	2	2019	5	0.040584351	0.033580507	1.910674193
Concrete	2	2020	5	0.040584351	0.033580507	1.910674193
Concrete	2	2021	5	0.040584351	0.033580507	1.910674193
Concrete	3	2012	1	0.001809806	0.010735865	0.361604219
Concrete	3	2013	1	0.001785315	0.010603292	0.357274377
Concrete	3	2014	1	0.001756541	0.010431846	0.351668309
Concrete	3	2015	1	0.001734248	0.010290487	0.346802282
Concrete	3	2016	1	0.001704832	0.010105701	0.340711342
Concrete	3	2017	1	0.001679941	0.009953699	0.335588401
Concrete	3	2018	1	0.001653407	0.009783693	0.330013471
Concrete	3	2019	1	0.001626118	0.009632704	0.324902641
Concrete	3	2020	1	0.001605271	0.009489761	0.320154456
Concrete	3	2021	1	0.001585926	0.009362124	0.315367262
Concrete	3	2012	2	0.004637116	0.004483203	0.737390498
Concrete	3	2013	2	0.004634851	0.00447884	0.737041604
Concrete	3	2014	2	0.004630082	0.004475495	0.73676536
Concrete	3	2015	2	0.004632393	0.004473621	0.73657773
Concrete	3	2016	2	0.004631393	0.004471624	0.736382382
Concrete	3	2017	2	0.004631963	0.004470843	0.736253586

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	3	2018	2	0.00463014	0.004470614	0.736185771
Concrete	3	2019	2	0.00463286	0.004472448	0.736160954
Concrete	3	2020	2	0.004634527	0.004473503	0.736157205
Concrete	3	2021	2	0.004633219	0.004474796	0.736155673
Concrete	3	2012	3	0.021700648	0.01974743	1.235622463
Concrete	3	2013	3	0.021701025	0.019744698	1.235471833
Concrete	3	2014	3	0.021699216	0.019743593	1.235341188
Concrete	3	2015	3	0.021700208	0.01974375	1.235288337
Concrete	3	2016	3	0.021702915	0.019743801	1.235212891
Concrete	3	2017	3	0.021701502	0.019744206	1.235180817
Concrete	3	2018	3	0.021702597	0.019744185	1.235151301
Concrete	3	2019	3	0.021701422	0.019745245	1.235159013
Concrete	3	2020	3	0.021703559	0.019746307	1.235140712
Concrete	3	2021	3	0.021703838	0.019746898	1.235118669
Concrete	3	2012	4	0.040804776	0.036826095	1.746023962
Concrete	3	2013	4	0.040804744	0.036826904	1.746027204
Concrete	3	2014	4	0.040806945	0.036827212	1.74602839
Concrete	3	2015	4	0.04080668	0.036826954	1.746026596
Concrete	3	2016	4	0.040806806	0.036828098	1.746045048
Concrete	3	2017	4	0.040806858	0.036828457	1.746053475
Concrete	3	2018	4	0.0408087 0	0.03682797	1.746048675
Concrete	3	2019	4	0.040807015	0.036828243	1.746056274
Concrete	3	2020	4	0.040806459	0.036829349	1.746055191
Concrete	3	2021	4	0.040808642	0.036828958	1.746053316
Concrete	3	2012	5	0.041797028	0.033990126	1.88358281
Concrete	3	2013	5	0.041796642	0.033990118	1.883582643
Concrete	3	2014	5	0.0417937 0	0.033990394	1.883582694
Concrete	3	2015	5	0.041797028	0.033990126	1.88358281
Concrete	3	2016	5	0.041794482	0.033990433	1.883582937
Concrete	3	2017	5	0.041794482	0.033990433	1.883582937
Concrete	3	2018	5	0.041796914	0.03399015	1.883580147
Concrete	3	2019	5	0.041797028	0.033990126	1.88358281
Concrete	3	2020	5	0.041794482	0.033990433	1.883582937
Concrete	3	2021	5	0.041794482	0.033990433	1.883582937
Concrete	5	2012	1	0.001112367	0.009243156	0.459736358
Concrete	5	2013	1	0.001095652	0.009123471	0.454591213
Concrete	5	2014	1	0.001075436	0.008974102	0.448289536
Concrete	5	2015	1	0.001061666	0.008841135	0.442009861
Concrete	5	2016	1	0.001042799	0.008676324	0.43419209

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	5	2017	1	0.001025967	0.00853409	0.427393092
Concrete	5	2018	1	0.001005958	0.008383502	0.420467813
Concrete	5	2019	1	0.000989642	0.00824447	0.413873069
Concrete	5	2020	1	0.000975722	0.008118948	0.407833608
Concrete	5	2021	1	0.000962903	0.008008166	0.401781427
Concrete	5	2012	2	0.01131023	0.009566659	1.239884418
Concrete	5	2013	2	0.01131644	0.009564989	1.239987759
Concrete	5	2014	2	0.01131724	0.009563841	1.240084965
Concrete	5	2015	2	0.011316863	0.009564998	1.240201554
Concrete	5	2016	2	0.011320171	0.009563542	1.240285005
Concrete	5	2017	2	0.011323623	0.009563615	1.240376905
Concrete	5	2018	2	0.011321935	0.009564395	1.240467083
Concrete	5	2019	2	0.011324657	0.009565584	1.240557754
Concrete	5	2020	2	0.01132507	0.009565606	1.240645496
Concrete	5	2021	2	0.011326927	0.009565629	1.24070948
Concrete	5	2012	3	0.014485991	0.016772231	1.648606503
Concrete	5	2013	3	0.014486475	0.016770128	1.648694945
Concrete	5	2014	3	0.014486916	0.016767758	1.648755023
Concrete	5	2015	3	0.014489694	0.016767123	1.648928556
Concrete	5	2016	3	0.014490904	0.016766425	1.649025861
Concrete	5	2017	3	0.014492113	0.016766764	1.649171932
Concrete	5	2018	3	0.014493306	0.016766309	1.649295022
Concrete	5	2019	3	0.014494417	0.016768264	1.649427389
Concrete	5	2020	3	0.014498562	0.016768623	1.64954414
Concrete	5	2021	3	0.014499775	0.016768691	1.649647328
Concrete	5	2012	4	0.023501151	0.030461163	2.196265629
Concrete	5	2013	4	0.023500446	0.030461163	2.196276718
Concrete	5	2014	4	0.023503064	0.030461109	2.196286247
Concrete	5	2015	4	0.023503587	0.030460724	2.196296081
Concrete	5	2016	4	0.023502851	0.030460954	2.196306407
Concrete	5	2017	4	0.023502309	0.030460756	2.196316962
Concrete	5	2018	4	0.023501288	0.030461412	2.196324003
Concrete	5	2019	4	0.023503376	0.030461902	2.196331192
Concrete	5	2020	4	0.023503163	0.030461466	2.196340654
Concrete	5	2021	4	0.023502436	0.030462039	2.19634508
Concrete	5	2012	5	0.030717506	0.026279922	2.42664644
Concrete	5	2013	5	0.030717458	0.026279844	2.426649344
Concrete	5	2014	5	0.030716518	0.026279518	2.426647622
Concrete	5	2015	5	0.030717458	0.026279844	2.426649344

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Concrete	5	2016	5	0.030717458	0.026279844	2.426649344
Concrete	5	2017	5	0.030717893	0.02627993	2.426646606
Concrete	5	2018	5	0.030716518	0.026279518	2.426647622
Concrete	5	2019	5	0.030717506	0.026279922	2.42664644
Concrete	5	2020	5	0.030717506	0.026279922	2.42664644
Concrete	5	2021	5	0.030716587	0.026279488	2.426650387
Asphalt	2	2012	1	0.001832892	0.010971093	0.366811006
Asphalt	2	2013	1	0.001810107	0.010837027	0.362492072
Asphalt	2	2014	1	0.001780185	0.010664307	0.356885594
Asphalt	2	2015	1	0.001756906	0.010520561	0.352036862
Asphalt	2	2016	1	0.001727383	0.01033262	0.34595523
Asphalt	2	2017	1	0.001706508	0.010177795	0.340841415
Asphalt	2	2018	1	0.001680025	0.010005442	0.335268201
Asphalt	2	2019	1	0.001653871	0.00985167	0.330165197
Asphalt	2	2020	1	0.001631288	0.009706124	0.325422422
Asphalt	2	2021	1	0.001610878	0.009577169	0.32063898
Asphalt	2	2012	2	0.010324676	0.010959038	1.033040805
Asphalt	2	2013	2	0.010327937	0.010958597	1.032655227
Asphalt	2	2014	2	0.010326144	0.010959213	1.032367025
Asphalt	2	2015	2	0.010330585	0.010961194	1.03221586
Asphalt	2	2016	2	0.01033028	0.010962187	1.032027512
Asphalt	2	2017	2	0.010332876	0.010963638	1.031934767
Asphalt	2	2018	2	0.01033564	0.010966948	1.031920765
Asphalt	2	2019	2	0.010337022	0.010969922	1.031981622
Asphalt	2	2020	2	0.010340496	0.010972561	1.032074556
Asphalt	2	2021	2	0.010343359	0.010974557	1.03213105
Asphalt	2	2012	3	0.021453641	0.021726169	1.92640462
Asphalt	2	2013	3	0.02145471	0.021727467	1.926261633
Asphalt	2	2014	3	0.021457115	0.021728622	1.926151405
Asphalt	2	2015	3	0.021459212	0.021731476	1.926166252
Asphalt	2	2016	3	0.021462169	0.021734044	1.926144963
Asphalt	2	2017	3	0.021466399	0.021735863	1.926165276
Asphalt	2	2018	3	0.021467135	0.021738195	1.926179263
Asphalt	2	2019	3	0.021467697	0.021740596	1.92624777
Asphalt	2	2020	3	0.021473124	0.021742823	1.92630731
Asphalt	2	2021	3	0.021474837	0.021744901	1.926322277
Asphalt	2	2012	4	0.034038633	0.034148758	2.884736666
Asphalt	2	2013	4	0.034039537	0.03414389	2.884766668
Asphalt	2	2014	4	0.034036388	0.034146255	2.884779934

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	2	2015	4	0.034039791	0.034145911	2.884768827
Asphalt	2	2016	4	0.03403233	0.034142543	2.884830575
Asphalt	2	2017	4	0.034047129	0.034145447	2.88483877
Asphalt	2	2018	4	0.034030757	0.034140961	2.884848532
Asphalt	2	2019	4	0.034046075	0.034144738	2.884846858
Asphalt	2	2020	4	0.03404759	0.034148323	2.884845578
Asphalt	2	2021	4	0.034045924	0.034144608	2.884850847
Asphalt	2	2012	5	0.037975438	0.037365453	3.081135614
Asphalt	2	2013	5	0.037975438	0.037365453	3.081135614
Asphalt	2	2014	5	0.037975438	0.037365453	3.081135614
Asphalt	2	2015	5	0.037975438	0.037365453	3.081135614
Asphalt	2	2016	5	0.037995458	0.037358664	3.081147137
Asphalt	2	2017	5	0.037991795	0.037370069	3.081108499
Asphalt	2	2018	5	0.037997033	0.037362302	3.081132677
Asphalt	2	2019	5	0.037975438	0.037365453	3.081135614
Asphalt	2	2020	5	0.037975438	0.037365453	3.081135614
Asphalt	2	2021	5	0.037975438	0.037365453	3.081135614
Asphalt	3	2012	1	0.001849026	0.010778028	0.365530024
Asphalt	3	2013	1	0.00182524	0.010646261	0.361223996
Asphalt	3	2014	1	0.001794071	0.010475469	0.355642714
Asphalt	3	2015	1	0.001770678	0.010334379	0.350800552
Asphalt	3	2016	1	0.001743159	0.010149509	0.344731143
Asphalt	3	2017	1	0.001718887	0.009998113	0.339626797
Asphalt	3	2018	1	0.001691055	0.0098279	0.334074421
Asphalt	3	2019	1	0.001667178	0.009676049	0.328982501
Asphalt	3	2020	1	0.001644681	0.009533948	0.324251121
Asphalt	3	2021	1	0.001624315	0.009407218	0.319479088
Asphalt	3	2012	2	0.009773078	0.010673128	1.003532397
Asphalt	3	2013	2	0.009770389	0.010672854	1.00312251
Asphalt	3	2014	2	0.00977373	0.010673038	1.002810042
Asphalt	3	2015	2	0.009776177	0.010674401	1.002640175
Asphalt	3	2016	2	0.009775146	0.010675263	1.002435469
Asphalt	3	2017	2	0.009777784	0.010676914	1.002328262
Asphalt	3	2018	2	0.009781231	0.010679263	1.002303203
Asphalt	3	2019	2	0.009783248	0.010682428	1.002353336
Asphalt	3	2020	2	0.009784807	0.010686005	1.002435423
Asphalt	3	2021	2	0.009786231	0.010687324	1.002489368
Asphalt	3	2012	3	0.021085438	0.02156957	1.898623475
Asphalt	3	2013	3	0.02109012	0.021570499	1.898473506

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	3	2014	3	0.021090583	0.021572519	1.898355015
Asphalt	3	2015	3	0.021093964	0.021574957	1.898369878
Asphalt	3	2016	3	0.021096087	0.021577143	1.89834668
Asphalt	3	2017	3	0.021099314	0.021579936	1.898366822
Asphalt	3	2018	3	0.021101297	0.02158167	1.898380893
Asphalt	3	2019	3	0.021103933	0.021585059	1.898446278
Asphalt	3	2020	3	0.021108518	0.02158694	1.898506448
Asphalt	3	2021	3	0.021110907	0.021588414	1.898527492
Asphalt	3	2012	4	0.033815576	0.034088912	2.862028452
Asphalt	3	2013	4	0.033818345	0.034087616	2.86204531
Asphalt	3	2014	4	0.033808241	0.034094198	2.862049605
Asphalt	3	2015	4	0.033833524	0.034090648	2.862036126
Asphalt	3	2016	4	0.033804487	0.03409042	2.862103356
Asphalt	3	2017	4	0.033820839	0.034096953	2.862098548
Asphalt	3	2018	4	0.033802976	0.034088865	2.862122655
Asphalt	3	2019	4	0.033820109	0.034096188	2.862107482
Asphalt	3	2020	4	0.03380659	0.034092282	2.862130414
Asphalt	3	2021	4	0.033819622	0.034096091	2.862111847
Asphalt	3	2012	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2013	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2014	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2015	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2016	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2017	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2018	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2019	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2020	5	0.038621245	0.038309113	3.056549153
Asphalt	3	2021	5	0.038621245	0.038309113	3.056549153
Asphalt	4	2012	1	0.001876219	0.010914562	0.369037412
Asphalt	4	2013	1	0.001854146	0.010782085	0.364698365
Asphalt	4	2014	1	0.001824042	0.010609294	0.359077828
Asphalt	4	2015	1	0.001800295	0.010466722	0.354198022
Asphalt	4	2016	1	0.001771294	0.010279044	0.348078859
Asphalt	4	2017	1	0.001747518	0.010125342	0.342929998
Asphalt	4	2018	1	0.001716612	0.009953112	0.337329717
Asphalt	4	2019	1	0.001693318	0.009800209	0.332192688
Asphalt	4	2020	1	0.001670324	0.009655745	0.327420275
Asphalt	4	2021	1	0.001649835	0.009526733	0.322610986
Asphalt	4	2012	2	0.012553133	0.011560899	1.137285825

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	4	2013	2	0.012556451	0.011564851	1.137245199
Asphalt	4	2014	2	0.012560835	0.011567753	1.137226028
Asphalt	4	2015	2	0.012567335	0.011569839	1.137252925
Asphalt	4	2016	2	0.012570129	0.011572265	1.137252867
Asphalt	4	2017	2	0.012569885	0.011573786	1.137283153
Asphalt	4	2018	2	0.012574128	0.011575101	1.137331343
Asphalt	4	2019	2	0.012573549	0.011577828	1.137399586
Asphalt	4	2020	2	0.012579934	0.011580319	1.137466708
Asphalt	4	2021	2	0.012579104	0.011581478	1.137514732
Asphalt	4	2012	3	0.020332832	0.020636288	1.852893111
Asphalt	4	2013	3	0.020332659	0.02063766	1.85272051
Asphalt	4	2014	3	0.020335155	0.02063908	1.852587615
Asphalt	4	2015	3	0.020338004	0.020640802	1.852572009
Asphalt	4	2016	3	0.020339445	0.020643045	1.852523842
Asphalt	4	2017	3	0.020341408	0.020644932	1.852523067
Asphalt	4	2018	3	0.020342432	0.020646317	1.852535215
Asphalt	4	2019	3	0.020346548	0.020648752	1.852595174
Asphalt	4	2020	3	0.02034914	0.020651165	1.852659489
Asphalt	4	2021	3	0.020349193	0.020652665	1.852683241
Asphalt	4	2012	4	0.03209003	0.032090273	2.758342792
Asphalt	4	2013	4	0.032087897	0.032088419	2.758360044
Asphalt	4	2014	4	0.032086321	0.032086797	2.758374811
Asphalt	4	2015	4	0.032085216	0.03208582	2.758379921
Asphalt	4	2016	4	0.032098152	0.032087006	2.758407759
Asphalt	4	2017	4	0.032096003	0.032084993	2.758432849
Asphalt	4	2018	4	0.032088854	0.032083877	2.758443049
Asphalt	4	2019	4	0.032104124	0.032087527	2.758437597
Asphalt	4	2020	4	0.032103623	0.032087142	2.758445973
Asphalt	4	2021	4	0.032095589	0.032086779	2.758467041
Asphalt	4	2012	5	0.037893891	0.037303795	3.09205854
Asphalt	4	2013	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2014	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2015	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2016	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2017	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2018	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2019	5	0.037893891	0.037303795	3.09205854
Asphalt	4	2020	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2021	5	0.037897752	0.037303877	3.092060208

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	5	2012	1	0.001123943	0.009291257	0.463408019
Asphalt	5	2013	1	0.001105561	0.00917158	0.45826631
Asphalt	5	2014	1	0.001086466	0.00902329	0.451962561
Asphalt	5	2015	1	0.001069826	0.00888975	0.445687936
Asphalt	5	2016	1	0.001051139	0.008724436	0.437872925
Asphalt	5	2017	1	0.001035232	0.008582857	0.4310739
Asphalt	5	2018	1	0.001016327	0.008432073	0.42414879
Asphalt	5	2019	1	0.00099884	0.008293196	0.417555686
Asphalt	5	2020	1	0.000984978	0.008168213	0.41151665
Asphalt	5	2021	1	0.000971819	0.008057446	0.405466128
Asphalt	5	2012	2	0.010565975	0.011187059	1.533392639
Asphalt	5	2013	2	0.010570156	0.01118635	1.533467647
Asphalt	5	2014	2	0.010569591	0.0111876	1.53353856
Asphalt	5	2015	2	0.010567568	0.011189425	1.533655235
Asphalt	5	2016	2	0.010569009	0.011189809	1.533725459
Asphalt	5	2017	2	0.010570257	0.011190702	1.533822385
Asphalt	5	2018	2	0.01056964	0.011191805	1.533922413
Asphalt	5	2019	2	0.010571479	0.011192644	1.534033246
Asphalt	5	2020	2	0.010572735	0.011193107	1.534137269
Asphalt	5	2021	2	0.010574575	0.011193935	1.53421794
Asphalt	5	2012	3	0.014478114	0.017753547	2.182781492
Asphalt	5	2013	3	0.014475923	0.01775157	2.182844673
Asphalt	5	2014	3	0.014472473	0.017750311	2.182872809
Asphalt	5	2015	3	0.014473591	0.017750403	2.183076824
Asphalt	5	2016	3	0.014474015	0.017748859	2.183176454
Asphalt	5	2017	3	0.014472595	0.017749489	2.18335814
Asphalt	5	2018	3	0.014475593	0.017750001	2.18351221
Asphalt	5	2019	3	0.014474959	0.01775033	2.183692309
Asphalt	5	2020	3	0.014475617	0.017751342	2.183844433
Asphalt	5	2021	3	0.014477351	0.017751741	2.183991181
Asphalt	5	2012	4	0.024470713	0.030419196	3.062864751
Asphalt	5	2013	4	0.024467095	0.030413316	3.062887019
Asphalt	5	2014	4	0.024452382	0.030419111	3.062899945
Asphalt	5	2015	4	0.024466097	0.030413958	3.062908129
Asphalt	5	2016	4	0.02446283	0.030409967	3.062928233
Asphalt	5	2017	4	0.024455963	0.030415519	3.062927375
Asphalt	5	2018	4	0.024477094	0.030412192	3.062930359
Asphalt	5	2019	4	0.024476245	0.030410849	3.062945263
Asphalt	5	2020	4	0.024455374	0.030417168	3.062952729

Surface Type	Road Type and Access Type[1]	Year	Vehicle Type[2]	*a*1	*a*2	Intercept
Asphalt	5	2021	4	0.024445859	0.030413152	3.062976786
Asphalt	5	2012	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2013	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2014	5	0.030727395	0.03203113	3.398543389
Asphalt	5	2015	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2016	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2017	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2018	5	0.030727395	0.03203113	3.398543389
Asphalt	5	2019	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2020	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2021	5	0.030714692	0.032026537	3.398572515

Notes:

[1]: 2 represents rural restricted-access road; 3 represents rural unrestricted-access road; 4 represents urban restrictedaccess road; and 5 represents urban unrestricted-access road.

[2]: 1 represents passenger car; 2 represents 2-axle truck; 3 represents 3-axle truck; 4 represents 4-axle truck; 5 represents 5 or more axle truck.